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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 FUEL FROM ENRICHED URANIUM DIOXIDE

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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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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 enriched-uranium, light-water reactor (LWR) 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 1500 metric tons of LWR 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 Appendix A and ORNL-4992.

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

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1.0 SUMMARY AND CONCLUSIONS

A study was made to determine the cost and effectiveness of radioactive (radwaste) and chemical (chemwaste) treatment systems for decreasing the release of radioactive materials and nonradioactive noxious chemicals from model enriched-uranium, light-water reactor (LWR) fuel fabrication plants and to determine the radiological impact (dose commitment) of the released radioactive materials on the environment. The model plants convert enriched uranium hexafluoride (UF_6), containing 4% uranium-235, into uranium dioxide (UO_2) pellets which are inserted into fuel tubes. One model plant uses the wet ammonium diuranate (ADU) process, and the second plant the dry direct conversion (DC) process. The plants will each process 1500 metric tons of uranium per year, i.e., a nominal 5-ton/day plant operating for 300 days. The ^{231}Th, ^{234}Th, and ^{234}Pa daughters are in equilibrium with the uranium isotopes in the UF_6 feed. These radionuclides are considered in the radiological impact studies. The gaseous waste effluents from the plants are treated to remove radioactive materials and noxious chemicals, i.e., fluoride, nitrogen oxides, and ammonia and the treated gases are released. The liquid wastes are treated to remove radioactive materials and noxious chemicals, i.e., nitrate, fluoride, and ammonia, and the treated liquids are released through a system of lagoons. In advanced case studies the treated water, the recovered nitrogen oxides (as nitric acid) and the ammonia are recycled for reuse. The solid radwastes and chemwastes are retained on site in storage or are shipped to licensed commercial burial grounds. The model plants are evaluated at two locations, a midwestern site and a southeastern coastal site, and typical meteorological patterns and population densities are used for each site.

Four conceptual cases and their corresponding flowsheets were prepared for treating the wastes from each model plant. Case 1 is the base case and represents the lowest cost and the technology used in some current plants. In each of the succeeding cases, radwaste treatment equipment is added to accomplish specific objectives. The technology used in the advanced cases has been used in other industrial applications but has not been used at fuel fabrication plants and, consequently, additional development work is required for these techniques. It is expected that these techniques could be "reduced to practice" in a development program extending over a 5-year period. The advanced technology is generally suited to existing plants but backfitting must be considered on an individual basis. 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 Tables 4.8 and 4.9.

The annual amounts of radioactive materials released (the source term), the capital, annual, and contribution to power costs and the radiological impact are calculated for each case. The annual costs are then apportioned into the costs for removing chemical and radioactive materials (Table 8.1). The annual radwaste treatment costs are then compared with the radiological impact (dose commitment) from the released radioactive materials. All of the annual doses quoted in this study are dose commitments. The annual chemwaste treatment costs are compared with the amount of chemical removal achieved. Radiation dose commitments are estimated for each case. The dose commitments for gaseous effluents selected for comparison with treatment costs are (1) maximum annual individual total body - bone - kidney - and lung dose (mrem) at 0.5 mile from the plant (factors are provided to calculate longer distances), and (2) annual population dose (man-rem) out to a distance of 55 miles. Average annual individual total body dose out to a distance of 55 miles is also estimated but is not used in the cost-benefit comparison. Typical population densities are used for the 55-mile radii circles around each plant to estimate population dose from radioactive gaseous releases. Dose commitments from liquid effluents are compared with treatment costs on two bases, i.e., annual individual total body dose (mrem)

from aquatic pathways after dilution in a 15-cfs stream and after the 15-cfs stream flows into a 1300-cfs stream at the midwestern site. At the coastal site, the total body dose is estimated after the liquid effluent is diluted by a 15-cfs stream and after the 15-cfs stream flows into an estuary. The 15-cfs stream is not considered to be a credible source of drinking water or fish or a locale for swimming because of its very small size. This is particularly true for Case 1 where significant amounts of nonradioactive chemicals are released. However, it is used to illustrate the maximum impact at the point of discharge to an unrestricted area from the model plants. Population dose (man-rem) is not estimated for liquid effluents, since it is not practical to predict a population distribution along a river. However, comparisons of dose from gaseous and liquid effluents can be made. For example, for the midwestern plant, the maximum annual individual total body dose from the model plants in Case 1 is 0.89 mrem from gaseous effluents at a distance of 0.5 mile. This compares with an individual dose of 0.07 mrem from aquatic pathways in the 1300-cfs river, i.e., about 8% of the maximum gaseous dose. If 16,000 people are exposed to aqueous pathways from the river, the population dose is 1.1 man-rem, which is equal to the population dose from gaseous effluents to the 3.6 million people living in a circle 55 miles around the midwestern plant.

Internal exposure to radiation through inhalation and ingestion of radionuclides from gaseous effluents accounts for 68% of the total body dose to individuals and population around the plant. The principal radionuclide contributing to this dose is ^{234}U. Estimated maximum total body doses do not exceed 1 mrem/yr to individuals living within 0.5 to 1 mile from the base Case 1 plant at either site. Average dose to individuals is slightly lower at the midwestern than at the coastal site due to meteorological differences, but the maximum individual dose is not significantly different at the two sites. The population dose is slightly higher at the midwestern site because of the greater population density. Population dose commitments (0.85 man-rem for the coastal site and 1.1 man-rem for the midwestern site) represent only thousandths of a percent of the population dose received from background radiation.

The long-term 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 8.2×10^{-4} millirem (Sect. 7.8.3). This estimate is based on the assumptions that all of the radioactive material is deposited within 50 miles of the plant and that none of the material is lost by runoff in rainwater, deep penetration into the soil, etc. The estimated average annual dose is based on very conservative assumptions.

The radwaste treatment costs and the radiation dose from the gaseous effluents from the model ADU and DC plants are shown in Table 8.2. The doses in Case 4 are about 200,000 times lower than in Case 1. In both model plants the largest dose is for bone, followed by lung, kidney, and total body dose. The maximum annual individual dose from gaseous effluents at 0.5 mile from the ADU plant is compared with the annual gaseous radwaste treatment cost in Fig. 8.1. For the coastal site, the total body dose decreases from 0.89 mrem in Case 1 to 4.6×10^{-6} mrem in Case 4, a factor of about 200,000 for an additional annual cost of $351,000. Similarly, the annual average dose to the population at the coastal site decreases from 0.85 man-rem for Case 1 to 4.6×10^{-6} man-rem for Case 4 for the same additional cost (Fig. 8.2). (See Sect. 8.0 for comparable figures for the DC process.)

The incremental costs and doses between the case studies indicate that the cost-benefit ratio, in terms of dollars per mrem reduction of maximum annual total body dose from gaseous effluents at 0.5 mile, increases from $130,000 per mrem for the increment ADU Case 1/ADU Case 2, to $1,630,000 for ADU Case 2/ADU Case 3, to $369,000,000 for ADU Case 3/ADU Case 4 with a sharp increase in cost-benefit ratio for the increment ADU Case 3/ADU Case 4; i.e., the costs for the ADU and DC plants for the increment Case 1/Case 2 and Case 2/Case 3 show factors of increased cost of 7 to 13 vs an increase by factors of about 200 to 300 for the Case 3/Case 4 increment (Table 8.3).

The radwaste treatment costs and the radiation dose from the liquid effluents from the model ADU and DC plants are shown in Table 8.4 after dilution in the 15-cfs stream and 1300-cfs river at the midwestern site

and after dilution in the 15-cfs stream and the estuary at the coastal site. A comparison of the annual costs and dose for the ADU and DC model plants after dilution in the 1300-cfs river is shown in Fig. 8.6. The dose is the same for the midwestern and coastal sites from the 15-cfs stream, but the dose for the river and for the estuary are not exactly comparable because the estuary is not a source of drinking water. In ADU Case 1, the maximum annual individual dose from liquid effluents in the 15-cfs stream is 6.0 mrem, which is about 7 times higher than the maximum annual individual dose of 0.89 mrem from the gaseous effluents at a 0.5-mile distance for ADU Case 1. However, the annual dose in the 1300-cfs river at the midwestern site is 0.069 mrem, about 13 to 90 times lower than for either the gaseous or 15-cfs cases. In ADU Case 4, the annual dose from the 15-cfs stream is reduced to 1.3×10^{-5} mrem, a factor of 400,000 times lower than for ADU Case 1, for an additional annual expenditure of $896,000. The annual doses in the river and estuary are reduced to extremely low levels, i.e., 1.5×10^{-7} mrem and 3.2×10^{-17} mrem, respectively, for the same annual cost.

The incremental costs and doses between the case studies indicate that the cost-benefit ratio for the ADU process, in terms of dollars per mrem decrease in annual total body dose for the 15-cfs stream, increases from $65,000/mrem in ADU Case 1/ADU Case 2, to $73,000/mrem in ADU Case 2/ADU Case 3, to $1,170,000/mrem in ADU Case 3/ADU Case 4. Again, a sharp increase is noted for the ADU Case 3/ADU Case 4 increment; i.e., the cost-benefit ratio for the ADU plant for the increments Case 1/Case 2 and Case 2/Case 3 for the 15-cfs stream show moderate increases (about $65,000 to $73,000 per mrem) vs an increase by a factor of about 15 for the Case 3/Case 4 increment. The cost-benefit ratio for the 1300-cfs river increases from $5,470,000/mrem for the ADU Case 1/ADU Case 2 increment to $102,600,000 per mrem for the ADU Case 3/ADU Case 4 increment. The cost-benefit ratios for the DC Case 1/DC Case 2 and DC Case 2/DC Case 3 increments are higher than for the corresponding ADU cases, i.e., $26,300,000 and $9,110,000 per mrem, respectively (Table 8.6).

The amount of chemicals released in the liquid wastes is compared with the annual costs for chemwaste treatment for the model ADU and DC

plants in Figs. 8.8 and 8.9. In ADU Case 4, the fluoride and ammonia releases are effectively reduced to zero, and in Cases 3 and 4 the amount of nitrate to a low level, i.e., to less than 4 ppm in the plant effluent. The annual cost of chemwaste treatment in ADU Case 4 amounts to $924,000, about 40% of the total waste treatment cost. The ammonia and most of the nitrate is recycled in DC Cases 3 and 4. The amount of nitrate released in DC Cases 3 and 4 is reduced to less than 4 ppm in the plant effluent at an annual chemwaste treatment cost of $305,000 and $315,000. The fluoride entering the DC plant as UF_6 appears in the gaseous effluent and not in the liquid effluent as in the ADU case. Consequently, in the DC model plant part of the gaseous chemwaste treatment costs are assigned to removal of hydrofluoric acid from the gaseous wastes. These vary from about $8,000 per year in DC Case 1 to about $40,000 per year in DC Case 4 (Table 8.1).

In the preceding correlations, the annual waste treatment costs are divided between the liquid chemwastes, the liquid radwastes, and the gaseous radwastes (Sect. 8.0). However, it is also valid to correlate the total waste treatment costs with the radiological doses, since both radwaste and chemwaste treatments are required in some situations. On this basis, the cost-benefit ratios in terms of dollars/mrem reduction in the maximum annual individual total body dose from the ADU plant after dilution in the 15-cfs stream are $134,000 for the increment ADU Case 1/ ADU Case 2, $182,000 for ADU Case 2/ADU Case 3, and $2,120,000 for ADU Case 3/ADU Case 4. The increase in the second increment over the first is about 36%, and the third increment increases over the second by a factor of about 12. The cost-benefit ratios for the DC plants on the same basis are $674,000 for the increment DC Case 1/DC Case 2, $195,000 for DC Case 2/DC Case 3, and $201,000 for DC Case 2/DC Case 4.

The capital costs of the waste treatment systems in the case studies vary from a low of $0.586 million for DC Case 1 to $4.99 million for ADU Case 4 (Table 6.1) or up to about 14% of the $36 million which is taken as the cost for the base plant. The annual costs range from $202,000 to $2,515,000 per year which correspond to contributions to power costs of 5.5×10^{-4} and 6.4×10^{-3} mill/kWhr, respectively (Table 8.1). These values are less than 0.1% of an estimated total power generation cost of 7 to 10 mills/kWhr.

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 that fabricate slightly enriched uranium 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 alternative radioactive waste treatment systems under consideration is measured by comparing the amounts of radioactive materials released by the various systems and the relative impact of these releases on the environment. The amount of radioactive materials released in each case is called "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.

LWR fuels are fabricated from uranium that has been enriched in its content of ^{235}U. The enriching process occurs at a gaseous diffusion plant where the natural uranium is processed to increase the ^{235}U content from 0.7 up to 2 to 4 wt %. The uranium hexafluoride product is shipped in massive pressurized steel containers to LWR fuel fabrication plants where it is converted to solid uranium dioxide pellets and inserted into zirconium tubes. End caps are welded on the tubes and the tubes are then fabricated into fuel assemblies. The fuel assemblies are shipped to a nuclear power plant. The radioactive materials entering the fuel fabrication plant consist of isotopes of uranium, thorium, and protactinium. The thorium and protactinium isotopes are formed by the radioactive decay of the uranium. A small fraction of the radioactive materials is suspended in the off-gas from processing areas as dusts or aerosols 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 waste treatment systems are used to recover uranium and nonradioactive materials such as ammonia, nitric acid, and water which

are recycled to the processing areas. These systems minimize the release of radioactive materials in the liquid effluents from the plant and are also used to control the releases of noxious nonradioactive materials, such as nitrates, ammonia, and fluoride.

Two model plants which are typical of current designs for LWR fuel fabrication plants are used as the base cases in this study to represent the Ammonium Diuranate (ADU) and Direct (dry) Conversion (DC) processes. The radiological impact of the plants is considered at two typical sites, i.e., a midwestern and a southeastern coastal plain. Increasingly effective radwaste treatment systems are added to the "base" plants and the annual cost and environmental impact of each case is calculated as the basis for cost and benefit analysis. It was not feasible to include all possible variations of plant types and radwaste treatment systems. However, sufficient information is provided in the study so that the costs and impacts can be estimated for other radwaste treatment systems by extrapolation or interpolation from the data provided. The base case studies illustrate the important features of current plants. The advanced cases use technology which ranges from that which is being considered for installation in the near future to the foreseeable limits of available technology on the basis of expected typical operations over the next 30 years. All of the radwaste treatment equipment used in the advanced case studies is presently available but in many cases additional development work is required to adapt the treatment technology for use at fuel fabrication plants. It is expected that this technology could be "reduced to practice" in a development program within a five-year period (Sect. 4.3). However, it is necessary to use this technology in the study to predict the cost-benefit relationships over the next few decades.

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 plants which use current treatment systems, to very low levels by means of advanced, complex treatment systems; and (2) to determine the radiologic environmental impact (dose commitment) 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 less important in this study, since they vary with the plant size. Consequently, the incremental and absolute values derived in this study for a single size of conceptual plant can be extrapolated to larger or smaller plants. The volumes of radioactive wastes 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 operations over the 20-year lifetime of the fabrication plant. In a similar study for nuclear power reactors,[1] great emphasis was placed on maintaining continuous operation of the power plant. Consequently, the more complex radioactive waste treatment systems contained redundant (parallel) treatment units to assure 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 plants selected for the base cases (ADU Case 1 and DC Case 1) are similar to plants being operated or considered for licensing in 1973 and are representative of the plants which will fabricate the major load of fuel in the next two decades.[2-8] The Ammonium Diuranate (ADU) and the Direct (dry) Conversion (DC) processes are used in the case studies. The plants will each process 1500 metric tons of uranium per year, i.e., a nominal 5-ton/day plant operating for 300 days per year. The uranium hexafluoride (UF_6) feed to the plants contains 4 wt % ^{235}U and the thorium and protactinium daughters are in secular equilibrium with the uranium. In the Ammonium Diuranate (ADU) process, the UF_6 is hydrolyzed in water and the uranium is precipitated with ammonia to form $(NH_4)_2U_2O_7$ (ADU). The ADU is subsequently calcined to form uranium dioxide (UO_2). In the Direct (dry) Conversion (DC) process, the UF_6 is reacted with water vapor and hydrogen in fluidized beds to form UO_2. The UO_2 from both processes is formed into pellets and the pellets inserted into zirconium tubes. A third method, the Ammonium Uranyl Carbonate (AUC) process, is not used in this study. This method is not used extensively in the United States at present, but is proposed for use in a new installation.[9] In this process, UF_6 is reacted with CO_2, NH_3, and H_2O to form a slurry of ammonium uranyl carbonate. The solids are recovered and calcined as in the ADU process. Waste effluent treatment problems are expected to be similar to those encountered in the ADU process as represented in the model plant selected for this study.

The gaseous radwaste effluents from the process vessels in the ADU and DC processes are treated in different types of systems in the case studies, since the composition and volume of gases in the two processes are considerably different. The treatment systems for the ventilation effluent gases from the operating areas are the same for the two processes in the case studies. Four types of liquid radwaste effluents are formed

in the ADU process, i.e., the ADU process radwaste, the UO_2 recycle radwaste, the miscellaneous radwaste, and the scrap recovery radwaste. Fifteen percent of the production of the plant, i.e., 225 metric tons/yr of relatively pure UO_2, is processed through the recycle system. This uranium consists of cracked or chipped pellets, powders, etc. Two percent of the plant production, i.e., 30 metric tons/yr of incinerator ash, floor sweepings, etc., is processed through the scrap recovery system. The miscellaneous waste from floor drains, personnel showers, etc.

The UO_2 recycle, scrap recycle, and miscellaneous waste collection systems and the attendant radwaste treatment systems are assumed to be the same in the ADU and DC processes. The use of a large chemical UO_2 recycle system may not be completely valid for a plant handling a single enrichment concentration where some recycle can be accomplished by physical methods, such as regrinding or oxidation and reduction, prior to reblending with fresh UO_2. However, in plants handling a variety of enrichments in the range of 2 to 4 wt % ^{235}U, it is expedient to combine the various reject materials and produce a uniform product in a chemical recycle system, which can then be blended with fresh UO_2 to form a desired enrichment. Thus, handling batches of powders of a variety of enrichments is avoided. The use of the more complex chemical recycle system was selected for this study, since (1) the effluents from this type of system contribute significantly to the radwaste treatment and disposal problem, and (2) an objective of the study is to survey as broad a spectrum of radwaste treatment and disposal problems as possible.

3.3 Management of Radioactive Wastes

Gaseous Effluents. — Gaseous effluents from process vessels and the ventilation air from operating areas contain radioactive particulates that are either produced directly as solids or are formed from aerosols of process solutions that subsequently dry to form solids. The source terms are calculated on the basis that no separation of the radioactive nuclides occurs and that the relative proportion of uranium, thorium, and protactinium in the radioactive particulates is the same as in the feed material, i.e., they are in secular equilibrium. Increasingly effective

gaseous radwaste effluent treatment systems are added to the "base" plant in case studies. The 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. — The liquid effluents from process vessels and miscellaneous liquids from operating areas contain dissolved and suspended compounds of uranium, thorium, and protactinium. Consideration of the chemistry involved indicates that in most of the process systems the relative proportion of uranium, thorium, and protactinium in the liquid effluent will be the same as in the solids formed in a given operation. Exceptions occur during the production of ADU where the ratio of thorium and protactinium to uranium in the ADU process waste is 10 times higher than in the feed material and in the scrap recovery waste where the ratio of thorium and protactinium to uranium is 850 times the equilibrium value. The liquid radwastes effluents are treated such that increasingly large fractions of the radioactive and nonradioactive materials are retained in the various case studies.

In the advanced case studies, the liquid wastes are evaporated and 90% of the condensate is recycled for reuse and 10% is released. The condensate contains 10,000 times less radioactive materials than the original waste[10] (Sect. 4.5.1).

Solid Wastes. — Solid wastes consist of a large amount of calcium fluoride (CaF_2) that is generated in the process waste treatment systems and smaller amounts of miscellaneous wastes that are generated in other parts of the plant. The latter consist of rags, clothing, floor sweepings, sump sludges, disposable filters, and filter residues. Combustible wastes are incinerated and the residual ash constitutes an additional solid waste. Miscellaneous wastes which contain a significant amount of uranium are processed in the scrap recovery system to recover the uranium. In the early case studies (Cases 1 and 2), the residue from the scrap recovery system and other miscellaneous wastes are packaged in drums and stored on site or shipped to a licensed burial ground. The calcium fluoride, which contains small amounts of radioactive materials, is stored on site in a

lagoon or in a surface storage area. In the advanced case studies, the miscellaneous calcium fluoride wastes are incorporated in cement. The cemented product could be shipped to a licensed burial ground. The cemented wastes contain low concentrations of radioactive material and the leach rate of the radioactive materials and the fluoride is very low and, consequently, it may be technically feasible to bury the wastes on site or in a local landfill in accordance with federal and state laws (Sect. 4.3.3). The cost of final shipment or burial of the wastes is not included in the cost estimates.

3.4 Cost Parameters

The base cases are similar to some plants being operated in 1973. The capital and annual costs are estimated for the waste effluent treatment systems which are added to the base case in a series of case studies. The calculation of these incremental annual costs is a primary objective of the study. They are correlated with the changes in environmental impact for each case study in Sect. 8.0. The estimated costs are based on a 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 $36 million in 1973 based on an extrapolation from the estimated cost of an existing plant. 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 the cases studies. Complete details of the cost estimating procedure are listed in Sect. 6.0.

3.5 Equipment Operation

It is assumed that all radioactive wastes will be treated by the radioactive waste equipment, i.e., wastes will not bypass treatment systems and be discharged. The equipment is adequately sized to assure high operating flexibility and efficiency factors. For example, if the liquid radioactive waste is not decontaminated 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 contemporary nuclear fuel reprocessing and fuel fabrication facilities. Site 1 is located on 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 populations 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 is determined by averaging the distributions 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 which 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 and inhalation causes internal exposure. The deposition of radioactive particulates on the land surface leads to direct external exposure and to internal exposure by the ingestion of food products through various food chains. Similarly, swimming in waters containing radionuclides can lead to external exposure, whereas the harvest of fish or drinking from the waters can lead to internal exposures.

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 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

1. USAEC-Directorate of Regulatory Standards, Final Environmental Statement Concerning Proposed Rule Making Action: Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion "As Low As Practicable" for Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents, WASH-1258 (July 1973).

2. General Electric Company, Radioactive Waste Generation and Disposal, DOCKET 70-1007 (November 24, 1971).

3. Gulf United Nuclear Fuels Corp., Waste Management Program for Chemical Operations at Hematite, Missouri, AEC License No. SNM-33, DOCKET 70-36 (May 3, 1972).

4. Jersey Nuclear Company, Application dated June 15, 1970, and Supplements dated Aug. 18, 1970, Jan. 15, 1971, and Feb. 19, 1971, DOCKET 70-1257.

5. Kerr-McGee, letter dated October 11, 1971, DOCKET 70-925.

6. Nuclear Fuel Services, Waste Management Program, letter dated Oct. 4, 1971, DOCKET 70-143.

7. NUMEC, Waste Management Report, DOCKET 70-135 (April 13, 1972).

8. Westinghouse Electric Corp., Application for an Amendment to License SNM-1107, to Authorize Low Enriched SNM, DOCKET 70-1151 (Aug. 18, 1969).

9. Babcock and Wilcox Co., Application dated May 29, 1972, DOCKET 70-1201.

10. H. W. Godbee, Use of Evaporation for the Treatment of Liquids in the Nuclear Industry, ORNL-4790 (September 1973).

4.0 SOURCE TERM FOR RADIOACTIVE RELEASES

4.1 Origin of the Radioactive Wastes in LWR Fuel Fabrication Plants

The following sections describe the processing steps that produce the radwaste effluents and the amounts and compositions of these wastes. Both the radioactive and the nonradioactive noxious components of the waste effluents must be considered in treating the radwaste effluents. The large amount of nitrates, ammonia, and fluoride in the ADU effluents present a significant problem in waste management.

4.1.1 ADU Process

ADU Process Line. – Uranium hexafluoride is received at the fuel fabrication plant as a solid in a 25-ft^3 pressurized shipping vessel (Fig. 4.1). The shipping vessel is placed in a sealed system where the UF_6 is vaporized and transferred to the reaction vessels. The UF_6 is hydrolyzed with water and neutralized with NH_4OH at a pH of 8 to 9 to form a slurry of ADU in an aqueous solution of ammonium fluoride and ammonium hydroxide. The ADU is recovered in a centrifuge and a clarifier and is subsequently dried and calcined to form UO_2 powder. The UO_2 powder is pressed into pellets and the pellets placed in zirconium tubes. The amounts of material flowing through the process are listed in Table 4.1 and are identified in Fig. 4.1.

UO_2 Recycle System. – In the UO_2 recycle system, the off-specification, UO_2 product materials, such as chipped and cracked pellets, are dissolved in nitric acid and the solution transferred to the precipitation system (Fig. 4.2). The pH is raised to 3.0 by adding ammonia and uranium tetroxide is precipitated by adding hydrogen peroxide. In this system, the principal objective is to recover the uranium rather than achieve a high degree of separation from impurities, such as iron. Consequently, the reaction is carried out at a relatively high pH where precipitation is more complete for both the uranium and the impurities, rather than at lower pH's where a better separation but lower recovery of uranium is obtained. The uranium tetroxide is separated from the mother liquor (radwaste) in centrifuges and clarifiers. The material flow rates for this process are listed in Table 4.2 and are identified in Fig. 4.2.

Scrap Recovery System. — In the scrap recovery system, impure materials such as incinerator ashes and floor sweepings are treated to recover the contained uranium values (Fig. 4.3). The scrap is leached with nitric acid to dissolve the uranium and the solution is filtered to remove the insoluble impurities. The solution is then processed in a solvent extraction system which is specially designed to achieve a high recovery of uranium and a high degree of separation of the uranium from impurities. About 90% of the thorium is extracted with the uranium. In this system, the dissolver solution containing 3 *M* HNO_3 and 50 g/liter uranium is passed countercurrent to a solvent containing 20 vol % n-tributyl phosphate in a kerosene-type diluent in a 2-in.-diam by 20-ft-high pulsed column. The solvent rises in the column and extracts the uranium from the downward flowing acidic dissolver solution. The uranium is recovered (stripped) from the solvent by contacting the solvent with 0.01 *M* HNO_3. The solvent is then reused. The barren dissolver solution, or raffinate, constitutes the scrap recovery liquid waste. About once a year, the stripped solvent (a few hundred gallons) is removed from the system and is absorbed in a suitable solid material in drums. The drums of solidified waste are shipped to a licensed commercial burial ground for burial. Material flow rates in the scrap recovery system are listed in Table 4.3 and identified in Fig. 4.3.

Liquid Scrubber. — All of the process gaseous effluents in the ADU plant are passed through liquid scrubbers before release to the atmosphere. The water from these scrubbers contains uranium, NH_4OH, and NH_4F. The water from the scrubbers is added to the liquid waste from the ADU line and handled in the ADU liquid radwaste treatment system. The liquid effluents generated by the various sources in the ADU model plant are summarized in Table 4.4.

Miscellaneous Liquid Wastes. — Miscellaneous wastes are generated from the laundering of contaminated clothing, the showers for personnel working in areas where contamination is expected, the laboratory drains, and the occasional decontamination of equipment. The uranium in this stream is primarily UO_2 suspended in detergent solution.

Process Gaseous Effluent. – The processing units in the ADU production and waste treatment systems are connected to the process gaseous effluent treatment system. The gaseous effluents contain small amounts of UF_6 and HF gases and an aerosol of droplets of solution which contains a complete spectrum of the radioactive and nonradioactive materials in the process liquids. On drying, these droplets form radioactive particles containing uranium, thorium, and protactinium. Additional particulates are derived from the drying and calcining operations and from the radwaste treatment units. The process gaseous flow rate is ~69,000 scfm.

Ventilation Gaseous Effluent. – The air from the operating areas contains small amounts of radioactive particulates of uranium, thorium, and protactinium compounds. The suspension of these particles occurs during operations such as loading transfer containers with UO_2 powder, loading the pelletizing machines with UO_2 powder, and pellet grinding, or from the leakage and drying of process solutions from pipes or pump-packing glands. The ventilation gaseous flow rate is ~90,000 scfm.

4.1.2 Direct Conversion Process

The flowsheet for the direct conversion process for the production of UO_2 from UF_6 is shown in Fig. 4.4. Cylinders of UF_6 are placed in steam-heated cabinets to vaporize the contained UF_6. The UF_6 gas enters into a bed of UO_2F_2 particles which is fluidized by steam. The gas reacts with the steam on the hot, wet surface of the particles to form a coating of UO_2F_2. The reaction is $UF_6 + 2H_2O \rightarrow UO_2F_2 + 4HF$. The particles of UO_2F_2 overflow to a product hopper. The particles at this point are approximately 120 μm in diameter. After a given amount is accumulated, the batch is transferred to the next vessel where the bed is fluidized by steam and cracked ammonia. A second reaction yields $UO_2F_2 + H_2 \rightarrow UO_2 + HF$. A high percentage of the UO_2F_2 is converted to UO_2 in the second reactor, but the product goes into a third reactor where, by the same process, the reaction is carried to completion. The gaseous effluent from each of the three converter vessels passes through a sintered nickel filter in the top of each vessel before going to the gaseous effluent treatment system where HF and particulates are removed from the off-gas

stream. The process gaseous flow rate is ~19,000 cfm. The ventilation gaseous flow rate is ~90,000 cfm. There is no liquid effluent from this process. A material balance for the DC process is given in Table 4.5.

4.2 Composition and Amount of Radioactive Material Entering Model Plant

A list of the radionuclides used in this study is presented in Table 4.6. The selection of this list is based on the following criteria:

1. The feed to the fabrication plant from the enrichment plant contains 10% recycle uranium from a fuel reprocessing plant and 90% virgin uranium. Fission products cannot be detected in the combined feed material.

2. The feed contains 0.04 wt % ^{234}U, 4.0 wt % ^{235}U, 0.20 wt % ^{236}U, 95.76 wt % ^{238}U.

3. The feed has aged several months since passing through the gaseous diffusion plant.

4. Thorium-234 and ^{234}Pa are in secular equilibrium with ^{238}U; ^{234}Th requires 168 days to grow back to 99% of secular equilibrium with ^{238}U. Protactinium-234 requires approximately 7 minutes to grow back to 99% of secular equilibrium with ^{234}Th. Therefore, ^{234}Pa will be in secular equilibrium with ^{234}Th at all times.

5. Thorium-231 is in secular equilibrium with ^{235}U. Thorium-231 requires ~7.5 days to grow back to 99% of secular equilibrium with ^{235}U.

6. The radioactivity due to other daughters in the ^{235}U, ^{238}U, ^{234}U, and ^{236}U decay chains is negligible. The next daughters in the decay chains are ^{230}Th, $T_{1/2} = 9.0 \times 10^4$ yr (from ^{238}U); ^{231}Pa, $T_{1/2} = 3.43 \times 10^4$ yr (from ^{235}U); and ^{232}Th, $T_{1/2} = 1.3 \times 10^{10}$ yr (from ^{236}U).

The plant processes 1500 metric tons of uranium per year at a nominal rate of 5 tons per day. Table 4.7 shows the amount of alpha radioactivity from a gram of uranium being processed. About 82.3% of the alpha radioactivity is derived from ^{234}U.

4.3 Description of Waste Treatment Methods

4.3.1 Liquid Radwaste Treatment Processes

The radioactivity of the liquid effluents arises from the contained uranium and the decay products of uranium. The early stages of liquid radwaste treatment in all cases are directed at returning the valuable uranium component to the process lines with a minimum of intervening operations. As the uranium content of liquid effluent streams is diminished by treatment to the point where uranium can no longer be economically recovered, or where such recovery would return an intolerable amount of impurities to the process lines, the objective is to prevent the escape of these trace amounts of radioactive materials in liquid effluents. The solid residues are transferred to the scrap recovery system or to the solid radwaste treatment system (Sect. 4.3.3). While the direct conversion process has no liquid effluents from the main process line, the plant does include recycle and scrap recovery operations, and miscellaneous liquid wastes are produced from showers, floor drains, laboratory wastes, and laundry water. Thus, similar liquid radwaste treatment systems are used for the recycle, scrap recovery, and miscellaneous wastes in both plant types.

Holding and Settling. – The uranium in the liquid wastes is present as ADU or uranium tetroxide which is in solution or suspended as solids. The amount of uranium in solution can be particularly high for the ADU process and UO_2 recycle wastes when the solution has not been held up long enough to achieve complete precipitation, i.e., to approach the equilibrium solubility of these compounds. The use of holding tanks to allow time for additional precipitation, coalescence of colloidal particles, and settling of solid particles is an important treatment technique. A hold time of 16 to 20 hours significantly increases the amount of uranium which can be removed by filtration. Where the holding technique is utilized, gravity sedimentation allows the waste to be separated into a solids-rich portion and a relatively clear supernate.

Filtration and Centrifugation. – Filtration operations are employed to remove the insoluble uranium from liquid waste streams. The operations

are of the type known as clarification, since only a relatively small (100 ppm or less) amount of solids is present in the stream. Continuous rotating drum filters are used in this study but other types of filters could be used, and the difference in cost would be small in comparison to the total plant cost and would not significantly affect the waste treatment costs (Sect. 6.0).

In those cases where the waste stream is held for 16-20 hours to allow additional precipitation, the solids settle and a more concentrated slurry is formed in the bottom of the tank. In such cases, a centrifuge is used to separate the solids from the (more concentrated) stream prior to filtration. The large density difference between the liquid and solid phases is conducive to this type of separation. Centrifuges of the capacity required for the 5-MTU/day plant can provide an acceleration of several thousand times that of gravity. The centrifuge removes the bulk of the solids and in conjunction with subsequent filtration of both the light stream from the centrifuge and the supernate from the clarifier removes all but the finest particles from the stream.

Ammonia Recovery. — Recovery of ammonia from process waste streams is an established technique in the chemical industry where the ammonia may have a higher value than the product and must be returned to the plant for economic reasons. The actual operation consists of distillation from a basic solution. In the advanced radwaste treatment systems for the ADU plant, the ammonia is recovered and recycled to reduce the release of ammonia to the environment in the effluent stream.

Alkaline Precipitation. — A fraction of the uranium which remains in the liquid waste from both the ADU and the recycle systems is probably caused by the formation of soluble carbonate complexes due to CO_2 entering the process solutions from the air:[1]

$$UO_2^{2+} + 2\ CO_3^{2-} \rightleftarrows UO_2(CO_3)_2^{2-} \qquad K \cong 4 \times 10^{14}$$

$$UO_2^{2+} + 3\ CO_3^{2-} \rightleftarrows UO_2(CO_3)^{4-} \qquad K \cong 2 \times 10^{18}$$

While the complex formation can be avoided at either very high or very low pH values, the pH during precipitation has a strong influence on the physical properties of the UO_2 powder obtained.[2] For this reason the precipitation is carried out under conditions which will provide the desired powder properties. The addition of lime or ammonia in the radwaste treatment system raises the pH sufficiently to partially overcome the effect of carbonate complexing and allow further precipitation of uranium. However, the presence of carbonates as an impurity in the lime will contribute to the formation of soluble carbonate complexes and increase the amount of uranium in the radwaste effluent.

Fluidized Bed Spray Calciner. — The filtered ammonium nitrate (NH_4NO_3) waste stream from the UO_2 recycle system is decomposed to NO_x in a fluidized bed spray calciner. The NO_x is reacted with oxygen to form NO_2 and the NO_2 recovered as nitric acid in an absorption, fractionation, condenser system. The fluidized bed calciner is similar to a unit which was developed at the Idaho Chemical Processing Plant for solidification of high-level radioactive wastes.[3,4] The Idaho unit, in several modifications, has operated through a number of processing campaigns on highly radioactive waste generated by the recovery of uranium from spent nuclear fuels. Wastes which have been calcined in the Idaho unit include 270,000 gal of 1 *M* NH_4NO_3--1.6 *M* $Al(NO_3)_3$.

The operation of the calciner consists of spraying NH_4NO_3 solution into a bed of hot sand which is fluidized with air. The water is vaporized while the NH_4NO_3 is oxidized to NO_x. Residual nonvolatile materials, primarily uranium in this case, are deposited as a solid coating on the sand particles. The sand bed is fluidized to enhance heat transfer and mixing. Air is used as the fluidizing gas to provide an oxidizing atmosphere. Heat is supplied by a natural gas burner external to the fluidized bed and is transferred to the bed by flowing the natural gas combustion products through heat exchange tubes in the bed. The natural gas combustion products are then collected in a header and vented separately from the NH_4NO_3 oxidation products. The NH_4NO_3 oxidation products, primarily NO_2 and H_2O, along with the steam from the solvent water are fed to a fractionating still with an oxidizing atmosphere to recover water and an acid solution containing about 50% HNO_3.

The calciner is designed such that the ammonium nitrate is oxidized as fast as it is introduced into the calciner, thus preventing an accumulation of excess material. While NH_4NO_3 can detonate under certain conditions, the history of such explosions shows that either massive amounts (i.e., shiploads), the presence of organic materials, or detonation by another explosive[5] was involved. The U. S. Bureau of Mines has found that the transition from deflagration to detonation would appear to be possible, if at all, only in a pile of NH_4NO_3 of extremely large dimensions with ignition at the center or bottom of the pile. Ammonium nitrate without the addition of combustible materials did not undergo transition to detonation under the most rigorous test conditions employed.[6] The recycle liquid radwaste system uses no organic material and the oxidizing atmosphere of the calciner would keep such material from forming.

The possible recombination of unoxidized NH_3 to form NH_4NO_3 crystals in the off-gas system requires proper design to prevent solid crystals collecting at any point prior to the condenser.[3,4] Any NH_4NO_3 which may enter the fractionating tower would be dissolved as the vapor phase passed through the liquid-bearing trays. The safe decomposition of ammonium nitrate in a fluidized bed has been demonstrated in the Idaho Chemical Processing Plant.[3,4] It is expected that this technology could be "reduced to practice" for use at fuel fabrication plants in a development program within a 5-year period.

Ion Exchange. – Anion exchange is employed in ADU Cases 3 and 4 to reduce the uranium content of the ADU liquid waste from 20 to 2 ppm uranium. While this treatment is used in the fuel fabrication industry and provides a factor of 10 reduction in the amount of uranium in the waste effluent, the composition of the ion that is absorbed by the resin is not known. In addition to the ion exchange action, it is believed that the resin bed acts as an extended, activated surface which adsorbs ADU particles, promotes the coalescence and precipitation of colloidal ADU particles, and increases the rate of precipitation of ADU from the supersaturated ADU waste stream. In any case, when the bed is eluted with HNO_3, the uranium is recovered as $UO_2(NO_3)_2$.

Anaerobic Digestion. — The calcination of NH_4NO_3 to produce NO_x which is recovered as nitric acid results in more nitric acid than can be used by the plant in several of the cases. To avoid releasing nitrate to the environment in significant quantities, it is necessary to destroy the excess nitrate. The nitrate is destroyed by the action of anaerobic bacteria.[7] In the anaerobic digestion process, the acid is neutralized with lime and diluted to a concentration of 100 ppm nitrogen. The $Ca(NO_3)_2$ solution is then passed through a bed of finely divided coal which provides a favorable surface for the growth of the anaerobic bacteria. The growth of the bacteria converts the calcium nitrate to nitrogen gas and $Ca(OH)_2$. The nitrogen content of the waste stream is reduced from 1,000 ppm to 10 ppm. Anaerobic digestion has been used successfully in industry. It is expected that this technique could be "reduced to practice" for use at fuel fabrication plants in a development program within a 5-year period.

Evaporation. — Evaporation is commonly used in the chemical industry to concentrate aqueous solution by boiling off water and leaving behind dissolved solids and materials having lower vapor pressures than water. Only one part in 10,000 of low-vapor-pressure impurities will appear in the condensate, i.e., a decontamination factor of 10^4 is obtained in properly designed and operated equipment.[8]

4.3.2 Gaseous Radwaste Treatment Methods

The radioactivity of gaseous effluent streams arises from the entrainment of fine particles of uranium compounds and the decay products of uranium. These particles are generated from the drying of entrained droplets of process liquids or from the entrainment of small particles of UO_2 in the fabrication operations. The gaseous radwaste treatment systems are designed to remove these solid particles in liquid scrubbers or on filters. All of the process off-gas treatment systems for the ADU plants contain water scrubbers which remove particulate materials and gases, such as UF_6 or NH_3, from the off-gas. Similarly, the ventilation off-gas treatment systems contain roughing filters to retain and recover the bulk of the entrained uranium. The water scrubbers and the roughing filters

are part of the base plant, and the cost of these units is not included in the cost estimates.

Liquid Scrubbers. — Liquid scrubbers for gas streams have been credited with an efficiency of 90% for removal of entrained solids. The cases where liquid scrubbers are included in the radwaste treatment system are in the DC plant, Cases 2 through 4, where a KOH scrubber is included, primarily for HF removal. This type scrubber was tested both at ANL and ORNL and an efficiency of 90% per stage was demonstrated for fluorine.[9] Although the scrubber should be more efficient for HF removal than for fluorine removal because of the greater solubility of HF in water, the same efficiency listed in reference 9 was used in these calculations. The scrubber is a horizontal Monel pipe 1 ft in diameter and 12 ft long with baffled spray nozzles at 1-ft intervals. The gas stream and the KOH spray flow cocurrently. The unit contains eight spray nozzles. However, calculations are based on operating with seven nozzles to allow for operation with one plugged nozzle. Replacement of a plugged nozzle would require a short shutdown. In this system, HF removal is relatively low and, consequently, standard HEPA filters are not used. Uranium (and decay products) removal in the KOH scrubber is 50% per stage. The uranium concentration in the KOH solution is 20 ppb, well below the solubility of potassium diuranate (7 ppm).[10] The KOH concentration is reduced from 10 to 5 wt % in passing through the scrubber. About 65% of the solution from the scrubber (KOH + KF) is reacted with $Ca(OH)_2$ to recover the KOH, which is then returned to the KOH surge tank after filtration to remove the precipitated CaF_2. It is expected that this technology can be "reduced to practice" for use at fuel fabrication plants in a development program within a 5-year period.

HF Condenser. — The inclusion of condensers to remove HF as a liquid and KOH scrubbers in DC Cases 3 and 4 reduces the HF concentration in the gaseous effluent to a level which makes the installation of HEPA filters practical for this stream. The condensation of HF greatly reduces the amount of solid waste, i.e., CaF_2, generated in the DC process and conserves HF for recycle within the nuclear industry. The amount of HF removed by the condenser depends largely on the coolant temperature for

the condenser. In DC Case 4, a chilled-water condenser is added for more complete removal of HF which allows longer filter life and further reduces the formation of solid waste. It is expected that this technology can be "reduced to practice" for use at fuel fabrication plants in a development program within a 5-year period.

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.[11,12] These expendable filters, which are composed of pleated mats of fiberglass paper, are installed in banks to achieve the required system capacity. By definition, they must exhibit a minimum efficiency of 99.97% for removal of 0.3-μm particles and a maximum resistance (when clean) of 1.0 in. H_2O 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 rated filtration efficiency. The construction of large, tight filter enclosures is an exacting 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 particulate aerosols encountered. A literature survey by Davis, however, does not indicate a gross variation in the range of reported particle sizes in field operations of interest.[13]

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 (28,000 cfm) which produced overall mass removal efficiencies of 10^7 or greater.[11] 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 years old and does not represent the latest design practice for HEPA installations. Ettinger et al. have performed laboratory tests using plutonium aerosols in small (25 cfm) installations that are tightly sealed and tested periodically for leaks with DOP.[14,15] 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 recommended guidelines and is tested for leaks after the filters have been installed.[16] Consequently, a value of 99.95% has been used in this study to represent both the rated and installed efficiencies of a single bank of HEPA filters which is installed and tested according to the recommended guidelines. An installed efficiency of 95% is used for a HEPA bank which is not tested in place with DOP. Experience in industry shows that this is probably a realistic value for an installation where filter operation is monitored simply by pressure drop. The filters are changed when air sample monitors indicate that leakage has occurred.

Several factors must be considered 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, the second and third filters are exposed to much lower concentrations of particles with a size distribution that is probably strongly biased toward the smaller sizes.[14] Secondly, filter efficiencies are sensitive to gas flow rate, and in a large bank, all filters in the 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.[17] 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.[17] Consequently, the overall installed filter

system DFs used 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 effluents from the DC process contain significant amounts of hydrofluoric acid (HF); consequently, the use of regular HEPA filters may be impractical because of the corrosive action of HF on the filters. HF-resistant HEPA filters are under development[18] and are expected to be available commercially within the next five years, i.e. by 1979. The cost of these filters will be higher than the cost of standard HEPA filters but the increased purchase price does not contribute significantly to gaseous effluent treatment cost. In tests at the AEC filter test station at Oak Ridge, average particulate removal efficiencies of 99.92 and 99.93 were measured at 100% (Δp of 1.25 in water) and 20% of the rated flow rates, respectively, and 99.8% in a separate test at the 20% flow rate.[17] The objectives of the program are to develop filters which will have an efficiency approaching that of regular HEPA filters and which can be used as sacrificial filters which would precede regular HEPA filters in a multiple-stage system. In this study we assume that this objective will be achieved and, consequently, the same particulate removal efficiencies are assigned to regular and to HF-resistant HEPA filters.

HEPA filters used on the process gaseous effluents are preceded by water scrubbers in the ADU plant, and by sintered metallic filters and KOH scrubbers in the DC plant. These air pretreatment facilities remove the bulk of particulate matter and minimize "blinding" of the HEPA filters. In the ventilation system in both the ADU and DC plants, the HEPA filters are preceded by roughing filters that perform the same function. The water scrubbers and the sintered metallic filters are considered to be part of the base plant and are not included in the cost estimate.

Installed efficiencies of HEPA filters used in this study are as follows:

HEPA Filter System[a]	Percent Removal of Particulates	DF
Tested Periodically with DOP		
First filter	99.95	2×10^3
Second filter	99	1×10^2
Not Tested Periodically with DOP (Monitored by Pressure Drop)		
First filter	95	20

[a]Standard or HF-resistant construction; installed in accordance with AEC Regulatory Guide 3.12.

4.3.3 Solid Radwaste Treatment Methods

In the Case 1 and Case 2 studies for the ADU and DC model plants, the solid waste residues from the scrap recovery plant along with other miscellaneous wastes are packaged in drums for storage on site, or for shipment to a licensed, commercial burial ground. The CaF_2 solid waste that is produced in the process effluent waste treatment systems is retained in unlined or lined lagoons at the ADU plants and in unlined or lined surface storage areas at the DC plant. In the advanced case studies, i.e., Case 4 at the ADU plant and Cases 3 and 4 at the DC plant, the CaF_2 wastes are incorporated in cement. The concentrated bottoms from the evaporation of miscellaneous and scrap wastes are also incorporated in cement in Cases 3 and 4 at both the ADU and DC plants. The incorporation of solid wastes and evaporator concentrates in cement is an established technology that is widely practiced at power reactor stations,[19] and this technology is available for immediate use at fuel fabrication plants. Two current licenses[20,21] for operating fuel fabrication plants contain the stipulation that solid wastes (for example, CaF_2 wastes) which contain less than 1 μCi of uranium/lb of solid waste (≈770 ppm of uranium per pound of solid waste) can be considered essentially nonradioactive and that special precautions are not required for disposal of these wastes

based on their radioactive content. However, this stipulation is under review. In addition, the State of South Carolina has restricted the burial of large amounts of CaF_2 wastes because of their high fluoride content. Consequently, the incorporation of solid wastes in cement is used as a treatment method in the advanced case studies to illustrate a treatment technique that greatly reduces the potential leach rate of fluoride or radioactive materials from wastes after burial of the wastes. Thus, the cemented wastes could be shipped to any licensed, commercial burial ground or could potentially be acceptable for burial on-site or in local off-site landfills. The amounts of CaF_2 wastes and their uranium content are listed in the description of the case studies in Sect. 4.5.

4.4 Selection of Case Studies

The case studies were selected to reflect a decreasing release of radioactivity for an increasing sophistication of radwaste treatment. Inclusion of specific treatment techniques was not based on cost, but on effectiveness in reducing the radioactivity of plant effluents. All of the treatments included have been utilized in industrial-scale operations although no existing fabrication plant has used some of the treatment methods selected for the advanced cases. In addition, all ADU or DC plants do not operate with both the recycle and the scrap recovery systems which are included in the model plants covered by the case studies. However, these systems have been included to present a model plant which illustrates all of the major processes now used in the LWR fuel fabrication industry.

The cases which were studied along with the treatment systems and the decontamination factors for these systems are summarized in Tables 4.8 and 4.9 for the model ADU and DC plants.

4.5 Description of Case Studies and Calculation of Source Terms

The treatment methods used in the individual case studies are discussed in Sects. 4.5.1 and 4.5.2. The source terms, i.e., the concentrations of radionuclides in the effluents and the annual amounts of radioactive materials discharged in the effluents, are presented both in the flowsheets

(Figures) for the case studies and in Tables 4.10 through 4.13. The parameters used in the calculation of the source terms are presented in Sect. 4.5.3. The amounts of nonradioactive noxious materials (nitrates, ammonia, fluorides, etc.) are listed in the material balance tables for each case.

4.5.1 Ammonium Diuranate Cases

ADU Case 1. — This is the base case for the ADU process. A summary flowsheet is shown in Fig. 4.5. The effluents from the ADU and scrap recovery liquid radwaste systems are sent to a holding lagoon to allow the partial decay of beta activity which at this point is in excess of the equilibrium amount. The holding lagoon has a capacity of 140 days for the effluents from these two systems and provides an average decay time of 70 days. The holding lagoon overflows to an equalization lagoon which also accepts the effluents from the recycle and miscellaneous liquid radwaste treatment systems in addition to various nonradioactive streams such as treated sanitary wastes cooling water, etc.* The concentrations of the radioactive materials in the total plant effluent listed in Table 4.10 correspond to the overflow from the equalization lagoon* to the stream or river.

The ADU liquid radwaste treatment system is shown in Fig. 4.6 and consists of filtration and a holding lagoon. A material balance for this system is presented in Table 4.14. The recycle, scrap recovery, and miscellaneous radwaste treatment systems shown in Figs. 4.7, 4.8, and 4.9 are similar to the ADU treatment system (Fig. 4.6) and consist of filtration and holdup in a lagoon. The material balance for the recycle liquid radwaste treatment system is given in Table 4.15. No material balance is presented for the miscellaneous radwaste treatment system (22,000 gal/day) which would contain a variable quantity of detergents. The uranium is present primarily as UO_2. The effluent from the scrap

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*The nonradioactive streams amount to 228,540 gal/day and serve to dilute the radioactive streams (Tables 4.10 and 4.12).

recovery liquid radwaste system is saturated with TBP-kerosene solvent and consists of 686 gal/day of 16% HNO_3 containing 9 ppm uranium. In this base case, all of the process chemicals, ammonia, fluorides, and nitrates are released in the effluent.

The gaseous radwaste treatment system in ADU Case 1 consists of water scrubbers on all of the process gas streams and roughing filters on the ventilation streams.

The solid radwastes from the scrap recovery system and other miscellaneous wastes are packaged in drums and stored on site or shipped to a licensed, commercial burial ground (Sect. 4.3.3).

ADU Case 2. – The flowsheet in Fig. 4.10 summarizes the waste treatment processes for ADU Case 2. The flowsheet in Fig. 4.11 shows the radwaste treatment system for the ADU process waste. The liquid waste is allowed to age for 16-20 hours before the residual $(NH_4)_2U_2O_7$ (ADU) is separated by a combination of filtration and centrifugation. The fluoride is then precipitated by adding lime to form insoluble CaF_2. The waste flows to a lined lagoon where the CaF_2 settles out and the supernate overflows to the equalization lagoon. A lined lagoon is used in this case to prevent seepage of radioactive and nonradioactive materials in the ground water. The effluent from the lined lagoon contains 5 ppm of uranium and all of the ammonia from the process system. The material balance for ADU liquid process radwaste system is shown in Table 4.16.

The recycle liquid waste is neutralized with lime and allowed to age for 16-20 hours (Fig. 4.12 and Table 4.17). Uranium-bearing solids precipitate and are recovered by centrifugation and filtration and sent to the scrap recovery system. The supernate is pumped to a lined nitrate storage lagoon where it is retained. The scrap recovery liquid waste (same volume and composition as in ADU Case 1) is also retained in the nitrate storage lagoon (Fig. 4.13). A new lagoon must be constructed every 6 months to store the accumulated nitrate wastes.

The miscellaneous liquid radwaste and the miscellaneous radwaste treatment system are the same as in ADU Case 1. This effluent is combined

with the ADU process effluent, cooling water, etc., in the equalization lagoon.

The concentrations of the radioactive materials in the total plant effluent listed in Table 4.10 correspond to the overflow from the equalization lagoon to the stream or river.

The gaseous waste treatment for ADU Case 2 consists of water scrubbers and HEPA filters on the process gas and roughing filters and HEPA filters on the ventilation gas. It is assumed in this case that the gaseous radwaste treatment system is not designed for in-place testing of HEPA filters and that filters are changed when the pressure drop exceeds a predetermined value. Because of the lack of in-place testing to detect bypass leakage in the filter banks, the filtration efficiency is assumed to be 95% (Sect. 4.3.2).

The solid radwastes from the scrap recovery system and other miscellaneous solid wastes, with the exception of the CaF_2 waste formed in the process effluent treatment system, are packaged in drums and stored on site or are shipped to a licensed, commercial burial ground. The CaF_2 waste (~10,823 lb/day) is stored in a lined lagoon. This waste contains about 1,000 ppm of uranium (Sect. 4.3.3).

ADU Case 3. – The flowsheet in Fig. 4.14 summarizes the radwaste treatment systems for ADU Case 3. The flowsheet for the treatment of ADU liquid process waste is shown in Fig. 4.15 and the material balance in Table 4.18. The waste is aged for 16-20 hours, centrifuged, and filtered as in Case 2. The waste is then passed through an anion exchange column to reduce the uranium content from about 10 ppm uranium to about 1 ppm uranium (Fig. 4.15). After the ion exchange column, lime is added to the waste to precipitate CaF_2 and provide a basic solution for the ammonia still. The NH_3 and H_2O recovered from the still are recycled to the plant while water and CaF_2 from the bottom of the still are pumped to the lined lagoon where the CaF_2 settles out and the water overflows to the equalization lagoon. The effluent from the lined lagoon contains 1 ppm uranium.

The flowsheet for treatment of the recycle liquid radwaste is shown in Fig. 4.16 and the material balance in Table 4.19. The recycle liquid waste is neutralized with gaseous ammonia and allowed to age for 16-20 hours. The uranium concentration is reduced to about 20 ppm by a combination of aging, centrifugation, and filtration. The waste stream, which is primarily an aqueous solution of NH_4NO_3, is pumped to a fluidized bed spray calciner containing sand where the NH_4NO_3 is decomposed to NO_x and the residual uranium is converted to uranium oxide. The steam and NO_x are fed to a fractionation tower where NO_2 is absorbed in water to form HNO_3. The residual uranium in the waste stream when it enters the calciner amounts to about 1.2 lb/day. A mixture of sand and uranium oxide particles is periodically removed from the bed to prevent excessive buildup of uranium in the calciner. The mixture is transferred to the scrap recovery system where the uranium is recovered by leaching with nitric acid. The conversion of ammonia to nitric acid in the calciner produces more nitric acid than can be recycled and used in the plant. In the ADU plant, all of the water from the top of the fractionation column and about 80% of the nitric acid from the bottom of the column are recycled to the plant for reuse. About 150 gal/day of 50% nitric acid is produced in excess of the amount needed. This excess acid is neutralized, diluted, and treated by anaerobic digestion to reduce the nitrate content of the effluent by a factor of 100 before the liquid is released to the equalization lagoon. Essentially all of the radioactive material that enters the calcination, fractionation, and digestion system remains in the sand in the calciner and the amount released in the effluent to the equalization lagoon is about 1/10,000 of that entering the calciner.

The liquid wastes from the scrap recovery system and miscellaneous waste systems are evaporated to about 50% water content (Figs. 4.17 and 4.18). The condensate, containing nitric acid and water, is recycled to the plant.

The concentrations of the radioactive materials in the total plant effluent listed in Table 4.10 correspond to the overflow from the equalization lagoon to the stream or river.

The gaseous radwaste treatment in ADU Case 3 is similar to that of Case 2 and consists of scrubbers or roughing filters followed by HEPA filters. In Case 3, however, it is assumed that the filter banks are designed for in-place testing of filters upon installation, and periodically thereafter, so that a filtration efficiency of 99.95% for removal of particulates is achieved and maintained.

The solid radwastes from the scrap recovery system and other miscellaneous solid radwastes, with the exception of the CaF_2 waste formed in the process effluent treatment system, are incorporated in cement and packaged in drums. The evaporator bottoms from the miscellaneous and scrap recovery waste treatment systems are also incorporated in cement. The drums are (1) stored or buried on site, (2) buried in a local off-site landfill, or (3) shipped to a licensed commercial burial ground (Sect. 4.3.3). The CaF_2 waste (~10,823 lb/day) is stored in a lined lagoon. This waste contains about 14 ppm of uranium (Sect. 4.3.3).

ADU Case 4. – The flowsheet in Fig. 4.19 summarizes the radwaste treatment systems for ADU Case 4. The flowsheet for the treatment of ADU liquid waste and the corresponding material balance are shown in Fig. 4.20 and Table 4.20, respectively. The treatment of ADU process liquid wastes is identical to that in Case 3 except that the solid CaF_2 is removed by a centrifuge after the waste stream leaves the ammonia recovery unit and the liquid stream from the centrifuge is evaporated. The bottoms from both the centrifuge and the evaporator are incorporated in cement for disposal. All of the additional water produced during the evaporation of the ADU radwaste cannot be reused in the plant. About 18,000 gal/day of water containing a low concentration of radioactive materials is released to the equalization basin. The recycle, scrap recovery, and miscellaneous liquid radwaste treatment systems are identical to those in ADU Case 3. In this case study, the need for a holding or a lined lagoon as part of the radwaste treatment system is eliminated. The concentrations of the radioactive materials in the total plant effluent listed in Table 4.10 correspond to the overflow from the equalization lagoon to the stream or river.

The gaseous radwaste treatment for ADU Case 4 consists of the scrubbers, or roughing filters, and HEPA filters as in ADU Case 3 with the addition of a second bank of HEPA filters in series with the first bank. It is assumed that both HEPA filter banks are tested individually on installation and periodically thereafter to insure that each bank individually has an efficiency of 99.95%. For the reasons discussed in Sect. 4.3.2, the operational efficiency of the first bank is assumed to be 99.95% and that of the second bank 99%.

The solid wastes are processed the same as in ADU Case 3 with the exception that the CaF_2 waste is incorporated in cement and packaged in drums or larger bulk units for on-site storage (or burial) or for shipment off-site for burial (Sect. 4.3.3).

4.5.2 Direct Conversion Cases

In the Direct Conversion (DC) process, the HF, formed as a product of the conversion process, remains in the gaseous effluent as opposed to the ADU process where the fluoride remains in the liquid effluent (Sect. 4.1.2). No liquid waste is formed in the mainline DC process. However, the auxiliary systems for recycle, scrap recovery, and collection of miscellaneous radwastes are the same as those described for the ADU plant and produce the same amounts of liquid radwaste (Sect. 4.5.1). However, the amounts of liquid radwastes released in DC Cases 3 and 4 are different than the amounts released in ADU Cases 3 and 4 because the amounts of water that can be recycled are different. The gaseous effluents from the converters pass through sintered-metal (nickel) filters, as part of the processing system, where the bulk of the entrained solids are removed and returned to the main stream. The gases then pass into the gaseous effluent treatment system. The presence of a large amount of HF (33% HF by volume) in the off-gas presents a problem in effluent treatment, since HF can react with the silicone in the asbestos, boron-fiberglas HEPA filters and destroy their efficiency. Consequently, a major fraction of the treatment system for the DC process off-gas consists of equipment for the removal of HF to the levels where HEPA filters can be used. The newly developed HF-resistant, quartz HEPA filters have

been used in this study since they are more resistant to HF and the cost differential is negligible.[18]

DC Case 1. – The flowsheet in Fig. 4.21 summarizes the systems for DC Case 1. Material balances for all of the DC gaseous radwaste systems are shown in Table 4.21. In DC Case 1, the process off-gas is passed into a tower filled with crushed limestone ($CaCO_3$) (Fig. 4.22). This tower removes 90% of the HF, but the residual HF concentration is too high to permit the use of HEPA filters. The hydrogen in the gaseous effluent is removed by burning prior to release of the effluent to the atmosphere. The solid waste from the dry scrubbing tower consists of 9,800 lbs CaF_2 and 5,700 lbs of $CaCO_3$ per day and contains ~0.4 ppm uranium. This material is retained on-site in an unlined surface storage area. The liquid and solid radwastes from the scrap recovery, recycle, and miscellaneous radwaste collection systems are treated identically to those in ADU Case 1 except that the scrap recovery wastes must be retained in a holding lagoon for an average of 45 days rather than 70 days to allow for decay of beta activity. The ventilation gaseous radwaste treatment system consists of roughing filters.

DC Case 2. – A summary flowsheet for DC Case 2 is shown in Fig. 4.23. In the process-gaseous waste system shown in Fig. 4.24, the limestone tower is replaced by a KOH spray scrubber. The HF concentration of the gaseous waste is reduced by a factor of 10^7 in the liquid scrubber. The uranium concentration in the spray scrubber is reduced by 50% in each stage corresponding to an overall reduction in uranium concentration by a factor of 23. The gaseous effluent is diluted with air to reduce the hydrogen concentration below the explosive limit. The CaF_2 solid waste (~9,520 lb/day) from the scrubber system contains about 1.35 ppm uranium. This material is retained in a lined storage area. The liquid and solid radwastes from the scrap recovery, recycle, and miscellaneous radwaste collection systems are treated identically to those in ADU Case 2. The ventilation gaseous radwaste treatment system consists of roughing filters and a single bank of HEPA filters (95% efficiency, Sect. 4.3.2).

DC Case 3. – DC Case 3 is summarized in Fig. 4.25. The HF concentration of the process gaseous effluent is further reduced by incorporating

a condenser in the gaseous radwaste treatment system prior to the KOH scrubber (Fig. 4.26). The single water-cooled condenser will remove 90% of the HF as 45% HF solution which could be reused within the industry. The HF concentration in the scrubbed gas is reduced to one-third of that for DC Case 2. The liquid and solid radwastes from the miscellaneous, recycle, and scrap recovery waste treatment systems are treated identically to those in ADU Case 3 with the following exceptions: (1) in the recycle, liquid, radwaste system (Fig. 4.16), excess water from the top of the fractionation column (2,366 gal/day) is released to the equalization lagoon; and (2) in the miscellaneous liquid radwaste system (Fig. 4.17), all of the condensate water (22,000 gal/day) from the waste evaporator is released to the equalization lagoon. The solid CaF_2 radwaste (~952 lb/day, 13.5 ppm uranium) is incorporated in cement and packaged in drums or larger bulk units for on-site storage (or burial) or for shipment off-site for burial (Sect. 4.3.3). The additional recovery of HF in this case produces a corresponding reduction in the volume of solid CaF_2 waste generated. The reduced volume of CaF_2 is a significant economic saving in terms of reduced space required for storage or disposal of CaF_2. However, no monetary credit for sale of the recovered HF is assumed in the cost estimate. The gaseous effluent from the KOH scrubber passes through a single bank of HF-resistant HEPA filters (efficiency 99.95%) before release to the environment. The ventilation off-gas is passed through a roughing filter followed by single bank of standard HEPA filters (efficiency 99.95%, Sect. 4.3.2).

DC Case 4. — DC Case 4 is summarized in Fig. 4.27. The gaseous radwaste treatment in this case is improved by the addition of a brine-cooled condenser following the water-cooled condenser (Fig. 4.28). The addition of a low-temperature condenser increases the amount of HF recovered to 99% and decreases the amount of solid waste formed to ~95 lb of CaF_2/day. However, the total amount of uranium contained in the solid CaF_2 waste remains constant and, consequently, the uranium concentration in the CaF_2 increases to 135 ppm. The solid CaF_2 is incorporated into cement for storage or burial. The liquid and solid wastes from the miscellaneous, recycle, and scrap recovery systems are handled

the same as in DC Case 3. The gaseous effluent from the KOH scrubber passes through two HF-resistant HEPA filter banks in series before release to the environment (efficiencies 99.95 and 99%). The ventilation off-gas is passed through a roughing filter followed by two banks of standard HEPA filters in series (efficiencies of 99.95 and 99%, Sect. 4.3.2).

4.5.3 Calculation of Source Terms

The uranium concentrations in the effluent streams are multiplied by the average uranium specific activity (Table 4.7) to calculate the uranium source terms for liquid effluents. The source terms for the individual uranium isotopes are obtained by multiplying the total uranium specific activity by the fraction of uranium activity contributed by that isotope. With two exceptions, the activity of the thorium and protactinium beta emitters is set equal to the activity of their precursors, i.e., they are assumed to be in secular equilibrium. The exceptions occur in the ADU process liquid radwaste system for Case 1 and in the scrap recovery liquid radwaste systems for Cases 1 and 2. In the ADU process, experience has shown that the supernate from the ADU precipitation will contain about 10 times the equilibrium concentration of thorium. This value is reflected in ADU Case 1. However, when lime is added to precipitate CaF_2, thorium is precipitated and carried down with the solid CaF_2. We assume in ADU Cases 2 and 3 that most of the thorium is precipitated and that the amount that remains in the effluent from the general lagoon is in equilibrium with uranium contained in that stream.

In the scrap recovery system, it is expected that about 17% of the thorium charged to the system will remain in the liquid waste. Since the uranium concentration in the liquid waste is reduced by a factor of 5,000 and the thorium by a factor of only 6, the equilibrium value of thorium in the scrap recovery effluent is 850 times the equilibrium value. However, the volume of waste from this system is relatively small and its contribution to the total release of radionuclides in ADU Case 1 and DC Case 1 is limited. In the other cases, the scrap recovery liquid radwaste is not released.

The gaseous effluent source terms were derived from industrial experience with similar gas streams from ADU Case 1 and DC Case 1. Stack sample measurements of entrained radioactivity at enriched uranium fuel fabrication plants have indicated that ~0.001% of the activity fed to the plant is found in the process off-gas after treatment with a scrubber, and that ~0.003% is present in ventilation air from processing areas after roughing filters.[22,23] Assuming an efficiency of 90% for a scrubber (see Sect. 4.3.2) 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 filter efficiencies described in Sect. 4.3.2 were applied to obtain the source terms for more advanced cases. The source terms for gaseous and liquid effluents from the ADU model plant are listed in Tables 4.10 and 4.11. The source terms for the DC plant are listed in Tables 4.12 and 4.13.

The calculated concentrations of the radioactive materials in the liquid effluent at the outlet of the equalization lagoon are 100% of the Radiation Concentration Guides* (RCGs) for releases to unrestricted areas for the ADU and DC plants in the Case 1 studies; the concentrations of radioactive materials in the air at 0.5 mile from the plant are ~0.3% of the RCGs for unrestricted areas;* the concentrations in the gaseous effluent at the point of release from the stacks are ~32% of the RCGs for releases to restricted areas.** These percentages are obtained by calculating the ratio of the concentration of each of the radionuclides in the liquid and gaseous effluents 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. Thus, the model plants for Case 1 are within the federal guidelines listed for release of radioactive materials.

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*Code of Federal Regulations, Title 10, Part 20, Appendix B, Table II, Columns 1 and 2.

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

4.6 References

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5.0 NONRADIOACTIVE CHEMICAL RELEASES

The type and quantity of nonradioactive chemical releases from the model plants are strongly affected by the waste processing system. The amount of noxious chemicals released to the environment decreases as the amount of radioactive release decreases in Cases 1 through 4 in both the ADU and DC plants. The material balance tables presented for the description of the various cases in Section 4 (Table 4.14-4.21) show the amounts of chemicals released for each case.

The recovery and recycle for reuse within the plant of such chemicals as NH_3 and HNO_3 are established practice in the chemical industry for economic reasons. The value of the recovered NH_3 and HNO_3 should in some measure offset the cost of preventing their release to the environment. However, no credit has been allowed for the value of the recovered chemicals in the cost estimate (Sect. 6.0). The HF recovered in the DC cases is a slightly different problem, since there is no use for this material within the LWR fuel plant. It is assumed that the value of the HF is sufficient to pay for the cost of shipping the HF to some other plant for reuse within the nuclear industry.

Where the recycle of a chemical does not appear to be feasible, as with the CaF_2 waste from the ADU plant in Case 4, the production of this material in solid form and its incorporation in cement will effectively prevent the material from being released to the environment.

6.0 COSTS

Costs for the various waste treatment cases for the 1500-metric ton/yr model fuel fabrication plant are estimated as additions to the base plant for both the ADU and Direct Conversion (DC) processes. Treatment of the liquid wastes from the recycle, scrap, and miscellaneous waste systems is the same for both processes. The ADU process has an additional liquid waste treatment system for the ADU process effluent and the DC process has an expanded waste treatment system for the DC process off-gas, principally for HF removal. 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 detailed breakdown of the installed equipment costs is given in Tables 6.2 through 6.9.

Annual fixed charges are estimated at 26% of total capital investment. This is typical of investor-owned fuel reprocessing and waste treatment facilities.[1] 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) expense is normally 40% of the annual fixed charge. For certain capital costs such as lagoons and ductwork, no operating expense is added, while in other cases such as solid waste disposal where the material cost is appreciable, a higher operating expense is used (Sect. 6.2). The total annual cost for each case is divided by the equivalent annual electricity production of the fuel to obtain the cost of radwaste treatment per unit weight of fuel fabricated or the total contribution to the cost of power for each radwaste case. A fuel fabrication plant with a nominal production rate of 1500 metric tons/yr can service a nuclear economy of approximately fifty-five 1000-MW(electrical) 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 ±30%. Details of the cost estimate are provided in Appendix A.

6.1 Capital Cost

The capital cost of the radwaste treatment cases is the sum of direct cost and indirect cost. The interest during construction and contingency allowance are included as indirect costs.

6.1.1 Direct Costs

The major equipment components were sized and a base price estimated, based on the general methods used to cost conventional chemical plant equipment for conceptual designs. Appropriate factors were applied to the equipment cost to estimate the cost of installation, piping, instruments and controls, electrical, and quality assurance.[2-4]

Building requirements are estimated from equipment size with allowance made for auxiliary equipment, such as pumps, condensers, etc. The costs of warehouse building and other related facilities are not included. Total direct cost for each radwaste treatment case is the complete equipment installed (material and labor) cost.

6.1.2 Indirect Costs

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

	Percentage of Direct Cost
Engineering and supervision	15
Construction expense and contractor's fee	20
Engineering design (A-E)	15
Contingency	45
Other owner's cost	10
Interest[a]	35
Total	140

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

6.2 Annual Fixed Charges and Operating Costs

The annual fixed charges on invested capital are based on the FRTF annual fixed charge rate of 24%, which was, in turn, based on the following assumptions:

Plant lifetime	15 years
Capital investment in bonds	30%
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%, and for this study a fixed charge rate on invested capital of 26% is assumed.

The annual operating and maintenance cost is calculated as 40% of the fixed charges for the liquid and solid radwaste and chemwaste treatment systems. The annual cost of cement for the advanced cases is accumulated as an additional operating expense, i.e., ADU Case 3 - $19,800; ADU Case 4 - $801,000; DC Case 3 - $19,800; and DC Case 4 - $18,900. The annual operating cost for the gaseous effluent radwaste treatment systems is 40% of fixed charges for operating equipment plus the annual costs for testing and replacing HEPA filters. Annual operating costs are not assessed for the operation of the lagoons or for ventilation ducts.

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 operations, 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 over a 50-year period (essentially a lifetime dose) 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 dose received during the year that radioactive materials are taken into the body (the annual dose) is about the same as the dose commitment where the residence time of the radioactive materials in the body is short. This is the case in this study, since ^{234}U, ^{235}U, ^{236}U, and ^{238}U are eliminated from the body fairly rapidly and the half-lives of ^{231}Th, ^{234}Th, and ^{234}Pa are short. However, a detailed calculation is required to calculate the dose commitment and annual doses precisely (ORNL-4992).

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. Atmospheric transport of radioactive materials to the terrestrial environment is calculated according to the Gaussian plume model.[4] A computer code[5] 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 mid-western and southeastern coastal regions[6] are used to calculate average values of X/Q' ($sec \cdot m^{-3}$), 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} $sec \cdot m^{-3}$ for the coastal site. X/Q' values for the same distance ranged from 1.7×10^{-6} to 4.6×10^{-7} $sec \cdot m^{-3}$ 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} $sec \cdot m^{-3}$ at the coastal site and 4.2×10^{-6} $sec \cdot m^{-3}$ 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] Vg, for a one-year time interval. Deposition velocity values for particles and reactive gases commonly range from 0.1 to 1.0 $cm \cdot sec^{-1}$.[7,8] For micron-sized particles, Vg's may approach 10 $cm \cdot sec^{-1}$. A value of 1.0 $cm \cdot sec^{-1}$ 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 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 case, 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 5 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 5 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 codes[13] 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 code[14] 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 calculation 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.

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. Total population dose out to 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 1.0 millirem/year to individuals living within 0.5 to 1 mile from the model plant at either site. The relative contributions of exposure modes to total body dose from gaseous effluents are given in Table 7.5. Internal exposure from inhalation and ingestion accounts for 68% 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 (man-rem) is only 1.3 times greater for the midwestern site. This is because the gaseous releases are essentially at ground level 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 (Table 7.6) 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 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 ^{234}U, which is the radionuclide which contributes the major alpha radioactivity in uranium particulates. The dose from submersion in air comes mainly from ^{235}U and ^{234}Pa. Since about 49% of the total body dose is due to ingestion of radioactivity (Table 7.5), ^{234}U and ^{238}U, which account for 93% of the dose due to ingestion (Table 7.8), are the most important radionuclides in the gaseous effluent of a fuel fabrication plant.

7.3.2 Dose to Organs of Individuals

Maximum annual doses to organs of individuals from gaseous effluents at 0.5 mile from the model plant located on both sites are given in Table 7.4 for all radwaste treatment cases. Only organs receiving doses greater than those to the total body are listed. 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 ^{234}U and ^{238}U. Radiation dose to organs is largely dependent on the specificity of certain radionuclides to accumulate 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 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 an order of magnitude less than those for radwaste Case 1 (Table 7.4).

7.4 Radiation Dose from Liquid Effluents

Since the model fuel fabrication plant has a radioactive liquid effluent, it is necessary to evaluate aquatic pathways leading to a potential radiation dose to man and other biota.

For the midwestern site, it is assumed that liquid effluents are released to a small (15-cfs) stream which flows into a freshwater river which has a minimum flow of 1300 cfs. For the coastal site, it is assumed that liquid effluents are released into a 15-cfs stream which flows into an estuary which is 1 mile long by 0.5 mile wide by 2 meters deep. All radionuclides remain in the water with no further dilution due to tidal influences or settling out.

7.4.1 Radiation Doses from Aquatic Pathways

The annual total body doses estimated for exposures by aquatic pathways in the river and estuary are summarized in Table 7.10 for all radwaste treatment cases. These doses represent a small fraction (less than 10%) of the dose to individuals estimated for terrestrial pathways. The relative contributions of radionuclides in the liquid effluent to total body doses are given in Table 7.11 for the aquatic pathways. With the exception of the dose from swimming, to which ^{234}Pa contributes greatly, ^{234}U and ^{238}U are the main contributors to dose from aquatic exposures.

Annual doses to total body and bone from drinking water are given in Table 7.12 for all radwaste treatment cases. Doses from this exposure pathway have been calculated for the 15-cfs stream as well as the 1300-cfs river. It is unlikely that individuals would routinely obtain drinking water from this small stream. It is possible that an occasional individual may drink from such a source. It is more probable that the river would serve as a source of drinking water for segments of the population around

a fabrication plant. The estuary at the coastal site is not considered to be a source of drinking water.

Annual doses to individuals from eating fish from waters around the model plant are given in Table 7.13 for all radwaste treatment cases. Doses from freshwater sources of fish are higher because bioaccumulation factors for radionuclides in fish are higher for freshwater than for saline water.[15,16] In addition, under the assumptions used in the calculations, the estuary furnished more dilution than the freshwater river. Although estimates were made for eating fish from the 15-cfs streams into which liquid effluents were released, it is unlikely that streams of this size would furnish a substantial portion of fish in local diets. It is more probable that fish in the diet of local populations would come from the river or estuary.

Annual total body doses to individuals swimming in waters around a fuel fabrication plant are given in Table 7.14 for all radwaste treatment cases. Dose from this mode of exposure is less than that from other aquatic pathways. The unlikely event of individuals swimming in the 15-cfs stream for 1% of the year yields an annual total body dose, for the worst case, which is less than 4% of the maximum total body dose from gaseous effluents.

7.5 Total Radiation Dose From All Pathways

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

7.6 Radiation Doses to Organisms Other Than Man

Radiation dose to aquatic plants, invertebrates, fish and waterfowl are estimated for undiluted liquid effluents, the 15-cfs streams, the 1300-cfs river, and the estuary. Annual doses to biota living in these bodies of water are given in Table 7.15. It is unlikely that higher organisms, such as fish or waterfowl, could tolerate living in direct

liquid effluents due to the presence of nonradioactive chemicals and the fact that these effluents would not be found in a physical habitat conducive to higher aquatic life.

For radwaste treatment Case 1, doses to organisms living in the 15-cfs streams (freshwater and saline) are orders of magnitude higher than those estimated for organisms living in the river or estuary where appreciable dilution takes place. Doses to organisms inhabiting the freshwater river are greater than those for organisms in the estuary because bioaccumulation factors for freshwater biota[15] are higher than those for saline water biota.[16] The estuary, under the assumptions used, also furnished more dilution for the radionuclides.

Table 7.16 gives the relative contribution of radionuclides in the aquatic habitats to dose to the biota. For both freshwater and saline water organisms, ^{234}U and ^{238}U are important contributors to dose. Due to relatively high bioaccumulation factors, ^{234}Th and ^{234}Pa are important contributors to dose to plants in freshwater and saline water and dose to invertebrates and fish in saline water.

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 whole body and organ dose 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 7.17). 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 7.17). 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 two to four. 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 two (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 an Enriched Uranium 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 uranium 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 generation 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 (ADU process, Case 1) releases 0.184 Ci of uranium radionuclides 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 7.18 lists these radionuclides and the total quantities released from the model fuel fabrication facility. The longest-lived radionuclides, ^{234}U, ^{235}U, ^{236}U, and ^{238}U, 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 $cm \cdot sec^{-1}$ 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 life-time of the model plant are uniformly distributed in the 50-mile radius area (2.03×10^{10} 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 redeposition 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 uranium radionuclides 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 fraction of uranium radionuclides 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 5×10^{-3} of the concentration in the soil in which the plants grow, that there is no downward movement of the uranium in the soil beyond the root zone (15 cm), and that uranium is not lost by drainage of water. With a soil density of 1.5 g cm^{-3}, the uranium radionuclides deposited on a square meter of earth are contained in 2.25×10^5 g of soil. The following expression is used to estimate the intake via ingestion of plants:

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

Additional intake from the ingestion of plants contaminated via resuspended radionuclides was calculated using the TERMOD code referenced in Section 7.3.

Contaminated Ground. – Exposure via contaminated ground is also estimated. It is assumed that there is no loss of deposited uranium except through radioactive decay.

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 occurs. The average annual doses to the individual out to 50 miles for the various radionuclides and exposure modes are shown in Table 7.19. Almost 99% of the total body dose of 8.2×10^{-4} millirem resulted from exposure to contaminated ground. The average annual total body dose due to ^{234}U, which accounted for about 49% of the total dose, was 4.0×10^{-4}

millirem. These doses are the average doses out to 50 miles, and the dose range, as a function of distance, is indicated by the fact that during operation the total body dose to an individual in the prevailing wind direction at a distance of 1 mile is over 1500 times 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 7.20. The bone receives the highest organ dose, which is about 4 times the dose to the kidney and 1.4 times that to the lungs.

Population Doses. – The average annual dose to the population, given as man-rems per million persons, is shown in Table 7.21. The average annual dose to the population (total body and organs) is again primarily due to ^{234}U which accounts for 99% of the dose. The bone receives the highest organ dose. The total body population dose, 0.82 man-rem/10^6 people, is about the same as the doses estimated for the populations around the plants while the plants are operating, i.e., the coastal plant - 1.54 man-rem/10^6 people and the midwestern - 0.31 man-rem/10^6 people.

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 Sect. 4.5 and the impact of radioactive materials released (dose commitment) from these systems as described in Sect. 7.0 are presented in this section. The accuracy of the cost estimates is about ±30% and the dose commitments represent maximum values. The most advanced waste treatment systems use conventional technology, and it is expected that these techniques could be adapted for use at fuel fabrication plants within a 5-year period. Similarly, many of the models for the movement and concentration of the radionuclides in the environment are receiving additional study to increase their accuracy. In all cases, conservative assumptions are made in selecting treatment efficiency ratings for equipment, in estimating costs, in defining the movement of radionuclides in the environment, and in selecting food and liquid consumption patterns.

Fuel fabrication plants must meet federal and state regulations governing the release of both radioactive and chemical materials, and the waste treatment costs for each category amount to a large fraction of the total cost. Consequently, the costs for the waste treatment systems are divided into the cost for removal of radioactive materials and the cost for removal of noxious chemicals from the wastes. The cost of removing the radioactive materials from the wastes is further divided into the gaseous radwaste treatment cost and the liquid radwaste cost, and the cost for removal of the noxious chemicals is divided into costs for removal of fluoride, ammonia, and nitrate. Similarly, the cost for treatment of solid wastes is assigned to the appropriate radwaste or chemwaste system. The itemized costs for the treatment of chemwastes and radwastes are shown in Table 8.1. The separation of these costs is complicated, particularly for the liquid waste treatment systems, where a number of items, such as pumps, buildings, etc., contribute to both chemwaste and radwaste treatment processes. In assigning the treatment costs to one objective or another, simple tests are used. If a particular item is required for both chemwaste and radwaste treatment work,

the annual cost for that item is divided equally between chemwaste and radwaste costs. The cost or portion of cost for any item used for chemwaste treatment which assists in the removal of two or more species has been divided among those species based on the weight ratio entering that waste treatment system. The zero costs for chemwaste treatment in ADU Case 1 and DC Case 1 (Table 8.1) show that no effort is made to remove chemicals from the effluents with the exception of the removal of a fraction of the hydrofluoric acid in DC Case 1.

The method for prorating the costs is illustrated as follows. The waste processing building is used by all of the waste systems and, consequently, its costs are prorated to the various systems according to the volume of waste treated in each. In ADU Case 2 the waste processing building is assigned 73.5% to process liquid waste, 6.6% to recycle liquid waste, 0.6% to scrap recovery liquid waste, and 19.4% to miscellaneous liquid waste. The miscellaneous liquid waste is used solely for the control of radioactive materials in the effluent and, consequently, the 19.4% of the waste processing building assigned to miscellaneous liquid waste is charged to liquid radwaste cost. Conversely, the recycle liquid waste system is used to reduce the release of nitrate and ammonia in the effluents in addition to controlling radioactive releases. Consequently, the 6.6% of the waste processing building assigned to the recycle liquid waste system is apportioned one-half (or 3.3%) to liquid radwaste cost while the other half is charged to liquid chemwaste costs. On the basis of the weight ratio of nitrate to nitrate-plus-ammonia, the 3.3% of the waste processing building assigned to chemwaste control in the recycle liquid waste system is finally divided into 2.8% of building annual cost for nitrate control and 0.5% for ammonia control. Details of the cost estimate are provided in Appendix A.

The dose commitments from gaseous effluents selected for comparison with treatment costs are (1) maximum annual individual total body, bone, kidney, and lung dose (mrem) at 0.5 mile from the plant; and (2) annual population dose (man-rem) out to a distance of 55 miles. Average annual individual total body dose out to a distance of 55 miles is presented in Sect. 7.0 but is not used in the cost-benefit comparison. Dose commitments

from liquid effluents are compared with treatment costs on two bases, i.e., annual total body dose (mrem) from aquatic pathways after dilution in a 15-cfs stream and after the 15-cfs stream flows into a 1300-cfs stream at the midwestern site. At the coastal site, the total body dose is estimated after the liquid effluent is diluted by a 15-cfs stream and after the 15-cfs stream flows into an estuary. Incremental costs and doses between the cases, i.e., the cost-benefit ratios, are also compared.

8.1 Gaseous Radwaste

The radwaste treatment costs and the radiation dose from the gaseous effluents from the model ADU and DC plants are shown in Table 8.2 and Figs. 8.1 to 8.4. The doses in Case 4 are about 200,000 times lower than in Case 1. In both model plants the largest dose is for bone, followed by lung, kidney, and total body dose. This similarity is expected since the same radionuclides occur in similar compounds in both plant effluents. The individual doses at the midwestern and coastal sites are essentially equal and, consequently, the sites are not presented separately in the tabular and graphical comparison.

The maximum annual individual dose from gaseous effluents at 0.5 mile from the ADU plant is compared with the annual gaseous radwaste treatment cost in Table 8.2 and Fig. 8.1. For the coastal site, the total body dose decreases from 0.89 mrem in Case 1 to 4.6×10^{-6} mrem in Case 4, a factor of about 200,000, for an additional annual cost of $351,000. The degree of reduction in dose is the same for the organ doses. Similarly, the annual average dose to the population at the coastal site decreases from 0.85 man-rem for Case 1 to 4.6×10^{-6} man-rem for Case 4 for the same additional cost (Table 8.2 and Fig. 8.2). The midwestern site shows a slightly higher population dose (but the same degree of reduction in dose) because of the greater population density around the plant. The incremental costs and doses between the case studies indicate that the cost-benefit ratio, in terms of dollars per mrem reduction of maximum annual total body dose at 0.5 mile, increases from $130,000/mrem in increment ADU Case 1/ADU Case 2 to $1,630,000/mrem in ADU Case 2/ADU Case 3 to $369,000,000/mrem in ADU Case 3/ADU Case 4. The cost-benefit, in terms

of dollars per man-rem reduction in the average annual dose to the population out to 55 miles, increases from $136,000/man-rem in increment ADU Case 1/ADU Case 2 to $1,630,000/man-rem in increment ADU Case 2/ADU Case 3 and to $369,000,000/man-rem for the increment ADU Case 3/ADU Case 4. The cost-benefit ratio in the second increment is increased by a factor of about 13 over the cost-benefit ratio of the first increment, but the cost-benefit ratio for the third increment is increased by a factor of 226 over that for the second increment (Table 8.3).

The maximum annual individual dose from gaseous effluents at 0.5 mile from the DC plant is compared with the annual gaseous radwaste treatment cost in Table 8.2 and Fig. 8.3. At the coastal site, the annual total body dose decreases from 0.69 mrem in Case 1 to 3.5×10^{-6} in Case 4, a factor of about 200,000 for an additional annual cost of $289,000. The degree of reduction in dose is the same for the organ doses. Similarly, the average annual dose to the population decreases from 0.66 man-rem for Case 1 to 3.3×10^{-6} man-rem in Case 4 at the coastal site for the same additional cost (Table 8.2 and Fig. 8.4). As with the ADU case, the population dose is slightly higher at the midwestern site because of the greater population density.

The cost-benefit ratio in terms of dollars per mrem reduction in maximum annual individual total body dose is $185,000/mrem in the increment DC Case 1/DC Case 2, $1,240,000/mrem in the increment DC Case 2/DC Case 3, and $364,000,000/mrem in the increment DC Case 3/DC Case 4. The cost-benefit ratio in terms of dollars per man-rem reduction in the average annual dose to the population out to 55 miles for the three increments is $190,000/man-rem, $1,310,000/man-rem, and $385,000,000/man-rem, respectively. The cost-benefit ratios for the DC model plant are quite similar to those seen for the ADU model plant in that both progress from hundreds of thousands of dollars per mrem or man-rem to hundreds of millions of dollars per mrem or man-rem (Table 8.3 and Fig. 8.5). The sharp increase in cost-benefit ratio for the third increment (Case 3/Case 4) of more than two orders of magnitude greater than the second increment (Case 2/Case 3) is obvious for both plant types.

8.2 Liquid Radwaste

Two points are selected for analysis of the impact of the liquid waste effluent, i.e., (1) after dilution in a 15-cfs stream and (2) after the 15-cfs stream is diluted by a 1300-cfs river (midwestern site) or by an estuary (coastal site). The very small 15-cfs stream is a hypothetical case since, realistically, there is little chance that this small stream will provide an appreciable amount of water or fish for consumption or be used for swimming, particularly in Case 1 where a significant amount of chemicals are released. However, it is included to illustrate the maximum impact at the point of discharge from the model plants. The doses for drinking water, fish consumption, and swimming are combined in the cost-benefit analyses. However, the dose from the river and from the estuary are not exactly comparable because the estuary is not a source of drinking water.

The maximum annual individual total body doses from liquid effluents from the ADU plant after dilution in the 15-cfs stream and 1300-cfs river are compared with the annual liquid radwaste treatment costs in Table 8.4 and Figs. 8.5 and 8.6 and with the coastal estuary in Fig. 8.7. Dose is the same for the midwestern and coastal sites in the 15-cfs stream, but the doses in the river and in the estuary are not exactly comparable because the estuary is not a source of drinking water. In ADU Case 1, the maximum annual individual dose from aquatic pathways associated with the 15-cfs stream is 6.0 mrem which is about 7 times higher than the maximum annual individual dose of 0.89 mrem from the gaseous effluent for ADU Case 1. However, the more realistic annual dose associated with the 1300-cfs river at the midwestern site is 0.069 mrem, about 13 times lower than the gaseous and about 90 times lower than the 15-cfs stream cases. In ADU Case 4, the annual dose from the 15-cfs stream is reduced to 1.3×10^{-6} mrem, a factor of 400,000 times lower, for an additional annual expenditure of $896,000. The annual doses in the river and estuary are reduced to extremely low levels, i.e., 1.5×10^{-7} mrem and 3.2×10^{-17} mrem, respectively, for the same annual cost. The incremental costs and doses between the ADU case studies are listed in Tables 8.5 and 8.6.

Using the doses calculated for the 15-cfs stream, which are essentially the same for coastal and midwestern sites, the cost-benefit ratios for liquid effluents from the ADU plant are $65,000/mrem for the increment ADU Case 1/ADU Case 2, $73,000/mrem for the increment ADU Case 2/ADU Case 3, and $1,170,000/mrem for the increment ADU Case 3/ADU Case 4. The increase in the second increment over the first is about 12%, but the third increment is increased by a factor of 16. When the doses calculated for the 1300-cfs river (which occurs only at the midwestern site) are considered, the cost-benefit ratios are much higher than for the 15-cfs stream because the doses are lower by a factor of about 100 in the river as a result of the greater dilution. In this case, the cost-benefit ratios are $5,470,000/mrem for the increment ADU Case 1/ADU Case 2, $6,630,000 for the increment ADU Case 2/ADU Case 3, and $102,600,000/mrem for the increment ADU Case 3/ADU Case 4. Although the cost-benefit ratios are much higher than for the 15-cfs stream, they have about the same relationship to each other. The second increment is about 20% greater than the first, and the third increment is about 15 times the second. When the extremely small doses calculated for the coastal estuary are considered, the cost-benefit ratios are many orders of magnitude greater than for the stream and river, but the same relative increase in cost-benefit occurs.

The maximum annual individual total body dose from liquid effluents from the DC plant after dilution in the 15-cfs stream and 1300-cfs river are compared with the annual radwaste treatment costs in Figs. 8.5 and 8.6. As in the ADU case, the doses are equal for the 15-cfs stream at the coastal and midwestern sites but are not directly comparable for the 1300-cfs river and estuary (Fig. 8.7). The costs and doses for DC Case 3 and DC Case 4 are identical as the treatment systems are the same. In DC Case 1, the maximum annual individual dose from liquid effluents is 2.0 mrem, which is slightly higher than the maximum annual individual dose of 0.69 mrem from the gaseous effluents from DC Case 1. However, the annual dose in the 1300-cfs river at the midwestern site is 0.022 mrem, about 30 times lower than the gaseous and 100 times lower than the 15-cfs stream cases. In DC Case 4, the annual dose in the 15-cfs stream is reduced to 1.9×10^{-4}, a factor of 10,000 times lower for an annual

additional expenditure of $313,000. The annual doses in the river and estuary are reduced to extremely low levels, i.e., 2.2×10^{-6} mrem and 1.1×10^{-15} mrem, respectively, for the same expenditure. The incremental costs and doses between case studies are listed in Tables 8.5 and 8.6.

Using the doses calculated for the 15-cfs stream, which are essentially the same at the coastal and midwestern sites, the cost-benefit ratios for liquid effluents for the DC model plant are $316,000/mrem for the increment DC Case 1/DC Case 2 and $116,000/mrem for the increment DC Case 2/DC Case 3. The liquid radwaste treatment systems are identical in DC Case 3 and DC Case 4. The cost-benefit ratio for the second increment is only about 30% of that for the first increment. If the doses calculated for the 1300-cfs river are considered, the cost-benefit ratios are greatly increased as was the case with the ADU plant. At the 1300-cfs river, the cost-benefit ratios are $26,300,000/mrem for the increment DC Case 1/DC Case 2 and $9,110,000/mrem for the increment DC Case 2/DC Case 3. Again, the cost-benefit ratio for the second increment is about 30% of that for the first increment. Because the doses calculated for the coastal estuary are so small, the cost-benefit ratios based on those doses are many orders of magnitude higher than the cost-benefit ratios for either the 15-cfs stream or the 1300-cfs stream, but the same trend is observed.

The cost-benefit ratios for the gaseous effluents of the ADU and DC model plants and for the liquid effluents of the ADU plants follow a similar trend in that the cost-benefit ratio increases as the dose is reduced and the lower the dose the more rapid the increase in the cost-benefit ratio. This trend was not followed by the cost-benefit ratios for the liquid effluents of the DC model plants which decreased for the second increment DC Case 2/DC Case 3 when compared to the first increment DC Case 1/DC Case 2. The reason for this unusual behavior is that environmental considerations required that the nitrate content of the liquid effluent be reduced. In DC Case 2, the treatment systems were designed to reduce the release of nitrate in effluents which did not contain a major fraction of the radionuclides. Therefore, the dollar cost in the increment DC Case 1/DC Case 2 is greatly increased. However, only a small decrease in total dose is obtained, since this stream contains only a minor amount of

radioactive materials. Thus, the cost-benefit ratio is proportionally higher. Had the nitrate not been a problem, the strategy of first treating the stream with the most radioactive materials could have been followed, and the cost-benefit ratios for liquid effluents from the DC plant would have been more in line with the trend seen for liquid effluents from the ADU plant.

As indicated in Sect. 8.0, the annual waste treatment costs are divided on an arbitrary basis between the chemical wastes and the radioactive wastes in the correlations presented in Sects. 8.1 and 8.2 and Tables 8.1-8.8 and Figures 8.1-8.9. However, it is also valid to correlate the total liquid waste (i.e., radwaste plus chemwaste) treatment costs with the radiological doses, since both chemwaste and radwaste treatments are required in some situations. In addition, the considerations involved in arbitrarily dividing the costs between radwastes and chemwastes are eliminated. The cost-benefit ratios for this comparison are presented in Table 8.7. The cost-benefit ratios in terms of dollars/mrem reduction in the maximum annual individual total body dose from the ADU plant after dilution in the 15-cfs stream are $134,000 for the increment ADU Case 1/ADU Case 2, $182,000 for ADU Case 2/ADU Case 3, and $2,120,000 for ADU Case 3/ADU Case 4. The increase in the second increment over the first is about 36%, and the third increment increases over the second by a factor of about 12. The cost-benefit ratios for the DC plants on the same basis are $674,000 for the increment DC Case 1/DC Case 2, $195,000 for DC Case 2/DC Case 3, and $201,000 for DC Case 2/DC Case 4.

The cement (Sect. 6.2) which is used to solidify evaporator concentrates and to decrease the leachability of the solid wastes (Sect. 4.3.3) is a significant operating cost in ADU and DC Cases 3 and 4. This is particularly true in ADU Case 4 where all of the fluoride that leaves the plant is incorporated in cement as CaF_2. In DC Case 3, 90% of the fluoride is recovered as 45% HF solution and in DC Case 4, 99% of the fluoride is recovered as 47.1% HF solution. The HF solution is recycled to the fuel cycle industry in both cases. Consequently, the amount of CaF_2 formed as solid waste in DC Cases 3 and 4 and the amount of cement required for cementing the CaF_2 is 10 to 100 times less than in ADU

Case 4. The cost for cement in ADU Case 3 and DC Cases 3 and 4 amount to 1.6 to 3.0% of the costs for treating liquid chemwastes or liquid radwastes or for treating the total wastes from the plant (Table 8.8). However, the costs for cement in ADU Case 4 are 36% of the liquid radwaste treatment cost, 43% of liquid chemwaste treatment cost, and 32% of the total plant waste treatment cost.

8.3 Chemical Wastes

The amount of chemicals released in the liquid wastes is compared with the annual costs for chemwaste treatment for the model ADU plant in Fig. 8.8. The annual costs are the total chemwaste treatment costs. In Case 4 the fluoride and ammonia releases are effectively reduced to zero, and in Cases 3 and 4 the amount of nitrate released is reduced to a low level, i.e., to less than 4 ppm* in the plant effluent. This is equivalent to 2400 pounds of nitrate per year which is too low to be shown in Fig. 8.8. The chemical releases from the DC plant are effectively reduced to zero in DC Case 2 by the storage of the liquid wastes. This may be satisfactory in locations where the evaporation rate exceeds the accumulation rate. A system with increased application is used in Cases 3 and 4 for the ADU and DC plants in which the ammonia is converted to nitrate in a calciner and as much nitric acid as can be used is recycled while the excess is subjected to anaerobic digestion to destroy most of the nitrate before being released. The annual cost of chemwaste treatment in ADU Case 4 amounts to $924,000, about 40% of the total waste treatment cost.

The amount of chemicals released by the model DC plant is compared with the annual costs for chemwaste treatment in Fig. 8.9. For the DC process, the fluoride entering the plant appears in the gaseous effluent and not in the liquid effluent. Consequently, fluoride is not listed in

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*Currently, EPA has no fixed guideline for nitrate releases. Each case is judged individually. The tentative guideline for the State of Tennessee is 1.6 ppm nitrogen (as ammonia) after dilution in a stream. A nitrate concentration of 4 ppm is equivalent to 0.7 ppm N. The U. S. Public Health Service maximum specification for nitrate in drinking water is 45 ppm.

Fig. 8.9 which shows liquid effluent treatment cases. Also, the amount of ammonia in the waste effluent is much less than in the ADU plant, since the ammonium diuranate precipitation step is not involved. In DC Cases 3 and 4, the nitrate concentration in the effluent is reduced to less than 4 ppm* or 2400 pounds per year.

In the DC model plant, part of the gaseous chemwaste treatment costs are assigned to removal of hydrofluoric acid from the gaseous wastes. These vary from about $8,000 per year in DC Case 1 to about $40,000 per year in DC Case 4 (Table 8.1).

*Currently, EPA has no fixed guideline for nitrate releases. Each case is judged individually. The tentative guideline for the State of Tennessee is 1.6 ppm nitrogen (as ammonia) after dilution in a stream. A nitrate concentration of 4 ppm is equivalent to 0.7 ppm N. The U. S. Public Health Service maximum specification for nitrate in drinking water is 45 ppm.

Table 4.1. Material Balance for Nominal ADU Process System

Stream[a]	Total gal/day	Flow Rate (lb/day)								
		UF_6	UO_2F_2	H_2O	HF	$(NH_4)_2U_2O_7$	NH_4F	NH_4OH	U_3O_8	UO_2
1	-	16,293	-	-	-	-	-	-	-	-
2	7,694	-	-	64,097	-	-	-	-	-	-
3	7,975	-	14,244	62,447	3,698	-	-	-	-	-
4	79,120	-	-	652,787	-	14,868	10,995	6,872	-	-
5	2,044	-	-	13,919	-	14,406	275	175	-	-
6	-	-	-	-	-	-	-	-	13,606	-
7	-	-	-	-	-	-	-	-	-	12,494
8	68,423	-	-	544,466	-	-	-	17,592	-	-
9	77,282	-	-	638,868	-	462	10,720	6,660	-	-
10	72,948	-	-	597,649	-	105	9,996	6,060	-	-
11	5,000	-	-	41,219	-	357	725	600	-	-

[a]Process streams are identified in Fig. 4.1.

Table 4.2. Material Balance for Nominal Recycle System

Stream[a]	Total gal/day	Flow Rate (lb/day)								
		UO_2	HNO_3	H_2O	Steam	$UO_2(NO_3)_2$	NH_4OH	NH_4NO_3	H_2O_2	$UO_4 \cdot 2H_2O$
1	2,491	-	2,952	19,252	-	-	-	-	-	-
2	-	-	-	-	1,000	-	-	-	-	-
3	-	1,874	-	-	-	-	-	-	-	-
4	2,461	-	1,203	20,502	-	2,735	-	-	-	-
5	281	-	-	1,406	-	-	703	-	-	-
6	2,675	-	-	22,270	-	2,735	-	1,667	-	-
7	4,673	-	-	37,931	-	-	-	-	1,000	-
8	9,150	-	921	72,453	-	-	-	2,006	745	110
9	330	-	28	2,237	-	-	-	62	23	2,350
10	-	1,866	-	-	-	-	-	-	-	-
11	7,577	-	737	57,962	-	-	-	1,605	596	10.4

[a]Process streams are identified in Fig. 4.2.

Table 4.3. Material Balance for Nominal Scrap Recovery System

Stream[a]	Total gal/day	Flow Rate,[b] lb/day			
		H_2O	HNO_3	Uranium	Organic
1	-	-	-	220	-
2	546	4,177	939	-	-
3	686	5,246	926	0.056	-
4	528	4,394	4.4	-	-
5	528	4,394	18	220	-
6	1,055	-	-	-	7,000
7	158	1,260	117	-	-

[a]Process streams are identified in Fig. 4.3.

[b]Flow rates are nominal daily rates. This system would not operate continuously to meet the plant needs.

Table 4.4. Liquid Radwaste Generated by the Model ADU Plant Before Effluent Treatment

Source	Volume (gal/day)	Percent of Total Volume	Uranium Concentration (ppm)	Relative β Concentration	Primary Chemical Constituents	
					Type	Concentration (g/liter)
ADU Process	73,000	64	130	10 x equilibrium	NH_4F	16
					NH_4OH	10
UO_2 Recycle	7,580	6.6	120	Equilibrium	NH_4NO_3	26
					HNO_3	12
					H_2O_2	10
Scrap Recovery	686	0.60	10	850 x equilibrium	HNO_3	158
Miscellaneous	22,000	19.	10	Equilibrium	Detergent	-
Liquid Scrubbers	11,000	9.6	5	Equilibrium	NH_4F	3
					NH_4OH	20

Table 4.5. Material Balance for Nominal Direct (Dry) Conversion Process

Stream[a]	Total scfm	Flow Rate (lb/day)						
		UF_6	UO_2F_2	UO_2	HF	H_2O	N_2	H_2
1	11.5	16,285	-	-	-	-	-	-
2	73	-	-	-	-	5,265	-	-
3	96	-	-	-	3,702	3,600	-	-
4	-	-	14,249	-	-	-	-	-
5	41.5	-	-	-	-	-	1,166	250
6	31.4	-	-	-	-	2,268	-	-
7	83.3	-	-	-	1,666	2,268	1,166	167
8	-	-	1,425	11,242	-	-	-	-
9	41.5	-	-	-	-	-	1,166	250
10	31.5	-	-	-	-	2,268	-	-
11	74.1	-	-	-	185	2,268	1,166	241
12	-	-	-	12,491	-	-	-	-
13	253	-	-	-	5,553	8,136	2,331	407

[a] Process streams are identified in Fig. 4.4.

Table 4.6. Characteristics of the Isotopes in the Feed to the Light-Water Reactor Fuel Fabrication Plant

Nuclide	Half-Life	Type of Decay
Gaseous		
None		
Semi-volatiles		
None		
Particulates		
U-234	2.48×10^5 yr	α
U-235	7.13×10^8 yr	α
Th-231	25.64 hr	β
U-238	4.49×10^9 yr	α
Th-234	24.10 day	β
Pa-234	1.175 min	β
U-236	2.39×10^7 yr	α

Table 4.7. Distribution of Alpha Radioactivity in 4% Enriched Uranium in the Feed to the Light-Water Reactor Fuel Fabrication Plant

Nuclide	$T_{1/2}$	Specific Activity of Pure Isotope (Ci/g)	Specific Activity of Each Isotope in 4% Enriched Fuel (Ci/g U)	Percent of Alpha Activity Contributed by Each Isotope
U-234	2.48×10^{5} yr	6.19×10^{-3}	2.47×10^{-6}	82.33
U-235	7.1×10^{8} yr	2.144×10^{-6}	8.56×10^{-8}	2.85
U-236	2.39×10^{7} yr	6.34×10^{-5}	1.27×10^{-7}	4.22
U-238	4.51×10^{9} yr	3.333×10^{-7}	3.19×10^{-7}	10.60

Table 4.8. Summary of Variables for Model LWR Fuel Fabrication Plant
Gaseous and Liquid Radwaste Treatment Systems

AMMONIUM DIURANATE (ADU) PROCESS

	Case 1	Case 2	Case 3	Case 4
Treatment Objective	Base Case	Reduce uranium release by 2, eliminate release of nitrate	Reduce uranium release by 15, reduce or eliminate release of ammonia and nitrate (recycle), produce low activity solid wastes [CaF_2, $Ca(OH)_2$][a]	Eliminate release of liquids (recycle), eliminate release of ammonia and nitrate (recycle), immobilize solid wastes in cement [CaF_2, $Ca(OH)_2$, residual radionuclides]
Plant Decontamination Factor for Uranium (wt U entering plant/wt U released)	1.1×10^3	2.1×10^3	1.7×10^4	4.9×10^9
		ADU Liquid Radwaste		
	Filter, lagoon, release	16-hr retention, centrifuge, filter, $Ca(OH)_2$-CaF_2 precipitation, store CaF_2 in lined lagoon, release liquid waste	16-hr retention, centrifuge, filter, ion exchange, $Ca(OH)_2$-CaF_2 precipitation, volatilize and recycle NH_3, lined lagoon, release liquid waste	16-hr retention, centrifuge, filter, ion exchange, $Ca(OH)_2$-CaF_2 precipitation, volatilize and recycle NH_3, evaporate and recycle H_2O, incorporate CaF_2 waste in cement, release excess water
		ADU Recycle Liquid Radwaste		
	Filter, lagoon, release	$Ca(OH)_2$ neutralization, 16-hr retention, centrifuge, filter, store $Ca(NO_3)_2$ in lined lagoon, no liquid discharge	Filter, NH_3 neutralization, 16-hr retention, centrifuge, filter, spray calcine in sand bed and recycle HNO_3, sand to scrap recovery, nitrate removal by anaerobic digestion	Same as Case 3
		ADU Miscellaneous Liquid Radwaste		
	Filter, lagoon, release	Filter, lagoon, release	Evaporate and recycle water, immobilize bottoms in cement for burial	Same as Case 3
		ADU Scrap Recovery Liquid Radwaste		
	Lagoon, release, ship solid waste to licensed burial ground	Store in lined lagoon, no liquid discharge, ship solid waste to licensed burial ground	Evaporate and recycle HNO_3, immobilize solid waste and bottoms in cement for burial	Same as Case 3
		ADU Process Gaseous Radwaste		
	Water scrubber[b]	Water scrubber, HEPA filter (efficiency 95%)	Water scrubber, HEPA filter (efficiency 99.95%)	Water scrubbers, HEPA filters in series (efficiency 99.9995%)
		ADU Ventilation Gaseous Radwaste		
	Roughing filter[b]	Roughing filter, HEPA filter (efficiency 95%)	Roughing filter, HEPA filter (efficiency 99.95%)	Roughing filter, HEPA filters in series (efficiency 99.9995%)

[a] < 1 uCi/lb, 770 ppm uranium.

[b] Part of the base plant.

Table 4.9. Summary of Variables for Model LWR Fuel Fabrication Plant
Gaseous and Liquid Radwaste Treatment Systems

DIRECT CONVERSION (DC) PROCESS[a]

	Case 1	Case 2	Case 3	Case 4
Treatment Objective	Base Case	Reduce uranium release by 3, reduce HF release by 10^7	Reduce uranium release by 10^5, recover 90% of HF, reduce release of HF by 3×10^7, reduce or eliminate release of ammonia and nitrate (recycle), eliminate release of liquids, produce low activity[b] solid wastes [CaF_2, $Ca(OH)_2$, residual radionuclides]	Reduce uranium release by 10^7, recover 99% of HF, reduce HF release by 3×10^7, immobilize solid wastes in cement [CaF_2, $Ca(OH)_2$, residual radionuclides]
Plant Decontamination Factor for Uranium (wt U entering plant/wt U released)	3.9×10^3	6.0×10^3	6.7×10^7	6.7×10^9
		DC Recycle Liquid Radwaste		
	Filter, lagoon, release	$Ca(OH)_2$ neutralization, filter, 16-hr retention, centrifuge, store $Ca(NO_3)_2$ in lined lagoon, no liquid discharge	NH_3 neutralization, 16-hr retention, centrifuge, filter, spray calcine in sand bed and recycle HNO_3, sand to scrap recovery, nitrate removal by anaerobic digestion	Same as Case 3
		DC Miscellaneous Liquid Radwaste		
	Filter, lagoon, release	Filter, lagoon, release	Evaporate and recycle water, immobilize bottoms in cement for burial, release excess water	Same as Case 3
		DC Scrap Recovery Liquid Radwaste		
	Lagoon, release, ship solid waste to licensed burial ground	Store in lined lagoon, no liquid discharge, ship solid waste to licensed burial ground	Evaporate and recycle HNO_3, immobilize solid waste and bottoms in cement for burial	Same as Case 3
		DC Process Gaseous Radwaste		
	Crushed limestone, tower, H_2 burner, store solid waste in unlined storage area	KOH scrubber, lime regeneration of KOH, store solid waste in lined storage area, H_2 dilution	Single-pass HF condenser 90% HF recovery, KOH scrubber, lime regeneration of KOH, HEPA filter (efficiency 99.95%), incorporate CaF_2 waste in cement, H_2 dilution	Multiple-pass HF condenser 99% HF recovery, KOH scrubber, lime regeneration of KOH, HEPA filters in series (efficiency 99.9995%), incorporate CaF_2 waste in cement, H_2 dilution
		DC Ventilation Gaseous Radwaste		
	Roughing filter[c]	Roughing filter, HEPA filter (efficiency 95%)	Roughing filter, HEPA filter (efficiency 99.95%)	Roughing filter, HEPA filters in series (efficiency 99.9995%)

[a] Dry process - no liquid waste for main process line.

[b] < 1 μCi/lb, 770 ppm uranium.

[c] Part of the base plant.

Table 4.10. Source Terms for Model ADU Plants – Calculated Release of Radioactive Material in Liquid Effluents

Nuclide	Case 1		Case 2		Case 3		Case 4	
	Concentration (μCi/ml)	Amount (Ci/yr)	Concentration (μCi/ml)	Amount (Ci/yr)	Concentration (μCi/ml)	Amount (Ci/yr)	Concentration (μCi/ml)	Amount (Ci/yr)
From ADU Radwaste System[a]								
U-234	2.5E-5	2.4	1.2E-5	1.2	2.5E-6	2.2E-1	2.5E-10	5.3E-6
U-235	8.6E-7	8.2E-2	4.2E-7	4.1E-2	8.5E-8	7.4E-3	8.5E-12	1.8E-7
U-236	1.3E-6	1.2E-1	6.3E-7	6.1E-2	1.3E-7	1.1E-2	1.3E-11	2.7E-7
U-238	3.3E-6	3.1E-1	1.6E-6	1.5E-1	3.2E-7	2.8E-2	3.2E-11	6.8E-7
Th-231	8.6E-6	8.2E-1	4.2E-7	4.1E-2	8.5E-8	7.4E-3	8.5E-12	1.8E-7
Th-234	3.3E-5	3.1	1.6E-6	1.5E-1	3.2E-7	2.8E-2	3.2E-11	6.8E-7
Pa-234	3.3E-5	3.1	1.6E-6	1.5E-1	3.2E-7	2.8E-2	3.2E-11	6.8E-7
From Recycle Radwaste System[b]								
U-234	2.4E-5	2.1E-1	2.4E-5	2.1E-1	2.4E-9	3.8E-7	2.4E-9	3.8E-7
U-235	8.2E-7	7.1E-3	8.2E-7	7.1E-3	8.2E-11	1.3E-8	8.2E-11	1.3E-8
U-236	1.3E-6	1.1E-2	1.3E-6	1.1E-2	1.3E-10	2.0E-8	1.3E-10	2.0E-8
U-238	3.0E-6	2.6E-2	3.0E-6	2.6E-2	3.0E-10	4.9E-8	3.0E-10	4.9E-8
Th-231	8.2E-7	7.1E-3	8.2E-7	7.1E-3	8.0E-11	1.3E-8	8.2E-11	1.3E-8
Th-234	3.0E-6	2.6E-2	3.0E-6	2.6E-2	3.0E-10	4.9E-8	3.0E-10	4.9E-8
Pa-234	3.0E-6	2.6E-2	3.0E-6	2.6E-2	3.0E-10	4.9E-8	3.0E-10	4.9E-8
From Scrap Recovery Radwaste System[b]								
U-234	2.4E-5	1.9E-2	2.4E-5	1.9E-2	0[d]	0[d]	0[d]	0[d]
U-235	8.3E-7	6.5E-4	8.3E-7	6.5E-4	0	0	0	0
U-236	1.2E-6	9.6E-4	1.2E-6	9.6E-4	0	0	0	0
U-238	3.1E-6	2.4E-3	3.1E-6	2.4E-3	0	0	0	0
Th-231	7.0E-4	5.5E-1	7.0E-4	5.5E-1	0	0	0	0
Th-234	2.6E-3	2.0	2.6E-3	2.0	0	0	0	0
Pa-234	2.6E-3	2.0	2.6E-3	2.0	0	0	0	0
From Miscellaneous Radwaste System								
U-234	2.5E-5	6.2E-1	2.5E-5	6.2E-1	0[d]	0[d]	0[d]	0[d]
U-235	8.4E-7	2.1E-2	8.4E-7	2.1E-2	0	0	0	0
U-236	1.3E-6	3.2E-2	1.3E-6	3.2E-2	0	0	0	0
U-238	3.2E-6	8.0E-2	3.2E-6	8.0E-2	0	0	0	0
Th-231	8.4E-7	2.1E-2	8.4E-7	2.1E-2	0	0	0	0
Th-234	3.2E-6	8.0E-2	3.2E-6	8.0E-2	0	0	0	0
Pa-234	3.2E-6	8.0E-2	3.2E-6	8.0E-2	0	0	0	0
Total Released From Plant[c]								
U-234	8.3E-6	3.2	4.7E-6	1.8	6.4E-7	2.2E-1	1.9E-11	5.7E-6
U-235	2.9E-7	1.1E-1	1.6E-7	6.2E-2	2.1E-8	7.4E-3	6.5E-13	1.9E-7
U-236	4.2E-7	1.6E-1	2.4E-7	9.3E-2	3.2E-8	1.1E-2	9.9E-13	2.9E-7
U-238	1.1E-6	4.1E-1	6.0E-7	2.3E-1	8.1E-8	2.8E-2	2.4E-12	7.3E-7
Th-231	2.9E-7	1.1E-1	1.6E-7	6.2E-2	2.1E-8	7.4E-3	6.5E-13	1.9E-7
Th-234	1.6E-6	6.1E-1	6.0E-7	2.3E-1	8.1E-8	2.8E-2	2.4E-12	7.3E-7
Pa-234	1.6E-6	6.1E-1	6.0E-7	2.3E-1	8.1E-8	2.8E-2	2.4E-12	7.3E-7

[a] ADU and scrap recovery radwastes in Case 1 are released to the equalization lagoon after retention for 70 days to allow decay of beta emitters (^{231}Th, ^{234}Th, ^{234}Pa).

[b] Recycle and scrap recovery radwastes in Case 2 are stored in a lined lagoon and are not released.

[c] All liquid radwastes from the plant are diluted with 228,540 gal/day of nonradioactive effluents in the equalization lagoon (Sect. 4.5.1). The liquid from the equalization lagoon is released to a stream or a river in a nonrestricted area.

[d] Water is recycled for reuse (Sect. 4.5.1).

Table 4.11. Source Terms for Model ADU Plants — Calculated Release of Radioactive Material in Gaseous Effluents[a]

Nuclide	Case 1		Case 2		Case 3		Case 4	
	Concentration (μCi/ml)	Amount (μCi/yr)	Concentration (μCi/ml)	Amount (μCi/yr)	Concentration (μCi/yr)	Amount (μCi/yr)	Concentration (μCi/ml)	Amount (μCi/yr)
				Process				
U-234	5.0E-11	4.2E+4	2.5E-12	2.1E+3	2.5E-14	2.1E+1	2.5E-16	2.1E-1
U-235	1.7E-12	1.4E+3	8.5E-14	7.0E+1	8.5E-16	7.0E-1	8.5E-18	7.0E-3
U-236	2.6E-12	2.2E+3	1.3E-13	1.1E+2	1.3E-15	1.1	1.3E-17	1.1E-2
U-238	6.5E-12	5.4E+3	3.3E-13	2.7E+2	3.3E-15	2.7	3.3E-17	2.7E-2
Th-231	1.7E-12	1.4E+3	8.5E-14	7.0E+1	8.5E-16	7.0E-1	8.5E-18	7.0E-3
Th-234	6.5E-12	5.4E+3	3.3E-13	2.7E+2	3.3E-15	2.7	3.3E-17	2.7E-2
Pa-234	6.5E-12	5.4E+3	3.3E-13	2.7E+2	3.3E-15	2.7	3.3E-17	2.7E-2
				Ventilation				
U-234	1.0E-10	1.1E+5	5.0E-12	5.5E+3	5.0E-14	5.5E+1	5.0E-16	5.5E-1
U-235	3.5E-12	3.7E+3	1.8E-13	1.9E+2	1.8E-15	1.9	1.8E-17	1.9E-2
U-236	5.2E-12	5.6E+3	2.6E-13	2.8E+2	2.6E-15	2.8	2.6E-17	2.8E-2
U-238	1.3E-11	1.4E+4	6.5E-13	7.0E+2	6.5E-15	7.0	6.5E-17	7.0E-2
Th-231	3.5E-12	3.7E+3	1.8E-13	1.9E+2	1.8E-15	1.9	1.8E-17	1.9E-2
Th-234	1.3E-11	1.4E+4	6.5E-13	7.0E+2	6.5E-15	7.0	6.5E-17	7.0E-2
Pa-234	1.3E-11	1.4E+4	6.5E-13	7.0E+2	6.5E-15	7.0	6.5E-17	7.0E-2
Total α		1.8E+5		9.2E+3		9.2E+1		9.2E-1
Total β		4.4E+4		2.2E+3		2.2E+1		2.2E-1

[a]The gaseous effluent is released from a stack at the roof top level in the restricted area.

Table 4.12. Source Terms for Model DC Plants – Calculated Release of Radioactive Material in Liquid Effluents[a]

Nuclide	Case 1		Case 2		Case 3		Case 4	
	Concentration (μCi/ml)	Amount (Ci/yr)	Concentration (μCi/ml)	Amount (Ci/yr)	Concentration (μCi/ml)	Amount (Ci/yr)	Concentration (μCi/ml)	Amount (Ci/yr)
			From Recycle Radwaste System[a]					
U-234	2.4E-5	2.1E-1	2.4E-5	2.1E-1	2.4E-9	6.8E-6	2.4E-9	6.8E-6
U-235	8.2E-7	7.1E-3	8.2E-7	7.1E-3	8.2E-11	2.4E-7	8.2E-11	2.4E-7
U-236	1.3E-6	1.1E-2	1.3E-6	1.1E-2	1.3E-10	3.5E-7	1.3E-10	3.5E-7
U-238	3.0E-6	2.6E-2	3.0E-6	2.6E-2	3.0E-10	8.8E-7	3.0E-10	8.8E-7
Th-231	8.2E-7	7.1E-3	8.2E-7	7.1E-3	8.2E-11	2.4E-7	8.2E-11	2.4E-7
Th-234	3.0E-6	2.6E-2	3.0E-6	2.6E-2	3.0E-10	8.8E-7	3.0E-10	8.8E-7
Pa-234	3.0E-6	2.6E-2	3.0E-6	2.6E-2	3.0E-10	8.8E-7	3.0E-10	8.8E-7
			From Scrap Recovery Radwaste System[a,b]					
U-234	2.4E-5	1.9E-2	2.4E-5	1.9E-2	0[d]	0[d]	0[d]	0[d]
U-235	8.2E-7	6.5E-4	8.3E-7	6.5E-4	0	0	0	0
U-236	1.2E-6	9.6E-4	1.2E-6	9.6E-4	0	0	0	0
U-238	3.1E-6	2.4E-3	3.1E-6	2.4E-3	0	0	0	0
Th-231	7.0E-4	5.5E-1	7.0E-4	5.5E-1	0	0	0	0
Th-234	2.6E-3	2.0	2.6E-3	2.0	0	0	0	0
Pa-234	2.6E-3	2.0	2.6E-3	2.0	0	0	0	0
			From Miscellaneous Radwaste System					
U-234	2.5E-5	6.2E-1	2.5E-5	6.2E-1	2.5E-9	5.5E-5	2.5E-9	5.5E-5
U-235	8.4E-7	2.1E-2	8.4E-7	2.1E-2	8.4E-11	1.9E-6	8.4E-11	1.9E-6
U-236	1.3E-6	3.2E-2	1.3E-6	3.2E-2	1.3E-10	2.8E-6	1.3E-10	2.8E-6
U-238	3.2E-6	8.0E-2	3.2E-6	8.0E-2	3.2E-10	7.1E-6	3.2E-10	7.1E-6
Th-231	8.4E-7	2.1E-2	8.4E-7	2.1E-2	8.4E-11	1.9E-6	8.4E-11	1.9E-6
Th-234	3.2E-6	8.0E-2	3.2E-6	8.0E-2	3.2E-10	7.1E-6	3.2E-10	7.1E-6
Pa-234	3.2E-6	8.0E-2	3.2E-6	8.0E-2	3.2E-10	7.1E-6	3.2E-10	7.1E-6
			Total Released From Plant[c]					
U-234	2.9E-6	8.5E-1	2.2E-6	6.2E-1	2.1E-10	6.2E-5	2.1E-10	6.2E-5
U-235	9.9E-8	2.9E-2	7.4E-8	2.1E-2	7.3E-12	2.1E-6	7.3E-12	2.1E-6
U-236	1.5E-7	4.4E-2	1.1E-7	3.2E-2	1.1E-11	3.2E-6	1.1E-11	3.2E-6
U-238	3.7E-7	1.1E-1	2.8E-7	8.0E-2	2.7E-11	8.0E-6	2.7E-11	8.0E-6
Th-231	9.9E-8	2.9E-2	7.4E-8	2.1E-2	7.3E-12	2.1E-6	7.3E-12	2.1E-6
Th-234	2.3E-6	6.9E-1	2.8E-7	8.0E-2	2.7E-11	8.0E-6	2.7E-11	8.0E-6
Pa-234	2.3E-6	6.9E-1	2.8E-7	8.0E-2	2.7E-11	8.0E-6	2.7E-11	8.0E-6

[a] Recycle and scrap recovery radwastes in Case 2 are stored in a lined lagoon and are not released.

[b] Scrap recovery waste in Case 1 is released to the equalization lagoon after retention for 45 days to allow decay of beta emitters (^{231}Th, ^{234}Th, ^{234}Pa).

[c] All liquid radwastes from the plant are diluted with 228,540 gal/day of nonradioactive effluents in the equalization lagoon (Sect. 4.5.2). The liquid from the equalization lagoon is released to a stream or river in a nonrestricted area.

[d] Water is recycled for reuse (Sect. 4.5.2).

Table 4.13. Source Terms for Model DC Plants – Calculated Release of Radioactive Materials in Gaseous Effluents[a]

Nuclide	Case 1		Case 2		Case 3		Case 4	
	Concentration (μCi/ml)	Amount (μCi/yr)	Concentration (μCi/ml)	Amount (μCi/yr)	Concentration (μCi/ml)	Amount (μCi/yr)	Concentration (μCi/ml)	Amount (μCi/yr)
				Process				
U-234	3.2E-11	7.5E+3	2.5E-12	4.1E+2	1.3E-15	2.1E-1	1.3E-17	2.1E-3
U-235	1.1E-12	2.5E+2	8.5E-14	1.4E+1	4.3E-17	7.0E-3	4.3E-19	7.0E-5
U-236	1.7E-12	3.9E+2	1.3E-13	2.1E+1	6.5E-17	1.1E-2	6.5E-19	1.1E-4.
U-238	4.2E-12	9.7E+2	3.3E-13	5.3E+1	1.7E-16	2.7E-2	1.7E-18	2.7E-4
Th-231	1.1E-12	2.5E+2	8.5E-14	1.4E+1	4.3E-17	7.0E-3	4.3E-19	7.0E-5
Th-234	4.2E-12	9.7E+2	3.3E-13	5.3E+1	1.7E-16	2.7E-2	1.7E-18	2.7E-4
Pa-234	4.2E-12	9.7E+2	3.3E-13	5.3E+1	1.7E-16	2.7E-2	1.7E-18	2.7E-4
				Ventilation				
U-234	1.0E-10	1.1E+5	5.0E-12	5.5E+3	5.0E-14	5.5E+1	5.0E-16	5.5E-1
U-235	3.5E-12	3.7E+3	1.8E-13	1.9E+2	1.8E-15	1.9	1.8E-17	1.9E-2
U-236	5.2E-12	5.6E+3	2.6E-13	2.8E+2	2.6E-15	2.8	2.6E-17	2.8E-2
U-238	1.3E-11	1.4E+4	6.5E-13	7.0E+2	6.5E-15	7.0	6.5E-17	7.0E-2
Th-231	3.5E-12	3.7E+3	1.8E-13	1.9E+2	1.8E-15	1.9	1.8E-17	1.9E-2
Th-234	1.3E-11	1.4E+4	6.5E-13	7.0E+2	6.5E-15	7.0	6.5E-17	7.0E-2
Pa-234	1.3E-11	1.4E+4	6.5E-13	7.0E+2	6.5E-15	7.0	6.5E-17	7.0E-2
Total α		1.4E+5		7.2E+3		6.7E+1		6.7E-1
Total β		3.3E+4		1.7E+3		1.6E+1		1.6E-1

[a]The gaseous effluent is released from a stack at the roof-top level in the restricted area.

Table 4.14. Material Balance for ADU Process Liquid Waste - Case 1

Stream	Total gal/day	Flow Rate (lb/day)			
		H_2O	NH_4OH	NH_4F	U
1	72,948	597,649	6,060	9,996	80.0
2	10,881	90,647	1,799	275	1.0
3	83,826	688,224	7,858	10,270	7.1
4	-	72	0.82	1.1	73.9

Table 4.15. Material Balance for Recycle Liquid Waste - Case 1

Stream	Total gal/day	Flow Rate (lb/day)				
		H_2O	HNO_3	NH_4NO_3	H_2O_2	U
1	7,577	57,962	737	1,605	596	7.3
2	-	6.7	-	-	-	6.7
3	7,577	59,655	737	1,605	596	0.61

Table 4.16. Material Balance for ADU Process Liquid Waste - Case 2

Stream	Total gal/day	Flow Rate (lb/day)					
		H_2O	NH_4OH	NH_4F	$Ca(OH)_2$	CaF_2	U
1	72,948	597,649	6,060	9,996	-	-	80.0
2	10,881	90,647	1,799	275	-	-	1.0
3	83,826	688,296	7,859	10,271	-	-	81.0
4	83,814	688,196	7,858	10,269	-	-	14.1
5	12	100	1.1	1.5	-	-	76.9
6	-	-	-	-	21,571	-	-
7	86,106	688,196	17,578	-	1,027	10,823	14.1
8	85,697	688,196	17,578	-	1,027	-	3.52
9	-	-	-	-	-	10,823	10.6

Table 4.17. Material Balance for Recycle Liquid Waste - Case 2

Stream	Total gal/day	Flow Rate (lb/day)						
		H_2O	HNO_3	NH_4NO_3	H_2O_2	$Ca(OH)_2$	$Ca(NO_3)_2$	U
1	7,577	57,962	737	1,605	596	-	-	7.3
2	-	-	-	-	-	433	-	-
3	2	6	-	-	-	-	-	6.1
4	7,575	57,957	737	1,605	596	-	958	1.21

Table 4.18. Material Balance for ADU Process Liquid Waste - Case 3

Stream	Total gal/day	Flow Rate (lb/day)					
		H_2O	NH_4OH	NH_4F	$Ca(OH)_2$	CaF_2	U
1	72,948	597,649	6,060	9,996	-	-	80.0
2	10,881	90,647	1,799	275	-	-	1.0
3	83,826	688,296	7,859	10,271	-	-	81.0
4	83,814	688,196	7,858	10,269	-	-	14.1
5	12	100	1.1	1.5	-	-	76.9
6	83,814	688,196	7,858	10,269	-	-	1.4
7	-	-	-	-	21,571	-	-
8	9,275	52,734	17,578	-	-	-	-
9	76,685	635,462	-	-	1,027	10,823	1.41
10	-	-	-	-	-	10,823	0.14
11	76,277	635,462	-	-	1,027	-	1.27
		H_2O	HNO_3	U	F^-		
A	169	1,339	160.6	-	-		
B	169	1,339	154	12.72	0.41		

Table 4.19. Material Balance for Recycle Liquid Waste - Cases 3 and 4

Stream	Total gal/day	Flow Rate (lb/day)								
		H_2O	HNO_3	NH_4NO_3	H_2O_2	NH_3	NO_2	$Ca(OH)_2$	U	$Ca(NO_3)_2$
1	7,577	57,962	737	1,605	566	-	-	-	7.3	-
2	-	-	-	-	-	230	-	-	-	-
3	7,577	57,962	-	2,572	596	-	-	-	1.2	-
4	-	59,330	-	-	-	-	2,958	-	-	-
5	-	-	-	-	-	-	74	-	-	-
6	705	3,849	3,849	-	-	-	-	-	-	-
7	-	6	-	-	-	-	-	-	6.1	-
8	-	-	-	-	-	-	-	-	1.2	-
9	6,703	55,481	-	-	-	-	-	-	-	-
10	1,525	763	763	-	-	-	-	-	-	-
11	-	-	-	-	-	-	-	448	-	-
12	21,213	176,704	-	-	-	-	-	-	-	-
13	21,460	176,704	-	-	-	-	-	435	-	13

Table 4.20. Material Balance for ADU Process Liquid Waste - Case 4

Stream	Total gal/day	Flow Rate (lb/day)						
		H_2O	NH_4OH	NH_4F	$Ca(OH)_2$	CaF_2	Cement	U
1	72,948	597,649	6,060	9,996	-	-	-	80.0
2	10,881	90,647	1,799	275	-	-	-	1.0
3	83,826	688,270	7,859	10,271	-	-	-	81.0
4	83,814	688,170	7,858	10,269	-	-	-	14.1
5	12	100	1.1	1.5	-	-	-	76.9
6	83,814	688,170	7,858	10,268	-	-	-	1.41
7	-	-	-	-	21,571	-	-	-
8	9,275	52,734	15,578	-	-	-	-	-
9	76,685	635,436	-	-	1,027	10,823	-	1.41
10	1,708	10,823	-	-	17.5	10,823	-	0.14
11	-	-	-	-	-	-	26,000	-
12	74,978	624,613	-	-	1,010	-	-	1.27
13	56,853	473,642	-	-	-	-	-	-
14	176	1,010	-	-	1,010	-	-	1.27
15	18,000	149,961	-	-	-	-	-	-

		H_2O	HNO_3	U	F^-
A	169	1,339	160.6	-	-
B	169	1,339	154	12.7	0.41

Table 4.21. Material Balances for DC Process Gaseous Radwaste Systems - Cases 1 through 4

Case	Stream	Total Flow (scfm)	Uranium Conc. (μCi/ml)	HF Conc. (ppb)	HF (lb/day)	N_2 (lb/day)	H_2O (lb/day)	H_2 (lb/day)	O_2 (lb/day)
1	1	253	2.3E-7	2.7E+8	5,553	2,331	8,136	407	-
	2	221	4.2E-10	1.9E+7	333	2,331	10,476	407	-
	3	8,500	1.1E-11	4.9E+5	333	729,211	14,148	-	230,400
2	1	253	2.3E-7	2.7E+8	5,553	2,331	8,136	407	-
	2	77.5	1.0E-8	3.3	2.0E-4	2,331	361	407	-
	3	2,577	3.0E-12	0.9	2.0E-4	230,722	361	407	64,178
3	1	253	2.3E-7	2.7E+8	5,553	2,331	8,136	407	-
	2	82.5	7.7E-7	1.1E+8	732	2,331	77	407	-
	3	77.5	1.0E-8	11	6.8E-5	2,331	361	407	-
	4	77.5	1.0E-9	-	-	2,331	361	407	-
	5	2,577	1.5E-13	-	-	230,722	361	407	64,178
4	1	253	2.eE-7	2.7E+8	5,553	2,331	8,136	407	-
	2	73.8	8.6E-7	1.2E+7	7.3E-6	2,331	29	407	-
	3	77.5	1.0E-8	1.2	7.3E-6	2,331	361	407	-
	4	77.5	1.0E-10	-	-	2,331	361	407	-
	5	2,577	1.5E-15	-	-	230,722	361	407	64,178

Table 6.1. Estimated Annual Costs and Contribution to Power Cost for the 1500-Metric Ton/yr Model ADU and Direct Conversion Fuel Fabrication Plants

Radwaste Case	Capital Cost[a] ($1000)	Annual Fixed Charges ($1000)	Annual Operating Cost ($1000)	Total[c] Annual Cost ($1000)	Contribution to Power Cost[b] (mills/kWhr)
ADU-1	1081	281	59	340	9.0E-4
ADU-2	1619	421	391	812	2.1E-3
ADU-3	4037	1050	365	1415	3.7E-3
ADU-4	4990	1297	1218	2515	6.4E-3
DC-1	586	153	49	202	5.5E-4
DC-2	1119	291	368	659	1.7E-3
DC-3	2808	730	264	994	2.6E-3
DC-4	3254	846	284	1130	2.9E-3

[a] Includes direct cost (building and installed equipment) and indirect cost. The interest during construction is included as an indirect cost.

[b] The contribution to power is computed from the total annual cost on the basis of a 1500-metric ton/yr fuel fabrication plant supplying fuel to be consumed at 33,000 MWd/ton with a thermal efficiency of 32.5%.

[c] Total cost for radwaste plus chemwaste treatment.

Table 6.2. Installed Cost of Equipment for Waste Treatment System - ADU Case 1

Item	Cost ($1000) Direct	Capital[a]
Batching tank, 90,000 gal	37	89
Centrifugal pump, 150 gpm	4	10
Rotary drum filter, 1/2 ft^2	2	5
Liquid waste pipeline, 12-in. diam, PV	16	38
Batching tank, 10,000 gal	17	41
Centrifugal pump, 12 gpm	2	5
Sump pump, 15 gpm	2	5
Sampling tanks (2), 25,000 gal	35	84
Centrifugal pump, 15 gpm	2	5
Rotary drum filter, 1 ft^2	3	7
Liquid waste pipeline, 1-in. diam, SS	10	24
Tank, 250 gal, SS	8	19
Centrifugal pump, 5 gpm, SS	3	7
Lagoon, unlined, holding, 1.2×10^7 gal	115	276
Lagoon, unlined, equalization, 3.6×10^5 gal	14	34
Processing building, 25 ft x 25 ft	12	29
Ventilation		
Ducts	83	199
Blowers	85	204
TOTALS	450	1081

[a]Capital cost is sum of direct and indirect costs.

Table 6.3. Installed Cost of Equipment for Waste Treatment System - ADU Case 2

Item	Cost ($1000) Direct	Capital[a]
Batching tank, 90,000 gal	37	89
Hold tank, 90,000 gal	40	96
Batching tank, 10,000 gal	17	41
Sampling tanks (2), 25,000 gal	35	84
Tank, 250 gal, SS	8	19
Hold tank, 10,000 gal	20	48
Centrifugal pump, 150 gpm	4	10
Centrifugal pump, 12 gpm	2	5
Centrifugal pump, 75 gpm	3	7
Sump pump, 15 gpm	2	5
Centrifugal pump, 15 gpm	2	5
Centrifugal pump, 5 gpm, SS	3	7
Centrifuge, 24 in.	21	50
Centrifuge, 20 in.	17	36
Rotary drum filter, 1/2 ft^2 (2)	4	10
Rotary drum filter, 1 ft^2	3	7
Liquid waste pipeline, 12-in. diam, PV	16	38
Liquid waste pipeline, 1-in. diam, SS	10	24
Lime storage tank, 750 ft^3	10	24
Lime screw conveyors (2)	6	15
Lime mix tanks (2)	4	10
Lagoon, lined, fluoride precipitation, 1.4×10^6 gal	42	100
Lagoon, unlined, equalization, 3.6×10^6 gal	14	34
Processing building, 40 ft x 40 ft	29	70
Ventilation		
Ducts	83	199
Blowers	85	204
HEPA filters	159	382
TOTAL	676	1,619

[a]Capital cost is sum of direct and indirect costs.

Table 6.4. Installed Cost of Equipment for Waste Treatment System - ADU Case 3

Item	Cost ($1000) Direct	Capital[a]
Batching tank, 90,000 gal	37	89
Hold tank, 90,000 gal	40	96
Batching tank, 10,000 gal	17	41
Hold tank, 10,000 gal	20	48
Sampling tanks, 25,000 gal (2)	35	84
Acid tanks, 250 gal, SS (2)	16	38
Centrifugal pump, 150 gpm	4	10
Centrifugal pump, 75 gpm	3	7
Centrifugal pump, 12 gpm (2)	4	10
Centrifugal pump, 15 gpm	2	5
Centrifugal pumps, 5 gpm, SS (2)	6	14
Sump pump, 15 gpm	2	5
Centrifuge, 24 in.	21	50
Centrifuge, 20 in.	17	36
Rotary drum filters, 1/2 ft^2 (2)	4	10
Rotary drum filter, 1 ft^2	3	7
Liquid waste pipeline, 12 in. PV	16	38
Lime storage tank, 750 ft^3	10	24
Lime screw conveyor	3	7
Lime mix tank	2	5
Ion exchange columns, 11 in. diam x 20 ft, SS (4)	48	115
Ammonia still, 20 ft^2, SS	185	444
Condenser, 125 ft^2	8	19
Condensers, 50 ft^2, SS (2)	30	72
Fluidized bed calciner, 8 ft diam x 21 ft, SS	351	842
Air blowers, 675 scfm, 3 psi (2)	3	7
Cyclone separator	2	5
Water evaporator, 200 ft^2	55	132
Acid evaporator, 70 ft^2, SS	90	216
Acid fractionating tower, 27 in. diam x 40 ft, SS	57	137
Lagoon, lined, fluoride precipitation, 1.4×10^6 gal	42	100
Lagoon, unlined, equalization, 3.6×10^5 gal	14	34
Cement plant	12	29
Nitrate digestion plant	25	61
Processing building, 60 ft x 60 ft	66	158
Ventilation		
Ducts	107	257
Blowers	85	204
HEPA filters	240	576
TOTALS	1,682	4,037

[a]Capital cost is sum of direct and indirect costs.

Table 6.5. Installed Cost of Equipment for Waste Treatment System - ADU Case 4

Item	Cost ($1000) Direct	Capital[a]
Batching tank, 90,000 gal	37	89
Hold tank, 90,000 gal	40	96
Batching tank, 10,000 gal	17	41
Hold tank, 10,000 gal	20	48
Sampling tanks, 25,000 gal (2)	35	84
Acid tanks, 250 gal, SS (2)	16	38
Centrifugal pump, 150 gpm	4	10
Centrifugal pump, 75 gpm	3	7
Centrifugal pumps, 12 gpm (2)	4	10
Centrifugal pump, 15 gpm	2	5
Centrifugal pumps, 5 gpm, SS (2)	6	14
Sump pump, 15 gpm	2	5
Centrifuge, 24 in. (very dilute slurry)	21	50
Centrifuge, 20 in. (very dilute slurry)	17	36
Rotary drum filters, 1/2 ft^2 (2)	4	10
Rotary drum filter, 1 ft^2	3	7
Lime storage tank, 750 ft^3	10	24
Lime screw conveyor	3	7
Lime mix tank	2	5
Ammonia still, 200 ft^2, SS	185	443
Condensers, 50 ft^2, SS (2)	30	72
Water evaporator, 1000 ft^2	122	293
Water evaporator, 200 ft^2	55	132
Condenser, 500 ft^2	19	46
Centrifuge (1.7% slurry - Westinghouse cost)	50	120
Cement plant	20	48
Fluidized bed calciner, 8 ft diam x 21 ft, SS	351	842
Air blowers, 675 scfm, 3 psi (2)	3	7
Cyclone separator	2	5
Condenser, 125 ft^2	8	19
Nitrate digestion plant	25	61
Acid fractionating tower, 27 in. diam x 40 ft, SS	57	137
Acid evaporator, 70 ft^2, SS	90	216
Ion exchange columns, 11 in. diam x 20 ft, SS (4)	48	115
Lagoon, unlined, equalization, 3.6×10^5 gal	14	34
Processing building, 60 ft x 60 ft	66	158
Ventilation - Ducts	129	309
Blowers	85	204
HEPA filters	477	1145
TOTALS	2,079	4,992

[a]Capital cost is sum of direct and indirect costs.

Table 6.6. Installed Cost of Equipment for Waste Treatment System - DC Case 1

Item	Cost ($1000) Direct	Capital[a]
Limestone tower, 2 ft diam x 15 ft	8	19
Hydrogen burner	4	10
Batching tank, 10,000 gal	17	41
Sampling tanks, 25,000 gal (2)	35	84
Acid tank, 250 gal, SS	8	19
Centrifugal pump, 12 gpm	2	5
Centrifugal pump, 15 gpm	2	5
Centrifugal pump, 5 gpm, SS	3	7
Sump pump, 15 gpm	2	5
Rotary drum filter, 1/2 ft^2	2	5
Rotary drum filter, 1 ft^2	3	7
Liquid waste pipeline, 12 in. diam, PV	16	38
Liquid waste pipeline, 1 in. diam, SS	10	24
Lagoon, unlined, equalization, 3.6×10^5 gal	14	34
Processing building, 20 ft x 20 ft	7	17
Ventilation - Ducts	50	120
Blowers	61	146
TOTALS	244	586

[a]Capital cost is sum of direct and indirect costs.

Table 6.7. Installed Cost of Equipment for Waste Treatment System - DC Case 2

Item	Cost ($1000) Direct	Capital [a]
HF scrubber, 1 ft diam x 12 ft, Monel	15	36
KOH tanks, 750 gal, steel (2)	16	38
Lime storage tank, 500 ft^3	9	22
Centrifugal pump, 50 gpm, 60 psig	3	7
Centrifugal pumps, 50 gpm, 30 psig (2)	4	10
Lime conveyor (2)	6	14
Lime mix tank, 2000 gal	5	12
Agitator, 5 hp	2	5
Batching tank, 10,000 gal	17	41
Sampling tanks, 25,000 gal (2)	35	84
Tank, 250 gal, SS	8	19
Hold tank, 10,000 gal	20	48
Centrifugal pump, 12 gpm	2	5
Sump pump, 15 gpm	2	5
Centrifugal pump, 15 gpm	2	5
Centrifugal pump, 5 gpm, SS	3	7
Centrifuge, 20 in.	17	40
Rotary drum filter, 1/2 ft^2	2	5
Rotary drum filter, 1 ft^2	3	7
Rotary drum filter, 10 ft^2	14	34
Liquid waste pipeline, 12 in. PV	16	38
Liquid waste pipeline, 1 in. SS	10	24
Lime mix tank	2	5
Lagoon, unlined, equalization, 3.6 x 10^6 gal	14	34
Processing building, 40 ft x 40 ft	29	70
Ventilation - Ducts	50	120
Blowers	58	139
HEPA filters	102	245
TOTALS	466	1,118

[a] Capital cost is sum of direct and indirect costs.

Table 6.8. Installed Cost of Equipment for Waste Treatment System - DC Case 3

Item	Cost ($1000) Direct	Capital [a]
HF scrubber, 1 ft diam x 12 ft, Monel	15	36
HF condenser, 115 ft^2, Karbate	6	14
HF tanks, 500 gal, lead-lined (2)	10	24
KOH tanks, 750 gal, steel (2)	16	38
Centrifugal pump, 50 gpm, 60 psig	3	7
Centrifugal pump, 50 gpm, 30 psig	2	5
Centrifugal pump, 5 gpm, 30 psig	2	5
Lime storage tank, 50 ft^3	3	7
Lime conveyor	3	7
Lime mix tank, 200 gal	3	7
Agitator, 1 hp	1	2
Rotary drum filters, 1 ft^2 (2)	6	14
Batching tank, 10,000 gal	17	41
Hold tank, 10,000 gal	20	48
Sampling tanks, 25,000 gal (2)	35	84
Acid tank, 250 gal, SS	8	19
Centrifugal pumps, 12 gpm (2)	4	10
Centrifugal pump, 15 gpm	2	5
Sump pump, 15 gpm	2	5
Centrifugal pump, 5 gpm, SS	3	7
Centrifuge, 20 in.	17	41
Rotary drum filter, 1/2 ft^2	2	5
Fluidized bed calciner, 8 ft diam x 21 ft, SS	351	842
Air blowers, 675 scfm, 3 psi (2)	3	7
Cyclone separator	2	5
Condenser, 50 ft^2, SS	15	36
Condenser, 125 ft	8	19
Water evaporator, 200 ft^2	55	132
Acid evaporator, 70 ft^2	90	216
Acid fractionating tower, 27 in. diam x 40 ft, SS	57	137
Nitrate digestion plant	25	61
Cement plant	12	29
Lagoon, unlined, equalization, 3.6×10^5 gal	14	34
Processing building, 60 ft x 60 ft	66	158
Ventilation - Ducts	66	158
Blowers	58	139
HEPA filters	168	404
TOTALS	1,170	2,808

[a] Capital cost is sum of direct and indirect costs.

Table 6.9. Installed Cost of Equipment for Waste Treatment System - DC Case 4

Item	Cost ($1000) Direct	Capital[a]
HF scrubber, 1 ft diam x 12 ft, Monel	15	36
HF condensers, 115 ft^2, Karbate (2)	12	29
Refrigeration unit, 2 ton with brine tank and pump	5	12
HF tanks, 500 gal, lead-lined (2)	10	24
KOH tanks, 750 gal, steel (2)	16	38
Centrifugal pump, 50 gpm, 60 psig	3	7
Centrifugal pump, 50 gpm, 30 psig	2	5
Centrifugal pump, 1 gpm, 30 psig	1	2
Lime storage, 5 ft^3	2	5
Lime conveyor	3	7
Lime mix tank with agitator	2	5
Rotary drum filters, 1/2 ft^2 (2)	4	10
Batching tank, 10,000 gal	17	41
Hold tank, 10,000 gal	20	48
Sampling tanks, 25,000 gal (2)	35	84
Acid tank, 250 gal, SS	8	19
Centrifugal pumps, 12 gpm (2)	4	10
Centrifugal pump, 15 gpm	2	5
Centrifugal pump, 5 gpm, SS	3	7
Sump pump, 15 gpm	2	5
Rotary drum filter, 1 ft^2	3	7
Centrifuge, 20 in.	17	41
Fluidized bed calciner, 8 ft diam x 21 ft, SS	351	842
Air blowers, 675 scfm, 3 psi (2)	3	7
Cyclone separator	2	5
Condenser, 50 ft^2, SS	15	36
Water evaporator, 200 ft^2	55	132
Condenser, 125 ft^2	8	19
Acid evaporator, 70 ft^2	90	216
Acid fractionating tower, 27 in. diam x 40 ft, SS	57	137
Nitrate digestion plant	25	60
Cement plant	12	29
Lagoon, unlined, equalization, 3.6 x 10^5 gal	14	34
Processing building, 60 ft x 60 ft	66	158
Ventilation - Ducts	81	194
Blowers	58	139
HEPA filters	333	800
TOTALS	1,356	3,254

[a]Capital cost is sum of direct and indirect costs.

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

	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——>		

[a]Standard deviation of the mean (total).

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

Sector	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 ———>		

[a]Standard deviation of the mean (total).

Table 7.4. Summary of Annual Doses to Individuals[a] and Population[b] from Gaseous Effluent of a Model Fuel Fabrication Plant at a Coastal and a Midwestern Site

Site	Radwaste Treatment Case	Maximum Total Body Dose (millirems)	Maximum Adult Organ Doses (millirems)			Population Total Body Dose (man-rem)
			Bone	Kidney	Lungs	
Coastal	ADU 1	8.9E-01	9.8E+00	2.3E+00	7.1E+00	8.5E-01
	DC 1	6.9E-01	7.6E+00	1.8E+00	5.4E+00	6.6E-01
	ADU 2	4.6E-02	4.9E-01	1.6E-00	3.6E-01	4.6E-02
	DC 2	3.5E-02	3.8E-01	9.0E-02	2.7E-01	3.3E-02
	ADU 3	4.6E-04	4.9E-03	1.6E-03	3.6E-03	4.6E-04
	DC 3	3.5E-04	3.8E-03	9.0E-04	2.7E-03	3.3E-04
	ADU 4	4.6E-06	4.9E-05	1.6E-05	3.6E-05	4.6E-06
	DC 4	3.5E-06	3.8E-05	9.0E-06	2.7E-05	3.3E-06
Midwestern	ADU 1	9.0E-01	9.9E+00	2.3E+00	7.3E+00	1.1E+00
	DC 1	6.9E-01	7.6E+00	1.8E+00	5.6E+00	8.5E-01
	ADU 2	4.5E-02	5.0E-01	1.6E-01	3.7E-01	5.5E-02
	DC 2	3.6E-02	3.8E-01	9.0E-02	2.8E-01	4.6E-02
	ADU 3	4.5E-04	5.0E-03	1.6E-03	3.7E-03	5.5E-04
	DC 3	3.6E-04	3.8E-03	9.0E-04	2.8E-03	4.6E-04
	ADU 4	4.5E-06	5.0E-05	1.6E-05	3.7E-05	5.5E-06
	DC 4	3.6E-06	3.8E-05	9.0E-06	2.8E-05	4.6E-06

[a]Dose to individual 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.

[b]Dose to the population is average total body dose to the population out to a distance of 55 miles.

Table 7.5. Contribution of Exposure Modes to Total Body Dose from the Gaseous Effluent of a Fuel Fabrication Plant[a]

Exposure Mode	Annual Dose (mrem)	Percent of Total Dose
Submersion in air	5.6E-05	6.3E-03
Contaminated ground	2.8E-01	3.1E+01
Inhalation	1.7E-01	1.9E+01
Ingestion	4.4E-01	4.9E+01

[a]Maximum total body dose at 0.5 mile, coastal site, ADU process, treatment Case 1.

Table 7.6. Average Annual Total Body Dose (millirems) to Individuals from Gaseous Effluents as a Function of Distance from a Model Fuel Fabrication Plant[a] at a Coastal and a Midwestern Site

Distance (miles)	Site	
	Coastal	Midwestern
0-0.5	5.9E-01	4.8E-01
0-1	3.8E-01	3.7E-01
0-2	3.7E-01	2.5E-01
0-3	3.3E-01	1.3E-01
0-4	1.6E-01	4.0E-02
0-5	1.0E-01	2.5E-02
0-10	1.0E-02	1.0E-02
0-15	6.0E-03	4.9E-03
0-25	4.0E-03	2.0E-03
0-35	2.4E-03	6.0E-04
0-45	2.0E-03	3.7E-04
0-55	1.0E-03	3.6E-04

[a]ADU process, treatment Case 1.

Table 7.7. Cumulative Population and Dose (man-rem) from Gaseous Effluents as a Function of Distance from a Model Fuel Fabrication Plant[a] at a Coastal and a Midwestern Site

Distance (miles)	Coastal		Midwestern	
	Population	Dose	Population	Dose
0.5	0	0	0	0
1	1,112	4.3E-01	260	9.3E-02
2	1,112	4.3E-01	406	9.9E-02
3	1,298	4.3E-01	871	1.2E-01
4	2,940	4.4E-01	3,371	1.5E-01
5	4,325	4.7E-01	7,488	1.8E-01
10	68,080	6.7E-01	30,130	2.8E-01
15	124,900	7.1E-01	71,560	3.4E-01
25	169,300	7.4E-01	238,900	4.6E-01
35	305,700	8.3E-01	1,088,000	7.3E-01
45	429,100	8.4E-01	2,412,000	9.7E-01
55	552,974	8.5E-01	3,562,135	1.1E+00

[a]ADU process, treatment 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 Fuel Fabrication Plant[a]

	Percent of Total Body Dose			
Radionuclide	Submersion in Air	Contaminated Ground	Inhalation	Ingestion
^{234}U	3.4	61.8	84.0	83.8
^{235}U	10.8	28.6	2.5	2.6
^{236}U	0.1	2.9	3.9	4.1
^{238}U	3.4	6.4	9.3	9.3
^{231}Th	4.8	<0.1	<0.1	<0.1
^{234}Th	2.0	0.4	0.4	<0.1
^{234}Pa	75.5	<0.1		

[a]ADU process, treatment Case 1.

Table 7.9. Percent Contribution of Inhaled and Ingested Radionuclides from the Gaseous Effluent of a Fuel Fabrication Plant[a] to Individual Organ Doses

	Bone		Kidney		Lungs	
Radionuclide	Inhaled	Ingested	Inhaled	Ingested	Inhaled	Ingested
^{234}U	83.3	83.4	83.7	83.8	83.5	83.8
^{235}U	2.6	2.7	2.6	2.6	2.7	2.6
^{236}U	4.1	4.1	4.1	4.1	4.2	4.1
^{238}U	9.8	9.6	9.4	9.3	9.4	9.3
^{231}Th	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
$^{234}Th + ^{234}Pa$	0.1	<0.1	0.1	<0.1	<0.1	<0.1

[a]ADU process, treatment Case 1.

Table 7.10. Summary of Annual Total Body Dose (mrem) from Aquatic Pathways of Drinking Water,[a] Eating Fish,[b] and Swimming[c]

Process and Treatment	Midwestern River	Coastal Estuary
ADU		
1	6.9E-02	1.4E-11
2	3.7E-02	7.7E-12
3	5.1E-03	1.0E-12
4	1.5E-07	3.2E-17
DC		
1	2.4E-02	5.3E-12
2	1.8E-02	3.7E-12
3	2.2E-06	1.1E-15
4	2.2E-06	1.1E-15

[a]Daily intake of 1.2 liters of water.

[b]Daily intake of 20 grams of fish.

[c]Swimming for 1% of the year.

Table 7.11. Major Radionuclides Contributing to Dose to Individuals via Aquatic Pathways at a Model Fuel Fabrication Plant[a]

Radionuclide	Percent of Total Body Dose			
	Drinking Water	Eating Fish		Swimming[d]
		F[b]	S[c]	
^{234}U	85.4	89.9	87.1	0.2
^{235}U	<0.1	<0.1	<0.1	0.8
^{236}U	<0.1	<0.1	<0.1	<0.1
^{238}U	14.4	10.0	9.7	<0.1
^{231}Th	<0.1	<0.1	<0.1	0.1
^{234}Th	<0.1	<0.1	3.1	0.2
^{234}Pa	<0.1			98.6

[a]ADU process, treatment Case 1.

[b]Freshwater.

[c]Saline water.

[d]Fresh and saline water.

Table 7.12. Annual Dose (mrem) from Drinking Water[a] Containing Liquid Effluents from a Fuel Fabrication Plant at a Midwestern Site

Process and Radwaste Case	15-cfs Stream		1300-cfs River	
	Total Body	Bone	Total Body	Bone
ADU				
1	5.1E+00	8.3E+01	5.9E-02	9.6E-01
2	2.8E+00	4.5E+01	3.2E-02	5.5E-01
3	3.8E-01	6.1E+00	4.4E-03	7.0E-02
4	1.1E-05	1.8E-04	1.3E-07	2.1E-06
DC				
1	1.7E+00	2.8E+01	2.0E-02	3.2E-01
2	1.3E+00	2.1E+01	1.5E-02	2.4E-01
3	1.2E-04	2.0E-03	1.4E-06	2.3E-05
4	1.2E-04	2.0E-03	1.4E-06	2.3E-05

[a]Individual drinks 1.2 liters of water per day.

Table 7.13. Annual Dose (mrem) from Eating Fish[a] from Waters Around a Fuel Fabrication Plant at a Midwestern and a Coastal Site

	Midwestern Site				Coastal Site			
	15-cfs Stream		1300-cfs River		15-cfs Stream		Estuary	
Radwaste Case	Total Body	Bone	Total Body	Bone	Total Body	Bone	Total Body	Bone
ADU								
1	8.6E-01	1.4E+01	9.9E-03	1.6E-01	8.8E-01	1.5E+01	1.4E-11	2.3E-10
2	4.6E-01	7.5E+00	5.3E-03	8.6E-02	4.7E-01	7.9E+00	7.6E-12	1.3E-10
3	6.3E-02	1.0E+00	7.2E-04	1.2E-02	6.4E-02	1.1E+00	1.0E-12	1.7E-11
4	1.9E-05	3.2E-05	2.3E-08	3.6E-07	2.0E-06	3.3E-05	3.2E-17	5.3E-16
DC								
1	2.8E-01	4.6E+00	3.3E-03	5.3E-02	3.1E-01	5.6E+00	4.8E-12	8.1E-11
2	2.2E-01	3.5E+00	2.5E-03	4.0E-02	2.4E-01	2.7E+00	3.7E-12	4.1E-11
3	6.7E-05	1.1E-03	7.7E-07	1.3E-05	7.3E-05	1.3E-03	1.1E-15	2.0E-14
4	6.7E-05	1.1E-03	7.7E-07	1.3E-05	7.3E-05	1.3E-03	1.1E-15	2.0E-14

[a]Ingestion of 20 g of fish per day.

Table 7.14. Annual Total Body Dose (mrem) from Swimming[a] in Waters Around a Fuel Fabrication Plant at a Midwestern and a Coastal Site

Process and Radwaste Case	15-cfs Stream (fresh or saline)	1300-cfs River	Estuary (saline)
ADU			
1	2.2E-02	2.6E-04	3.7E-13
2	8.4E-03	9.7E-05	1.4E-13
3	1.1E-03	1.3E-05	1.9E-14
4	3.4E-08	3.9E-10	5.6E-19
DC			
1	3.2E-02	3.6E-04	5.2E-13
2	3.9E-03	4.5E-05	6.5E-15
3	3.8E-07	4.4E-09	6.2E-18
4	3.8E-07	4.4E-09	6.2E-18

[a]Individual swims 1% of the year.

Table 7.15. Annual Dose (mrem) to Biota from Liquid Effluents from a Fuel Fabrication Plant[a]

	Algae		Invertebrates		Fish		Waterfowl	
	ADU	DC	ADU	DC	ADU	DC	ADU	DC
In effluent	4.7E+04	6.1E+04	5.8E+05	2.1E+05	9.6E+04	3.3E+04	9.6E+02	3.4E+02
In 15-cfs stream[b]	1.1E+03	1.4E+03	1.4E+04	4.9E+03	2.3E+03	7.8E+02	2.3E+01	8.0E+00
In 1300-cfs river[b]	1.3E+01	1.6E+01	1.6E+02	5.7E+01	2.6E+01	8.9E+00	2.6E-01	9.2E-02
In 15-cfs stream[c]	1.7E+04	7.8E+03	3.6E+03	2.6E+03	9.9E+03	1.0E+04	2.2E+02	7.6E+01
In estuary[c]	2.8E-07	1.3E-07	5.9E-08	4.3E-08	1.6E-07	1.7E-07	3.7E-09	1.2E-09

[a]Radwaste treatment Case 1.

[b]Freshwater at Midwestern site.

[c]Saline water at Coastal site.

Table 7.16. Percent Contribution of Radionuclides to Dose to Biota in Waters Around a Fuel Fabrication Plant[a]

Radionuclide	Plants		Invertebrates		Fish		Waterfowl	
	F[b]	S[c]	F[b]	S[c]	F[b]	S[c]	F[b]	S[c]
^{234}U	8.2	71.0	78.5	50.1	79.3	18.1	78.8	79.8
^{235}U	0.3	2.3	2.4	1.6	2.6	0.6	2.5	2.6
^{236}U	0.4	3.4	3.7	2.4	3.8	0.9	3.8	3.8
^{238}U	1.4	11.7	13.2	8.5	13.4	3.1	13.3	13.4
^{231}Th	3.1	0.4	0.1	1.3	<0.1	11.8	<0.1	<0.1
$^{234}Th + ^{234}Pa$	86.6	11.2	2.1	36.1	0.8	65.5	1.5	0.3

[a]ADU process, treatment Case 1.

[b]Freshwater.

[c]Saline water.

Table 7.17. Typical Variability of X/Q' Values and Population Data at Midwestern and Coastal Sites

		Midwestern	Coastal
X/Q'[a]	Mean, $sec \cdot m^{-3}$	2.67×10^{-8}	2.93×10^{-8}
	Standard Deviation, $sec \cdot m^{-3}$	1.24×10^{-8}	0.77×10^{-8}
	Coefficient of Variation (CV)	0.46	0.26
Population[b]	Mean	3.56×10^{6}	5.53×10^{5}
	Standard Deviation	3.34×10^{6}	1.86×10^{5}
	Coefficient of Variation (CV)	0.93	0.33

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

[b]Based on cumulative population for area with a 55-mile radius.

Table 7.18. Curies of Uranium Released During Lifetime[a] of the Model Fuel Fabrication Plant

Radionuclide	Half-Life (yr)	Curies Released[b]
^{234}U	2.48E+05	3.04
^{235}U	7.13E+08	1.02E-01
^{236}U	2.39E+07	1.56E-01
^{238}U	4.49E+09	3.88E-01

[a]A 20-year lifetime was assumed for plant operation.

[b]ADU process, treatment Case 1. These values divided by 2.03×10^{10} m^2 give the deposition assumed for the assessment of radiation doses.

Table 7.19. Contribution of Radionuclides and Exposure Modes to the Annual Total Body Dose[a] to Individuals from the Time of Cessation of Plant Operation Until Significant Decay of All Radionuclides Occurs

	Exposure Mode			
Radionuclide	Contaminated Ground (mrem)	Inhalation (mrem)	Ingestion (mrem)	Total (mrem)
^{234}U	3.9E-04	1.5E-06	3.8E-06	4.0E-04
^{235}U	3.2E-04	4.4E-08	1.2E-07	3.2E-04
^{236}U	1.9E-05	6.9E-08	1.9E-07	1.9E-05
^{238}U	8.2E-05	1.6E-07	4.3E-07	8.3E-05
Total	8.1E-04	1.8E-06	4.5E-06	8.2E-04

[a]Dose is average total body dose of the individual out to a distance of 50 miles.

Table 7.20. 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 Until Significant Decay of All Radionuclides Occurs

	Organ Dose (mrem) per Exposure Mode					
	Bone		Kidney		Lung	
Radionuclide	Inhalation	Ingestion	Inhalation	Ingestion	Inhalation	Ingestion
^{234}U	2.3E-05	6.2E-05	5.5E-06	1.5E-05	5.9E-05	3.8E-06
^{235}U	7.4E-07	2.0E-06	1.8E-07	4.7E-07	1.9E-06	1.2E-07
^{236}U	1.1E-06	3.1E-06	2.7E-07	7.3E-07	2.9E-06	1.9E-07
^{238}U	2.7E-06	7.3E-06	6.2E-07	1.7E-06	6.6E-06	4.3E-07
Total	2.8E-05	7.4E-05	6.6E-06	1.8E-05	7.0E-05	4.5E-06

[a]Dose is the average total body and organ dose of the individual out to a distance of 50 miles.

Table 7.21. 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 Until Significant Decay of All Radionuclides Occurs

	Dose (man-rem/10^6 persons)			
Radionuclide	Total Body	Bone	Kidney	Lung
^{234}U	4.0E-01	8.5E-02	2.1E-02	6.3E-02
^{235}U	3.2E-01	2.7E-03	6.5E-04	2.0E-03
^{236}U	1.9E-02	4.2E-03	1.0E-03	3.1E-03
^{238}U	8.3E-02	1.0E-02	2.3E-03	7.0E-03
Total	8.2E-01	1.0E-01	2.5E-02	7.5E-02

[a]Dose to the population is average total body dose out to a distance of 50 miles.

Table 8.1. Annual Costs for Treatment of Radioactive and Chemical Wastes from Model LWR Fuel Fabrication Plants

Radwaste Case	Chemwaste Cost ($1,000)				Radwaste Cost ($1,000)			Total Cost[a] ($1,000)	Contribution to Power Cost (mills/kWhr)
	Fluoride	Ammonia	Nitrate	Total	Liquid	Gaseous	Total		
ADU-1	0	0	0	0	214	126	340	340	9.0E-4
ADU-2	39	21	128	188	389	235	624	812	2.1E-3
ADU-3	41	220	244	505	601	309	910	1,415	3.7E-3
ADU-4	460	220	244	924	1,114	477	1,591	2,515	6.4E-3
DC-1	8	0	0	8	95	99	194	202	5.5E-4
DC-2	26	20	141	187	253	219	472	659	1.7E-3
DC-3	30	31	244	305	427	262	689	994	2.6E-3
DC-4	40	31	244	315	427	388	815	1,130	2.9E-3

[a]Total cost for chemwaste and radwaste treatment.

Table 8.2. Radiation Dose From Gaseous Effluents at Model LWR Fuel Fabrication Plants

Plant Type	Case	Maximum Annual Individual Dose at 0.5 Mile: Total Body (mrem)	Bone (mrem)	Kidney (mrem)	Lung (mrem)	Average Annual Dose to Population Out to 55 Miles (man-rem)	Annual Cost of Gaseous Radwaste Treatment (dollars)
				Coastal Site			
ADU	1	8.9E-01	9.8E+00	2.3E+00	7.1E+00	8.5E-01	1.26E+05
	2	4.6E-02	4.9E-01	1.6E-01	3.6E-01	4.6E-02	2.35E+05
	3	4.6E-04	4.9E-03	1.6E-03	3.6E-03	4.6E-04	3.09E+05
	4	4.6E-06	4.9E-05	1.6E-05	3.6E-05	4.6E-06	4.77E+05
DC	1	6.9E-01	7.6E-01	1.8E+00	5.4E+00	6.6E-01	9.9E+04
	2	3.5E-02	3.8E-01	9.0E-02	2.7E-01	3.3E-02	2.19E+05
	3	3.5E-04	3.8E-03	9.0E-04	2.7E-03	3.3E-04	2.62E+05
	4	3.5E-06	3.8E-05	9.0E-06	2.7E-05	3.3E-06	3.83E+05
				Midwestern Site			
ADU	1	9.0E-01	9.9E+00	2.3E+00	7.3E+00	1.1E+00	1.26E+05
	2	4.5E-02	5.0E-01	1.6E-01	3.7E-01	5.5E-02	2.35E+05
	3	4.5E-04	5.0E-03	1.6E-03	3.7E-03	5.5E-04	3.09E+05
	4	4.5E-06	5.0E-05	1.6E-05	3.7E-05	5.5E-06	4.77E+05
DC	1	6.9E-01	7.6E+00	1.8E+00	5.6E+00	8.5E-01	9.9E+04
	2	3.6E-02	3.8E-01	9.0E-02	2.8E-01	4.6E-02	2.19E+05
	3	3.6E-04	3.8E-03	9.0E-04	2.8E-03	4.6E-04	2.62E+05
	4	3.6E-06	3.8E-05	9.0E-06	2.8E-05	4.6E-06	3.88E+05

Table 8.3. Incremental Gaseous Radwaste Treatment Cost and Incremental Reduction in Individual Total Body and Population Dose Between Case Studies at Model ADU and DC LWR Fuel Fabrication Plants at Coastal and Midwestern Sites[a]

Case Increment	Decrease in Maximum Annual Individual Total Body Dose at 0.5 Mile (mrem)	Decrease in Average Annual Dose to Population Out to 55 Miles (man-rem)	Increase in Annual Cost for Treatment of Gaseous Radwaste ($1,000/yr)	Cost-Benefit ($1,000/mrem)	Cost-Benefit ($1,000/man-rem)
		ADU Plant			
ADU-1/ADU-2	0.84	0.80	109	130	136
ADU-2/ADU-3	0.0455	0.0455	74	1,630	1,630
ADU-3/ADU-4	0.000455	0.000455	168	369,000	369,000
		DC Plant			
DC-1/DC-2	0.65	0.63	120	185	190
DC-2/DC-3	0.0346	0.0327	43	1,240	1,310
DC-3/DC-4	0.000346	0.000327	126	364,000	385,000

[a]Doses are essentially equal at the two sites.

Table 8.4. Radiation Dose from Liquid Effluents at Model LWR Fuel Fabrication Plants

Plant Type	Case	Annual Individual Total Body Dose from 15-cfs Stream (mrem)	Annual Individual Total Body Dose from 1300-cfs River[a,b] (mrem)	Annual Individual Total Body Dose from Coastal Estuary[c,d] (mrem)	Annual Cost of Liquid Radwaste Treatment (dollars)
			Coastal Site		
ADU	1	6.0	-	1.4E-11	2.14E+05
	2	3.3	-	7.7E-12	3.89E+05
	3	4.4E-01	-	1.0E-12	6.01E+05
	4	1.3E-05	-	3.2E-17	1.11E+06
DC	1	2.0	-	5.3E-12	9.50E+04
	2	1.5	-	3.7E-12	2.53E+05
	3	1.9E-04	-	1.1E-15	4.27E+05
	4	1.9E-04	-	1.1E-15	4.27E+05
			Midwestern Site		
ADU	1	6.0	6.9E-02	-	2.14E+05
	2	3.3	3.7E-02	-	3.89E+05
	3	4.4E-01	5.1E-03	-	6.01E+05
	4	1.3E-05	1.5E-07	-	1.11E+06
DC	1	2.0	2.4E-02	-	9.50E+04
	2	1.5	1.8E-02	-	2.53E+05
	3	1.9E-04	2.2E-06	-	4.27E+05
	4	1.9E-04	2.2E-06	-	4.27E+05

[a] Dose is from drinking water, fish consumption, and swimming.

[b] River is involved only at the midwestern site.

[c] Dose is from fish consumption and swimming only.

[d] Estuary is involved only at the coastal site.

Table 8.5. Incremental Liquid Radwaste Treatment Cost and Incremental Reduction in Total Body Dose Between Case Studies at Model ADU and DC LWR Fuel Fabrication Plants at Midwestern and Coastal Sites[a]

(Liquid effluent is diluted by 15-cfs stream.)

Case Increment	Decrease in Annual[b] Individual Total Body Dose (mrem/yr)	Increase in Annual Cost for Treatment of Liquid Radwaste ($1,000/yr)	Cost-Benefit ($1,000/mrem)
	ADU Plant		
ADU-1/ADU-2	2.7	175	65
ADU-2/ADU-3	2.9	212	73
ADU-3/ADU-4	0.44	513	1,170
	DC Plant		
DC-1/DC-2	0.5	158	316
DC-2/DC-3	1.50	174	116
DC-3/DC-4[c]	-	-	-

[a]Doses are essentially the same at the two sites.

[b]Dose is from drinking water, fish consumption, and swimming.

[c]Cases DC-3 and DC-4 are identical for liquid radwaste effluents.

Table 8.6. Incremental Liquid Radwaste Treatment Cost and Incremental Reduction in Total Body Dose Between Case Studies at Model ADU and DC LWR Fuel Fabrication Plants at the Midwestern and Coastal Sites

Case Increment	Decrease in Annual Individual Total Body Dose (mrem/yr)	Increase in Annual Cost for Treatment of Liquid Radwaste ($1,000/yr)	Cost-Benefit ($1,000/mrem)
(Liquid effluent is diluted by 1300-cfs stream - Midwestern site)[a]			
	ADU Plant		
ADU-1/ADU-2	0.032	175	5,470
ADU-2/ADU-3	0.032	212	6,630
ADU-3/ADU-4	0.005	513	102,600
	DC Plant		
DC-1/DC-2	0.006	158	26,300
DC-2/DC-3	0.018	164	9,110
DC-3/DC-4[b]	-	-	-
(Liquid diluted by estuary - Coastal site)[c]			
	ADU Plant		
ADU-1/ADU-2	6.3E-12	175	2.8E+13
ADU-2/ADU-3	6.7E-12	212	3.2E+13
ADU-3/ADU-4	1.0E-12	513	5.1E+14
	DC Plant		
DC-1/DC-2	1.6E-12	158	9.9E+13
DC-2/DC-3	3.7E-12	164	4.4E+13
DC-3/DC-4[b]	-	-	-

[a] Dose is from drinking water, fish consumption, and swimming.

[b] Cases DC-3 and DC-4 are identical for liquid effluents.

[c] Dose is from fish consumption and swimming.

Table 8.7. Incremental Liquid Waste (Radwaste and Chemwaste) Treatment Cost and Incremental Reduction in Total Body Dose Between Case Studies at Model ADU and DC LWR Fuel Fabrication Plants at Midwestern and Coastal Sites[a]

(Liquid effluent is diluted by 15-cfs stream.)

Case Increment	Decrease in Annual[b] Individual Total Body Dose (mrem/yr)	Increase in Annual Cost for Treatment of Liquid Waste ($1,000/yr)	Cost-Benefit ($1,000/mrem)
	ADU Plant		
ADU-1/ADU-2	2.7	363	134
ADU-2/ADU-3	2.9	529	182
ADU-3/ADU-4	0.44	932	2,120
	DC Plant		
DC-1/DC-2	0.5	337	674
DC-2/DC-3	1.50	292	195
DC-2/DC-4[c]	1.50	302	201

[a]Doses are essentially the same at the two sites.

[b]Dose is from drinking water, fish consumption, and swimming.

[c]Cases DC-3 and DC-4 have identical liquid radwaste effluents and the incremental increase in annual cost is attributed to the increase in the annual cost of chemwaste for DC-4.

Table 8.8. Annual Cost of Cement for Solidification of Wastes in Case Studies 3 and 4

Case No.	Cement Cost[a] (dollars)	Percent of Annual Waste Treatment Cost		
		Liquid Radwaste	Liquid Chemwaste	Total Plant[b]
ADU-3	19,800	1.6	2.0	1.4
ADU-4	801,000	36	43	32
DC-3	19,800	2.3	3.2	2.0
DC-4	18,900	2.2	3.0	1.7

[a]Cement costs are divided equally between radwaste and chemwaste costs.

[b]Includes radwaste, chemwaste, and gaseous waste.

Fig. 4.1

ORNL-DWG 73-6509

Nominal ADU Process System

5 MTU/day

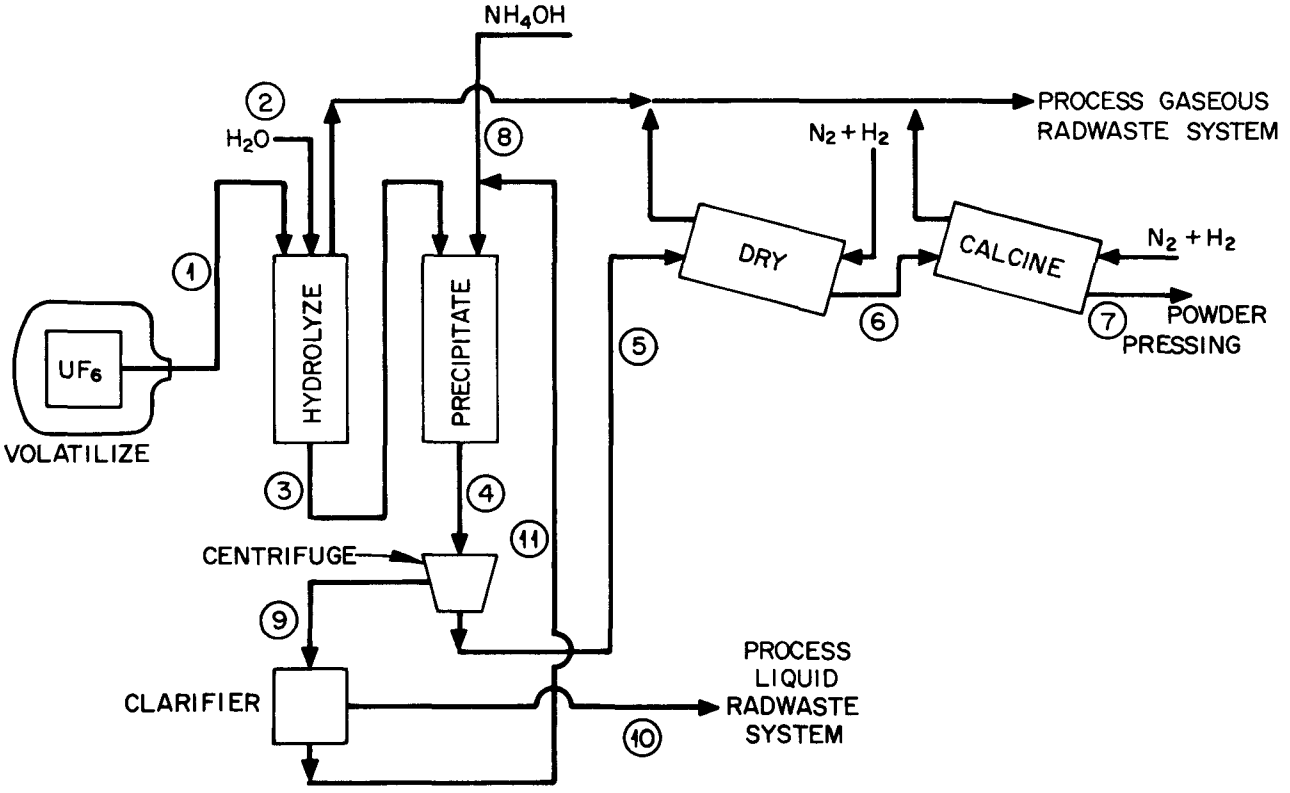


Fig. 4.2

ORNL-DWG 73-6503RI

Nominal Recycle System

0.75 MTU/day

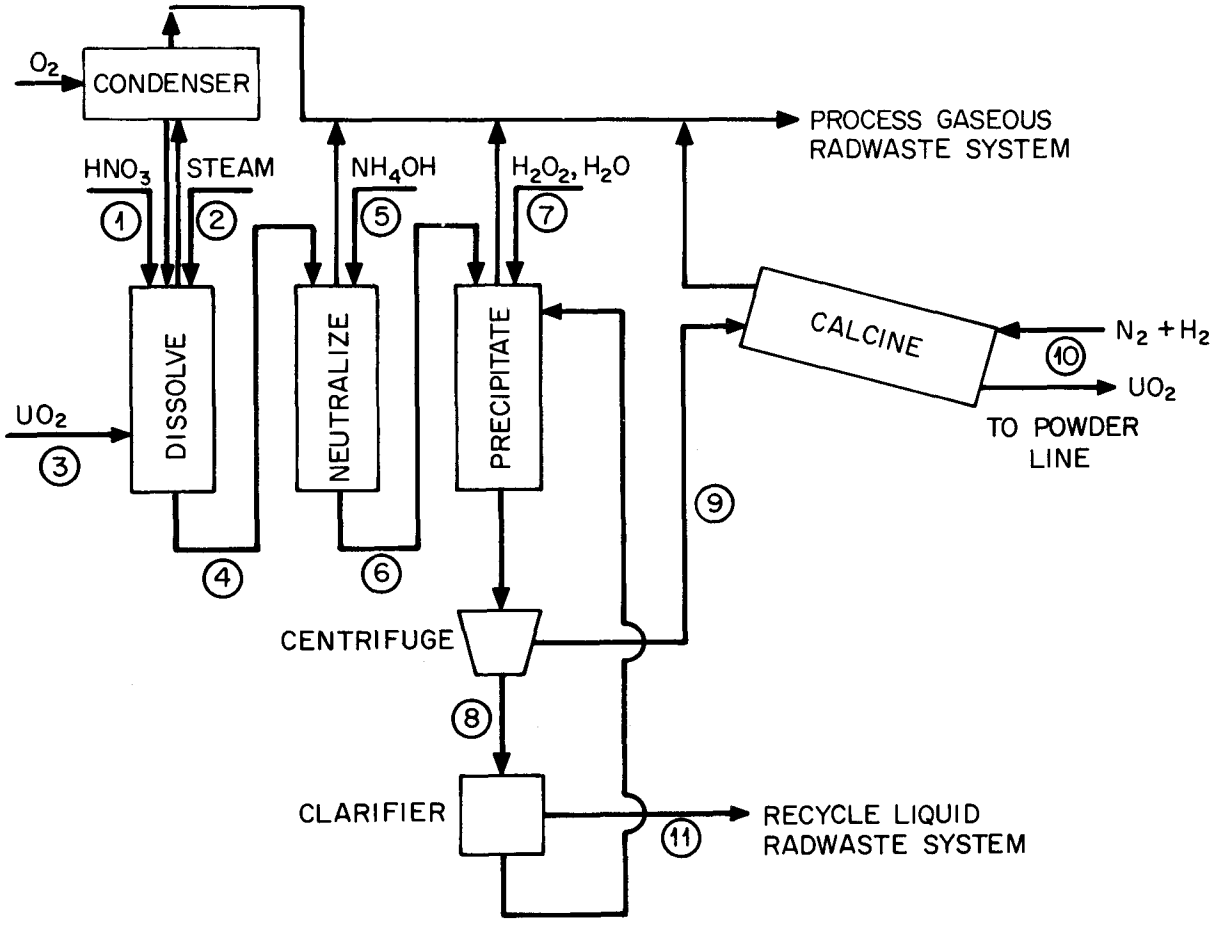


Fig. 4.3 ORNL-DWG 73-6502RI

Nominal Scrap Recovery System

0.1 MTU/day

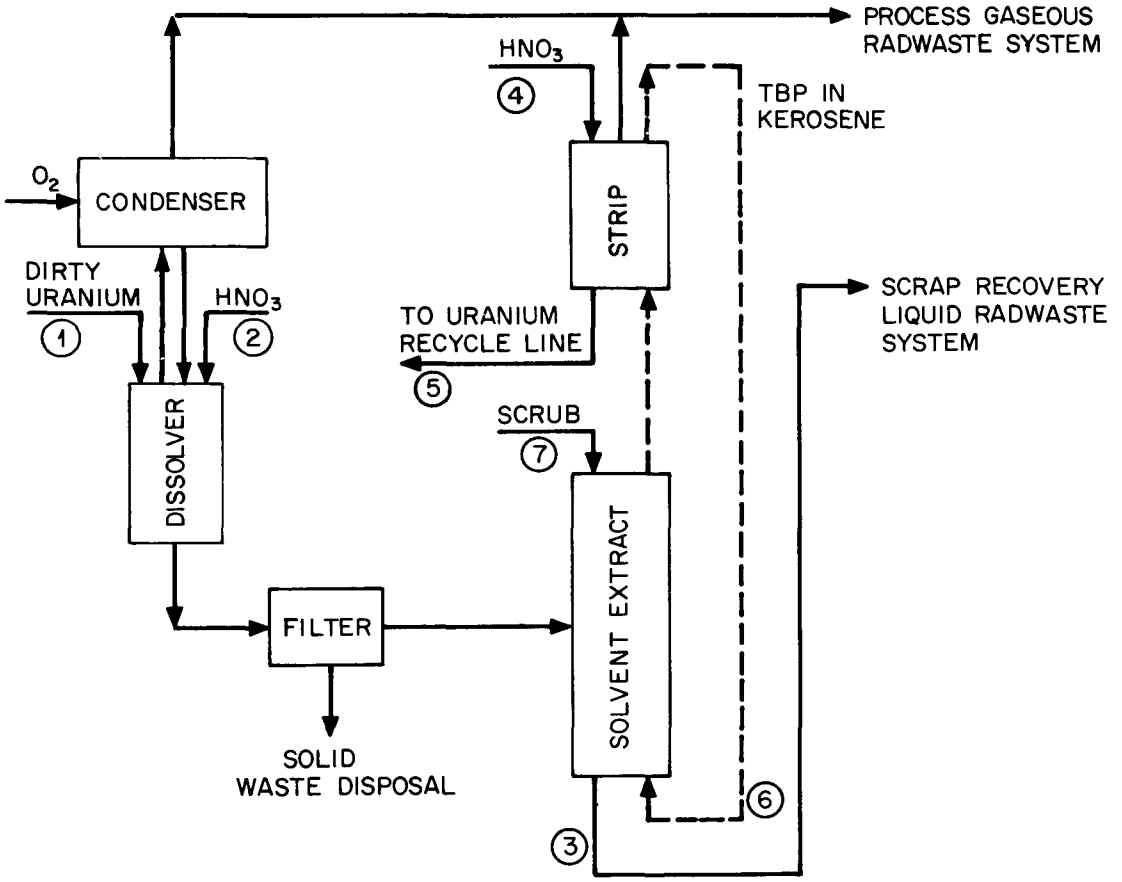


Fig. 4.4

ORNL-DWG 73-6514

Nominal DC Process System

5 MTU/day

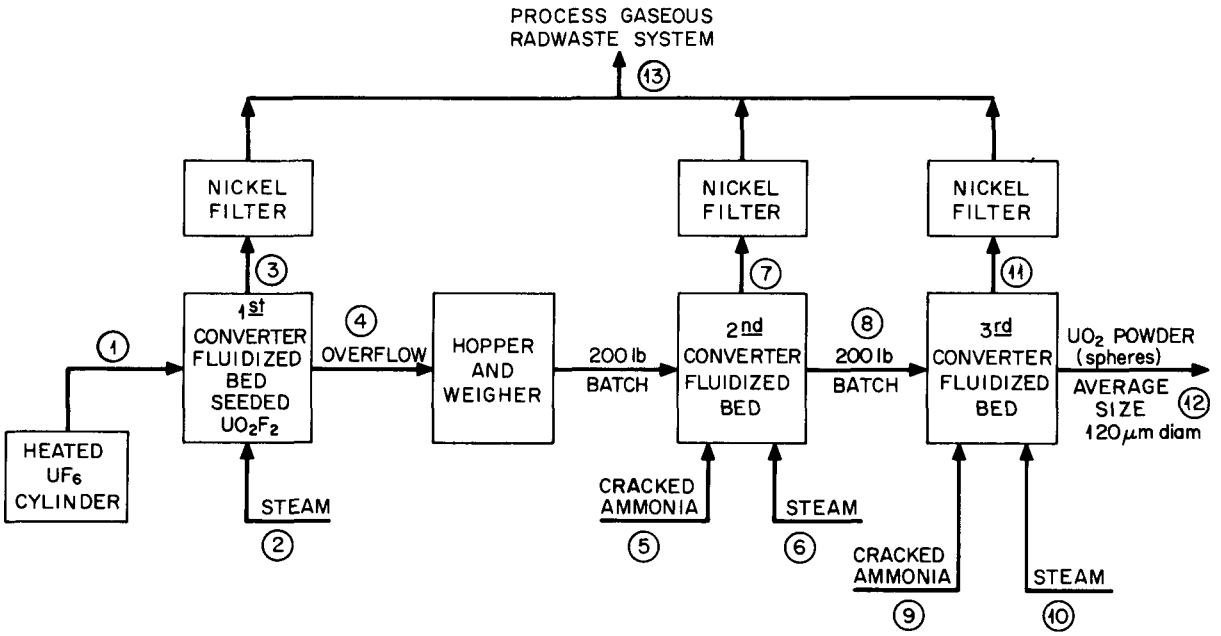


Fig. 4.5

ORNL-DWG 73-6511R2

Process and Radwaste Systems for ADU Plant

Case 1

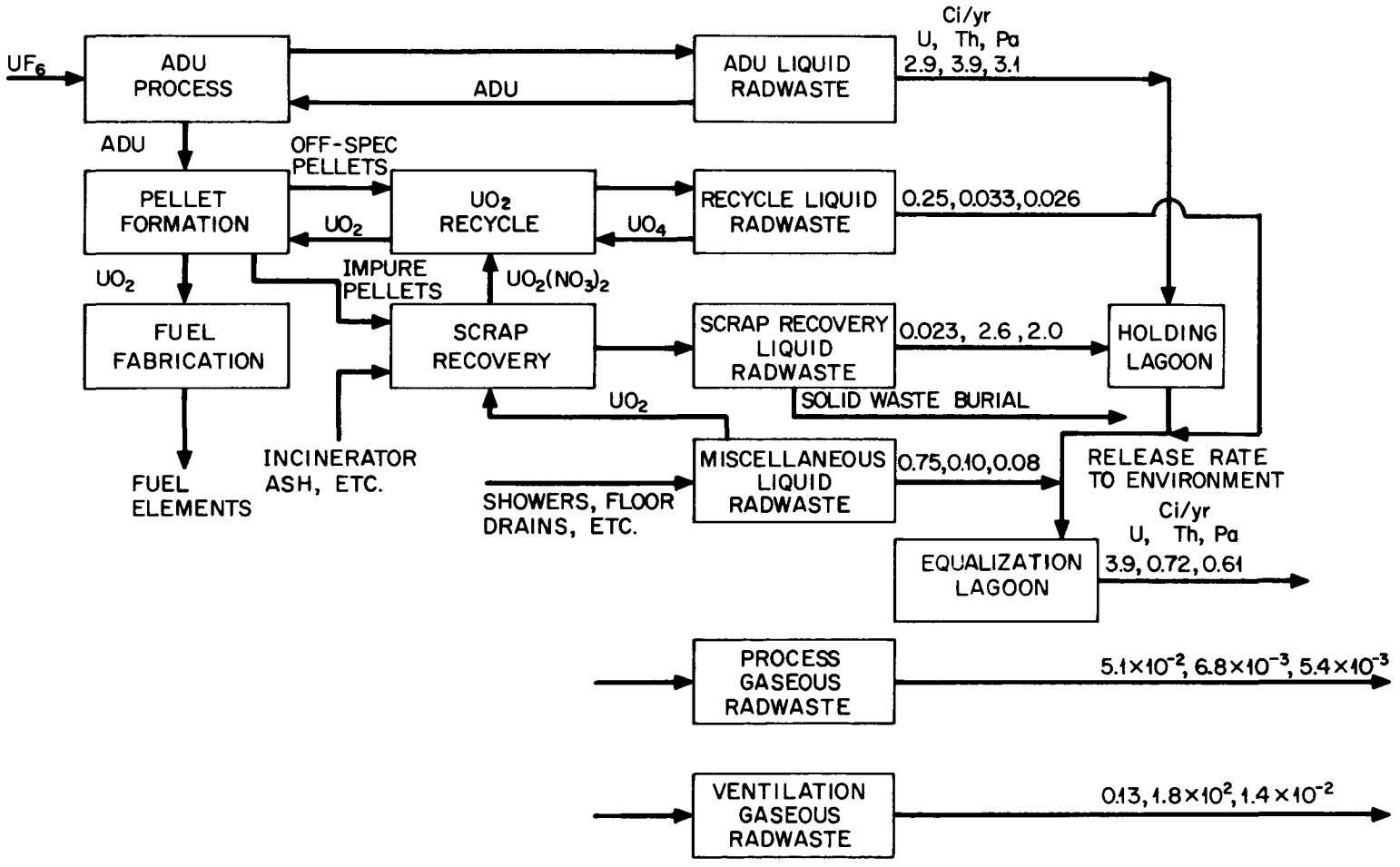


Fig. 4.6

ORNL-DWG 73-6498RI

ADU Radwaste Treatment Systems-ADU Process Liquid Waste

Case 1

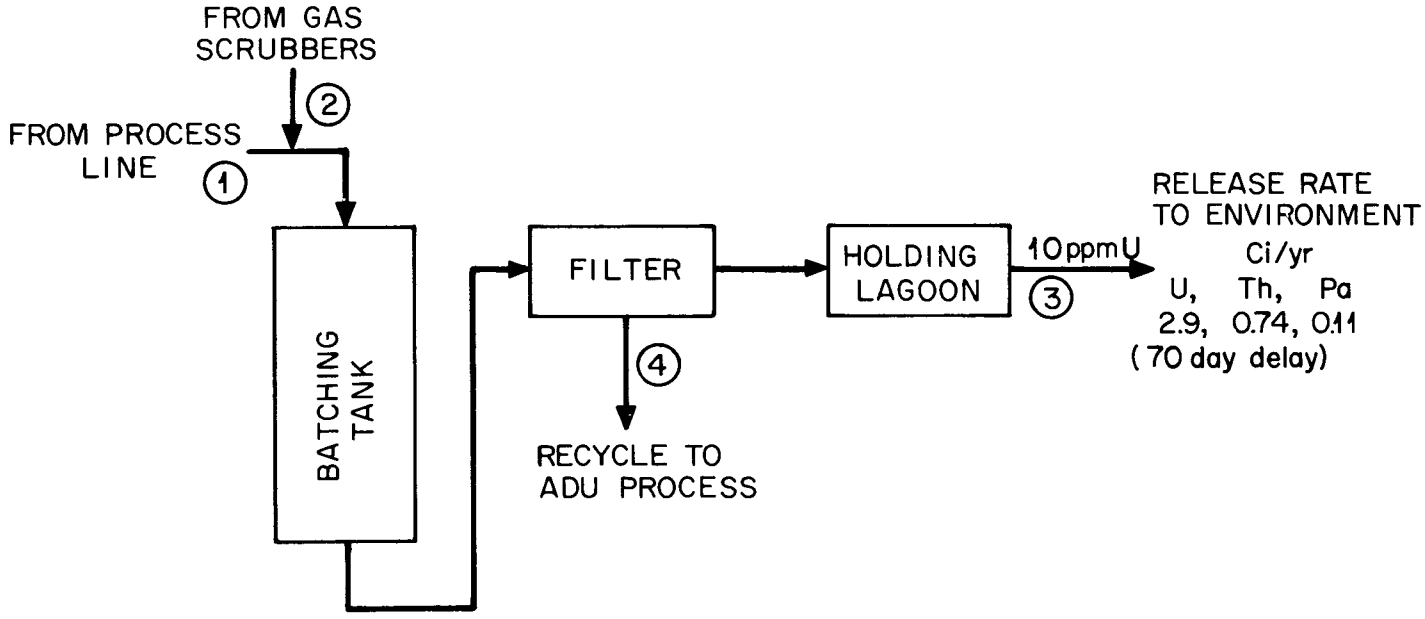
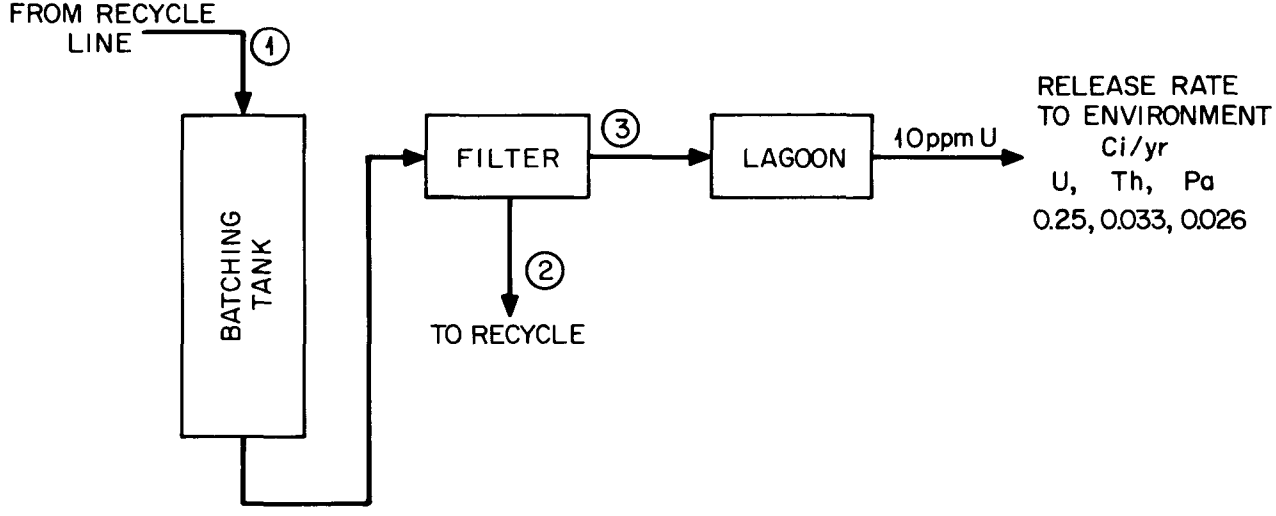


Fig. 4.7

ORNL-DWG 73-6499R

ADU and DC Radwaste Treatment Systems - Recycle Liquid Waste

Case 1



ORNL-DWG 73-6517

Fig. 4.8

ADU and DC Radwaste Treatment Systems - Scrap Recovery Liquid Waste

Case 1

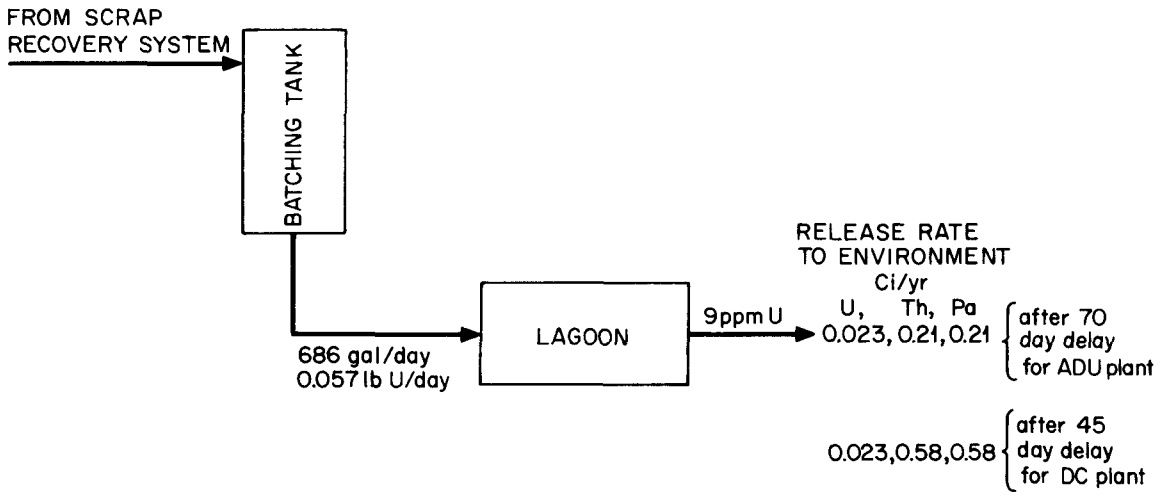


Fig. 4.9 ORNL-DWG 73-6497R

ADU and DC Radwaste Treatment Systems-Miscellaneous Liquid Waste

Cases 1 & 2

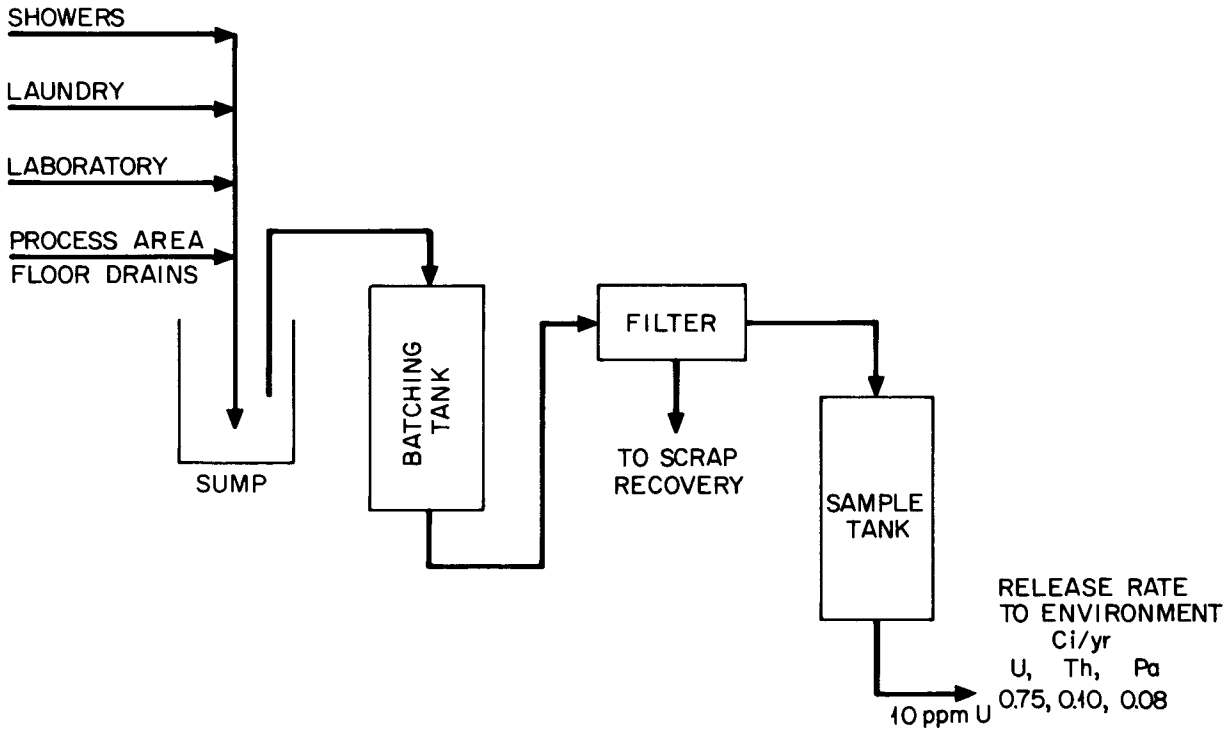
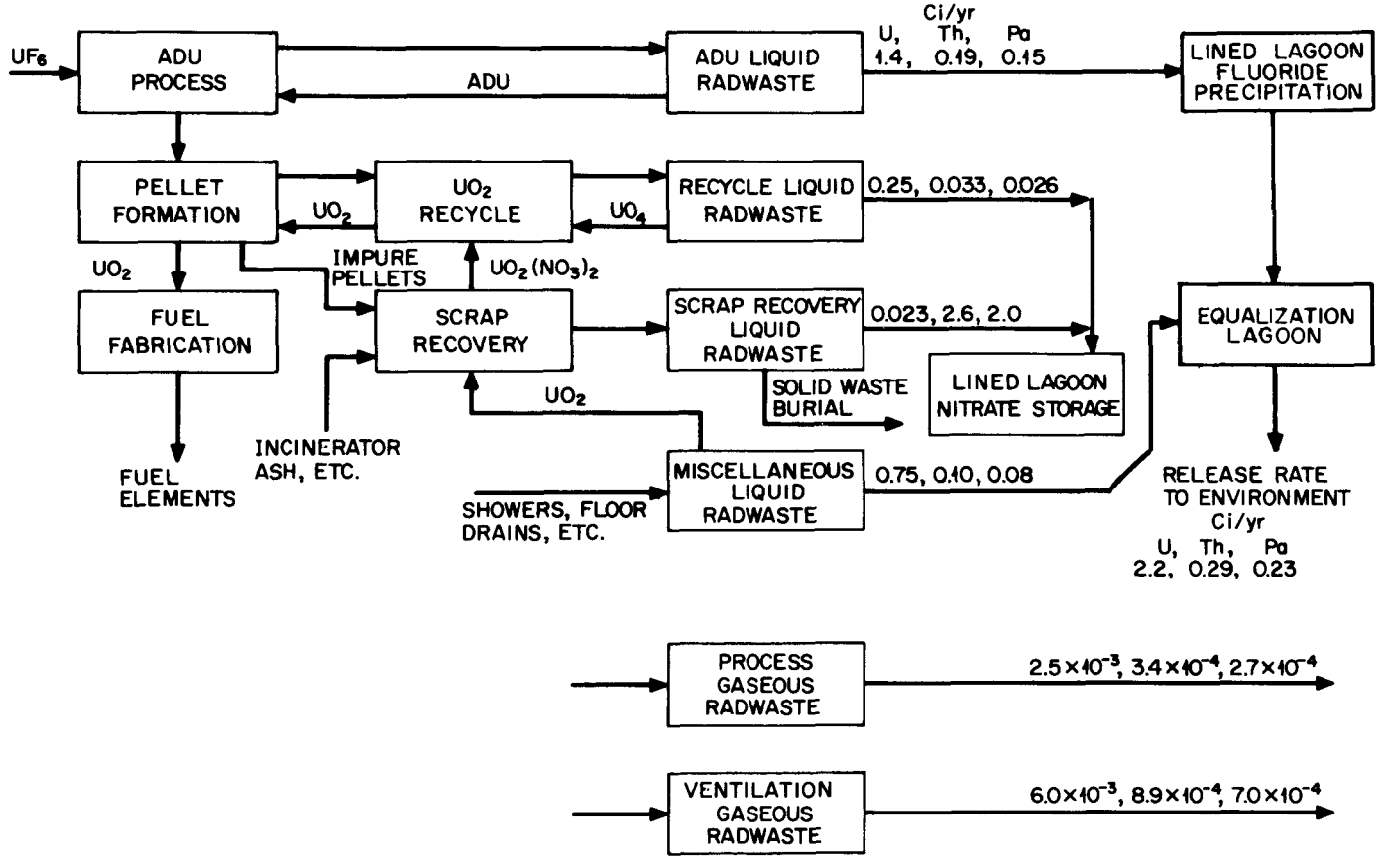


Fig. 4.10

ORNL-DWG 73-6512R2

Process and Radwaste Systems for ADU Plant

Case 2



ORNL-DWG 73-6515R2

Fig 4 11

ADU Radwaste Treatment Systems - ADU Process Liquid Waste

Case 2

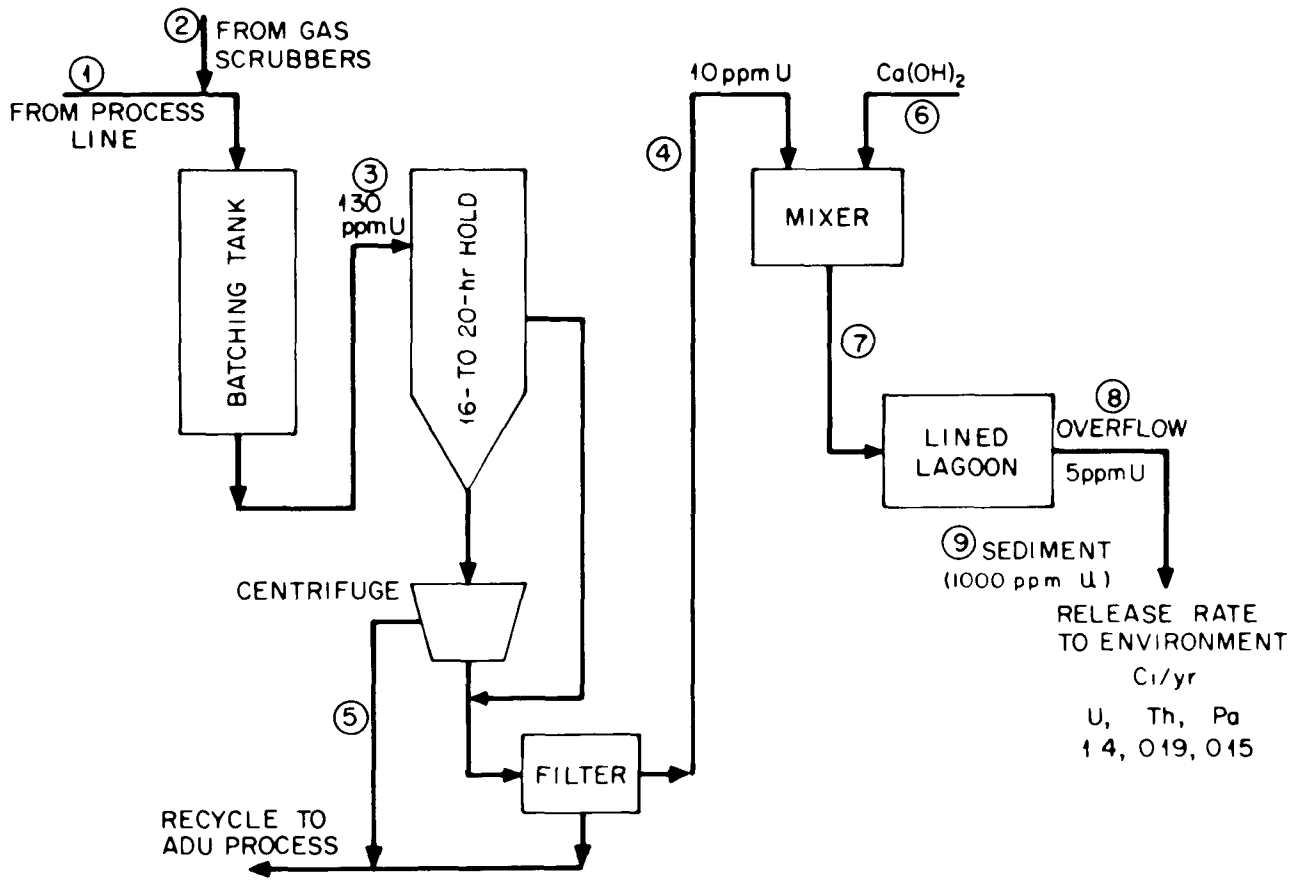
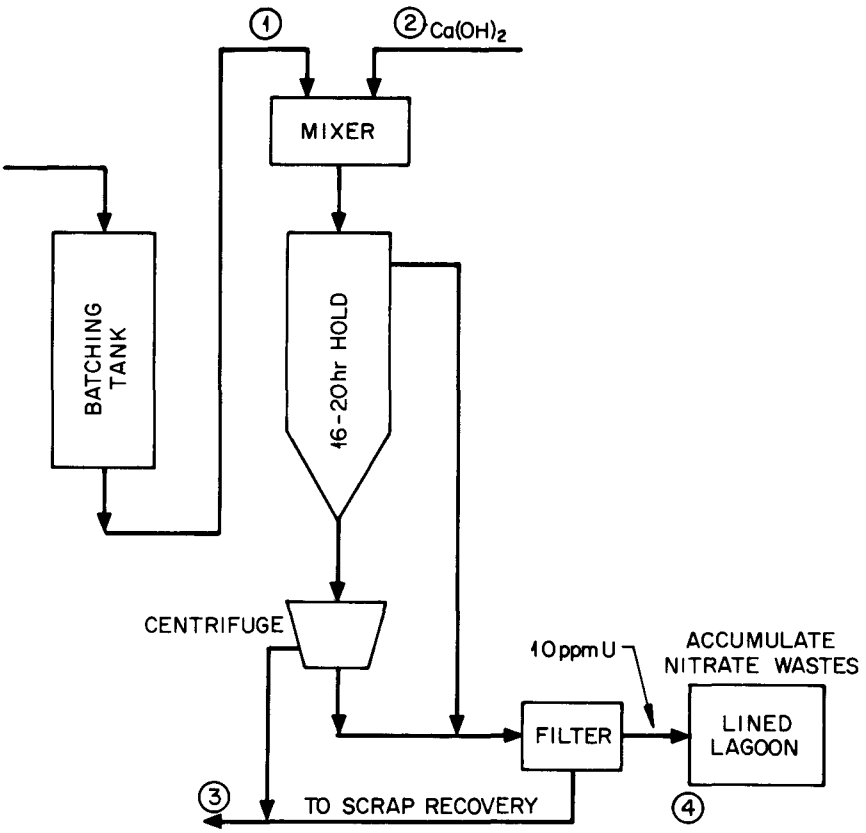


Fig. 4.12

ORNL-DWG 73-6500R

ADU and DC Radwaste Treatment Systems-Recycle Liquid Waste

Case 2



ORNL-DWG 73-6518

Fig. 4.13

ADU and DC Radwaste Treatment Systems-Scrap Recovery Liquid Waste

Case 2

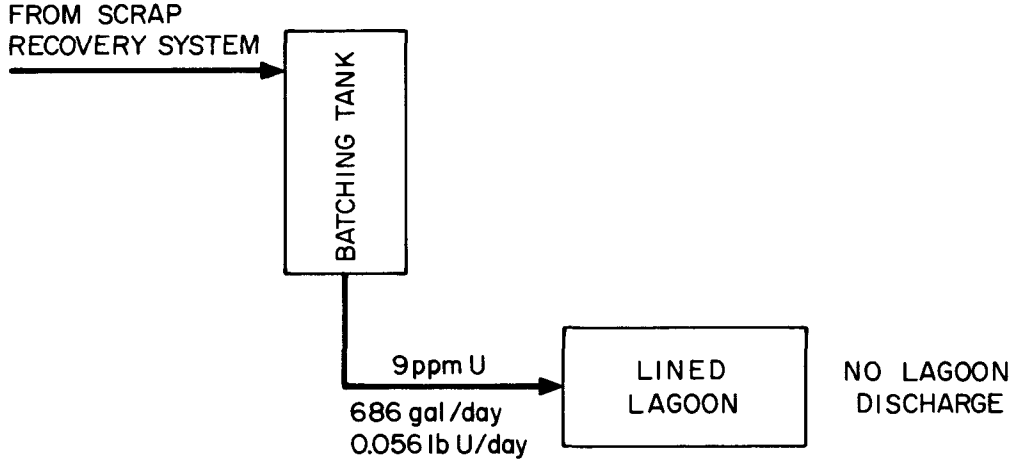
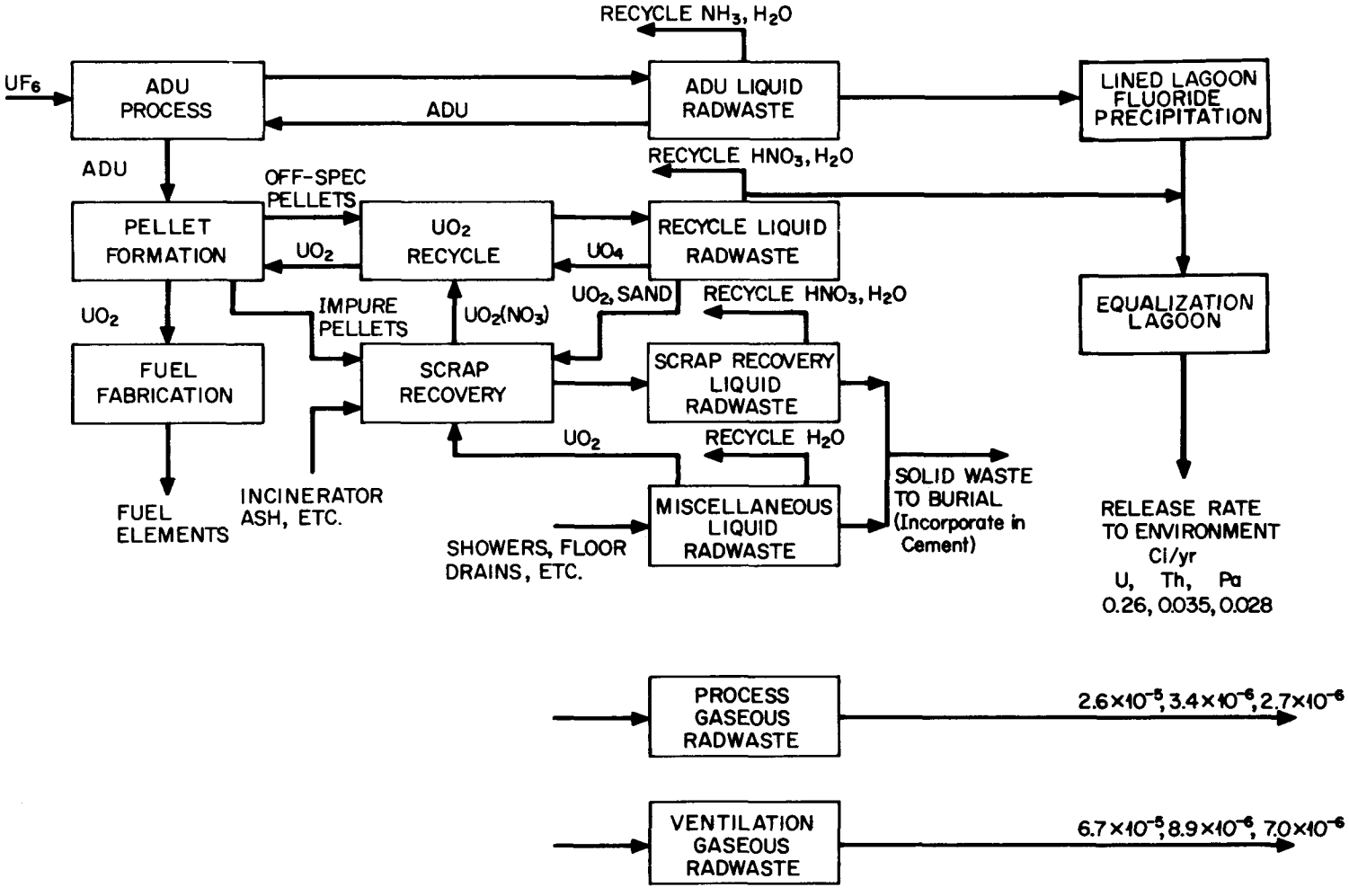


Fig. 4.14

ORNL-DWG 73-6510R2

Process and Radwaste Systems for ADU Plant

Case 3

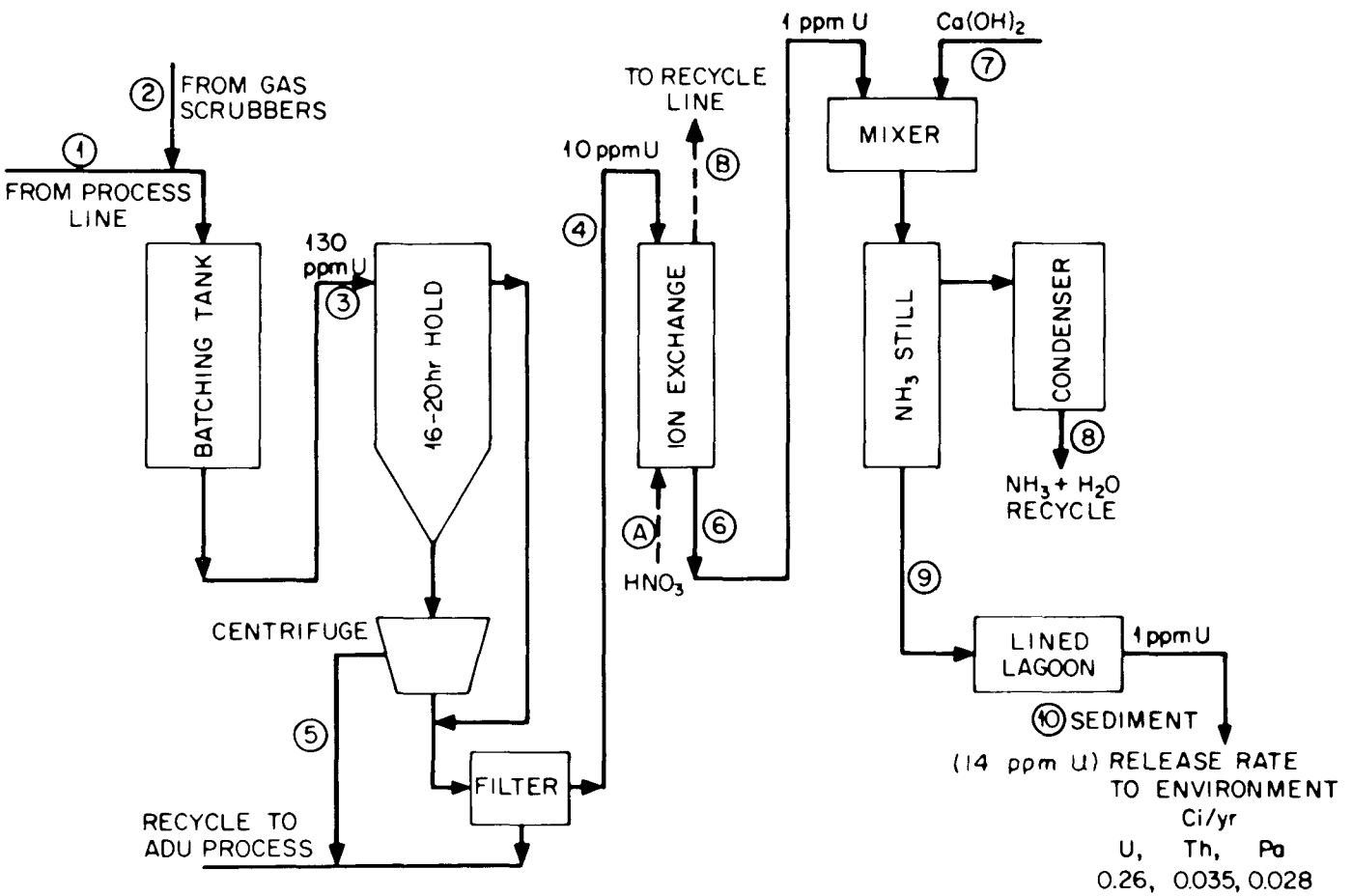


ORNL-DWG 73-6516 R1

Fig. 4.15

ADU Radwaste Treatment Systems - ADU Liquid Process Waste

Case 3

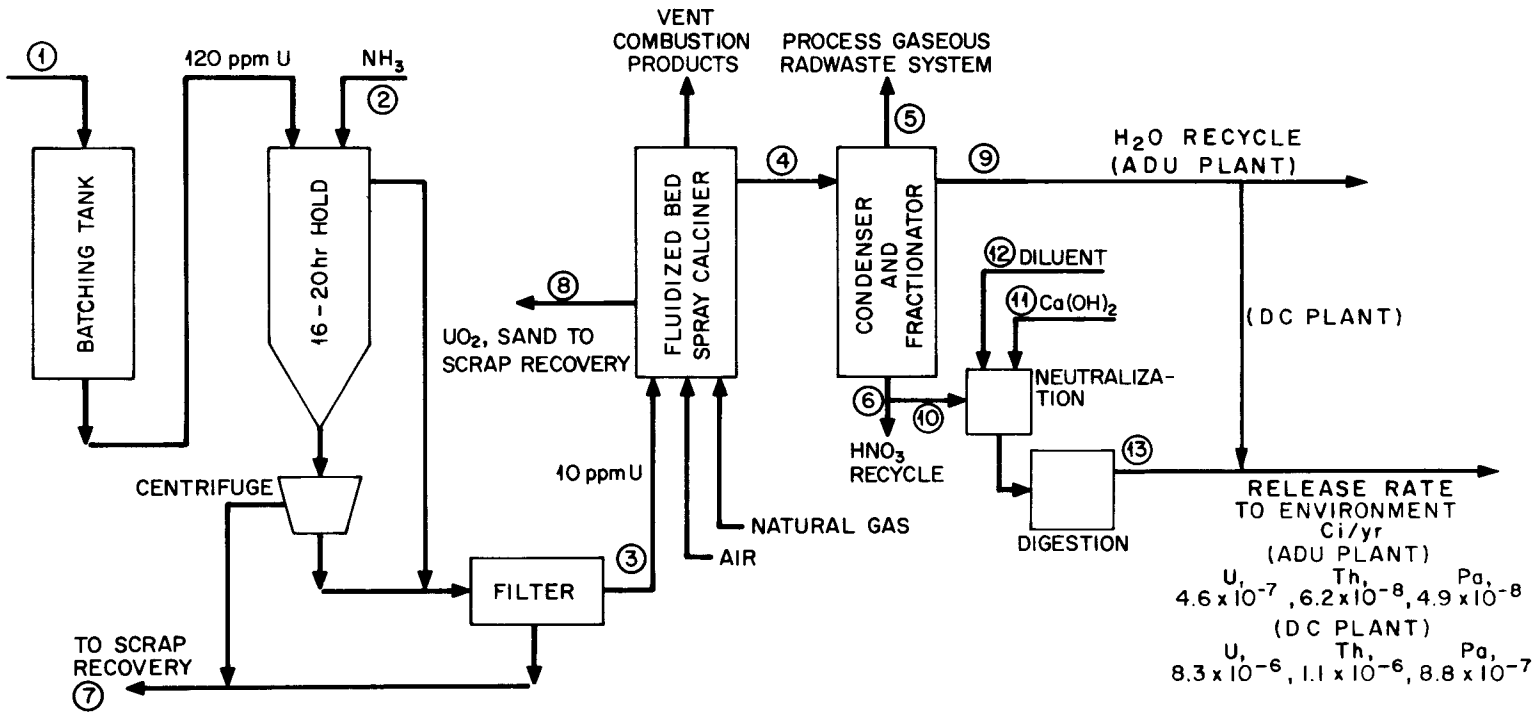


ORNL DWG 73-6519R2

Fig. 4.16

ADU and DC Radwaste Treatment Systems-Recycle Liquid Waste

Cases 3 & 4



ORNL-DWG 73-6520 R1

Fig. 4.17

ADU and DC Radwaste Treatment Systems-Miscellaneous Liquid Waste

Cases 3 & 4

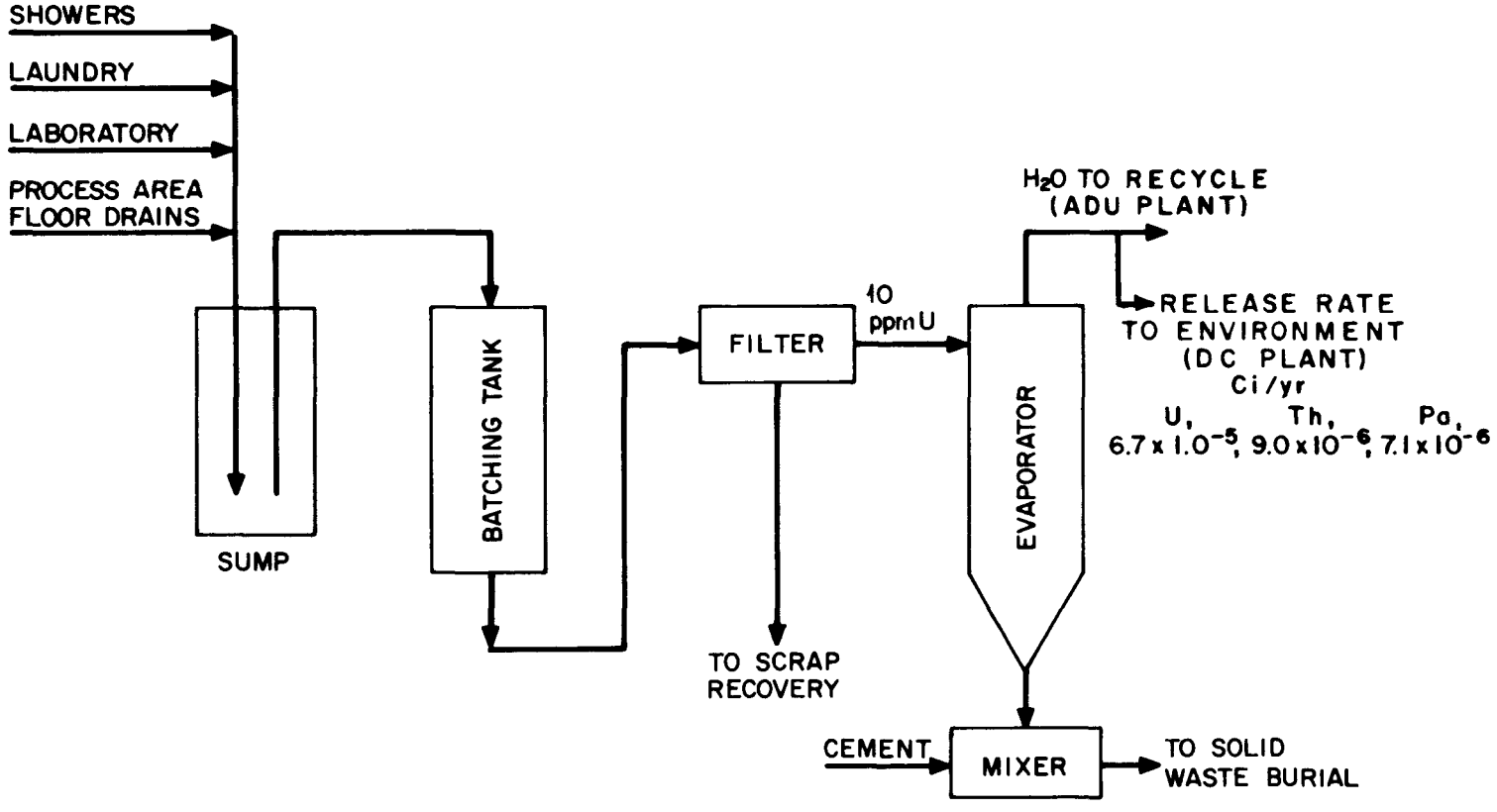


Fig. 4.18

ORNL-DWG 73-6521

ADU and DC Radwaste Treatment Systems-Scrap Recovery Liquid Waste

Cases 3 & 4

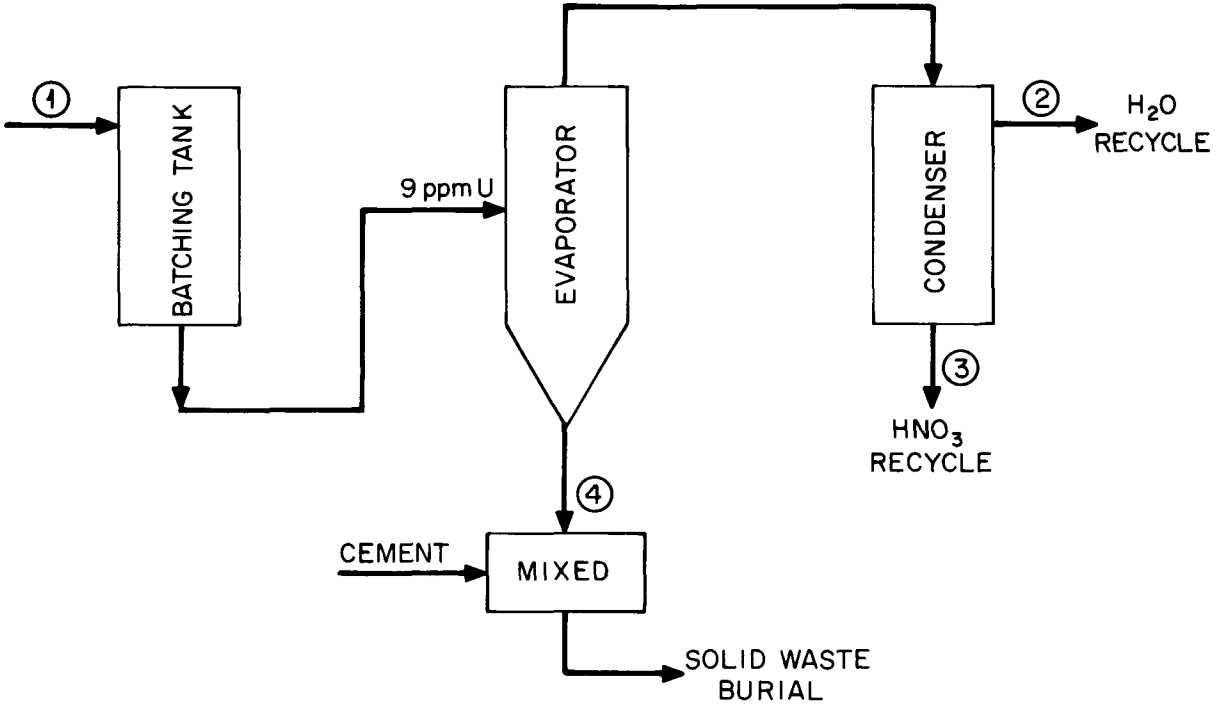
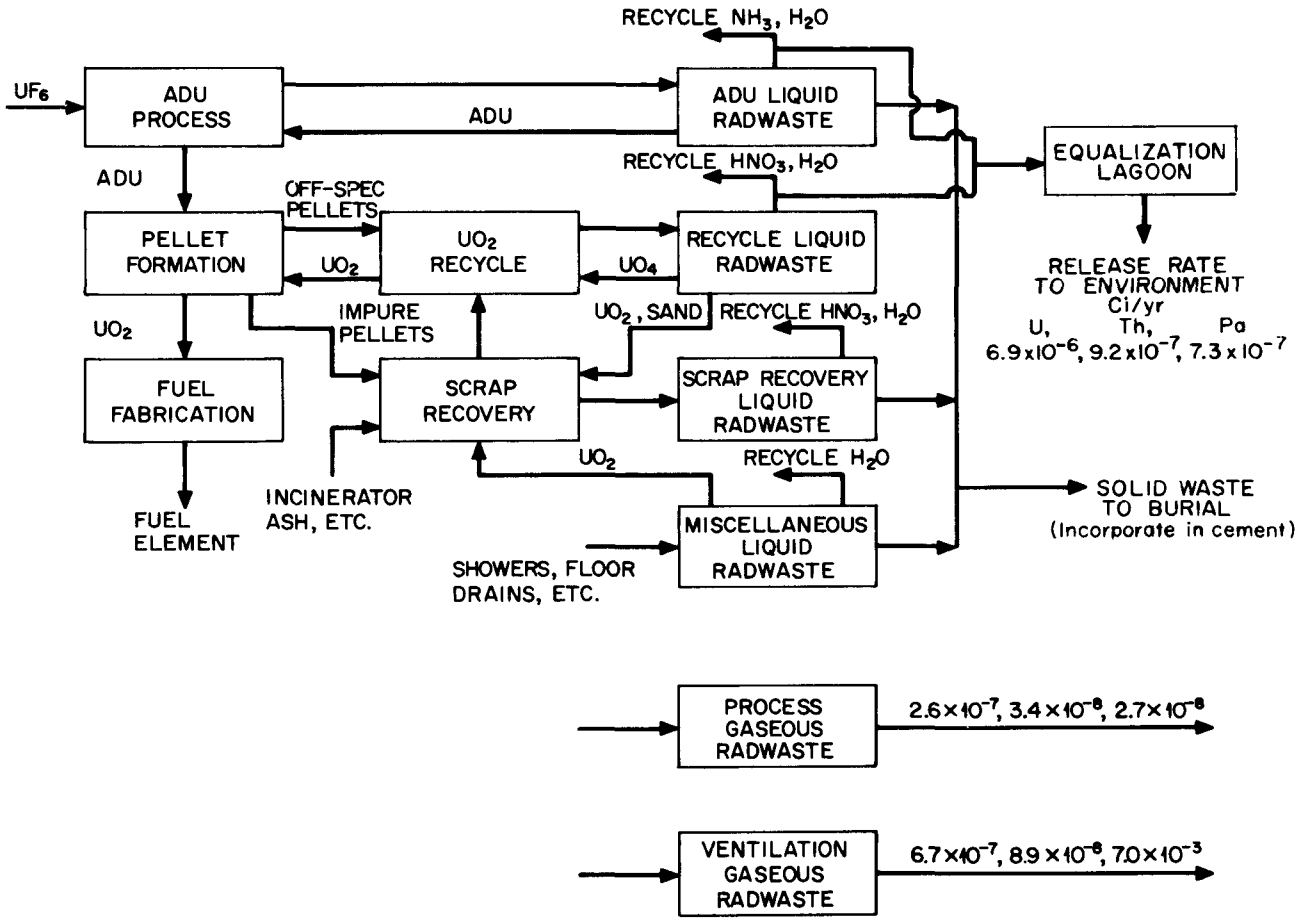


Fig. 4.19 ORNL-DWG 73-6508R2

Process and Radwaste Systems for ADU Plant

Case 4



ORNL-DWG 73-6522R

Fig 4 20

ADU Radwaste Treatment Systems – ADU Process Liquid Waste

Case 4

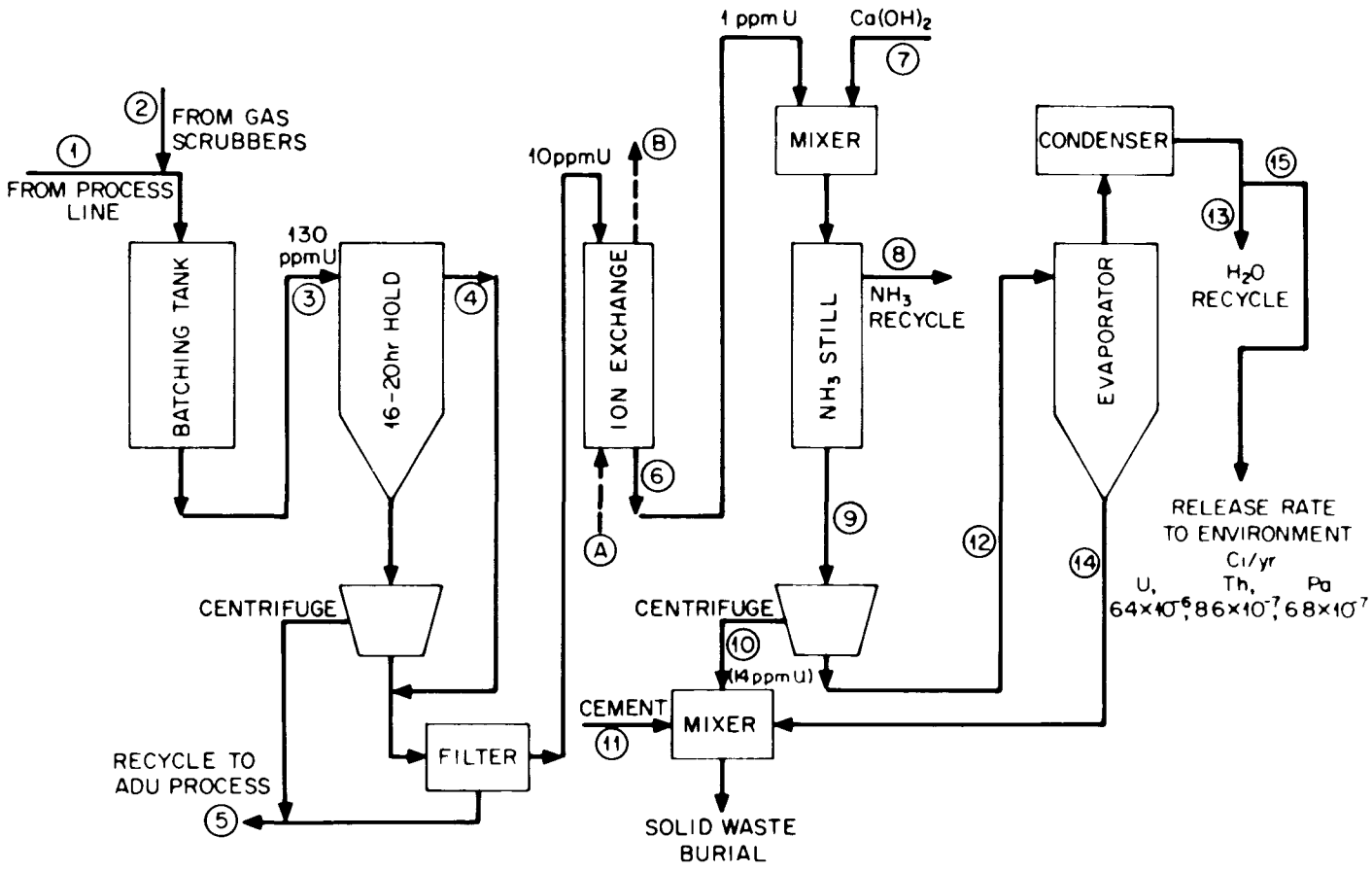


Fig. 4.21 ORNL-DWG 73-6504R2

Process and Radwaste Systems for DC Plant

Case 1

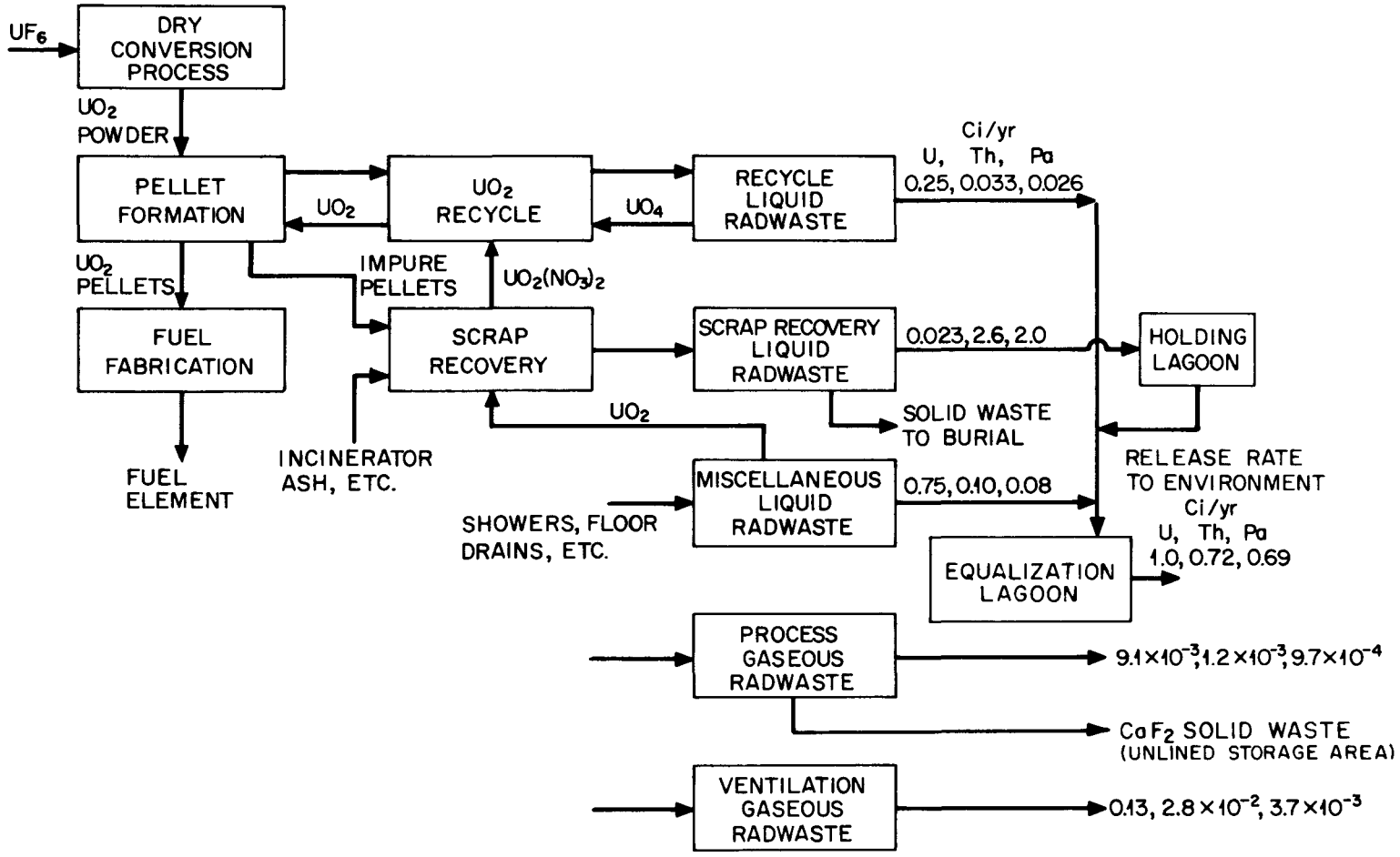


Fig. 4.22

ORNL-DWG 73-6501R2

DC Radwaste Treatment Systems-DC Process Gaseous Waste

Case 1

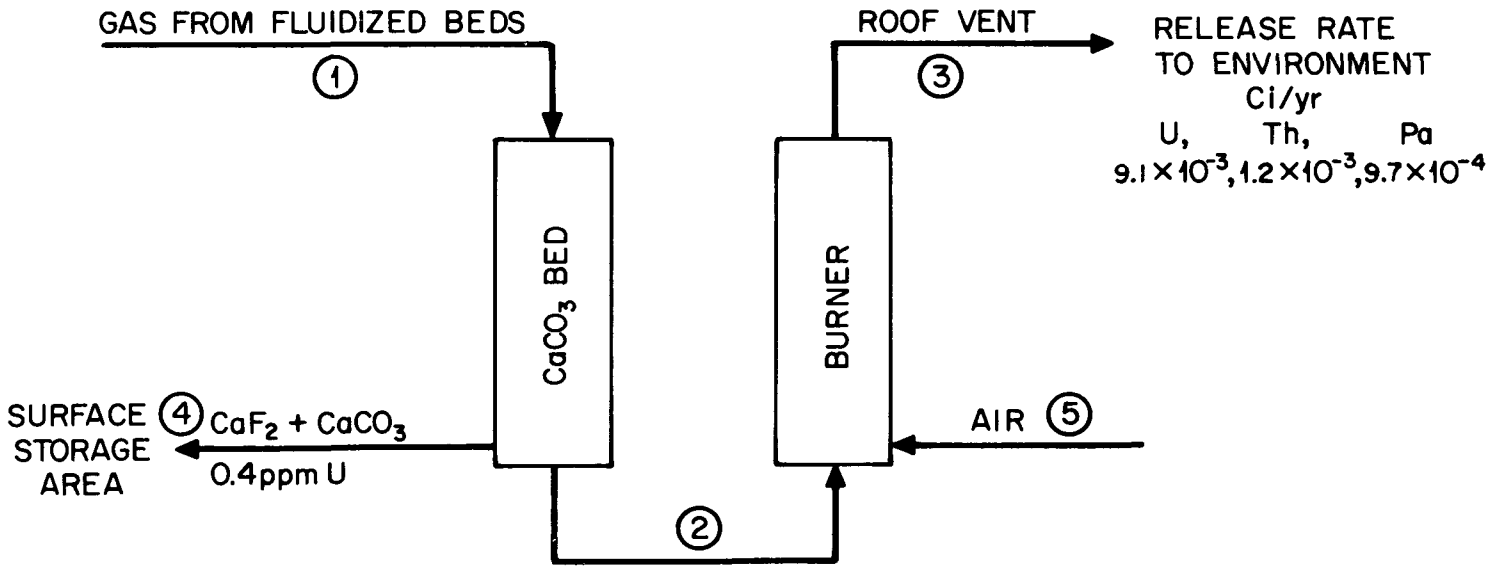
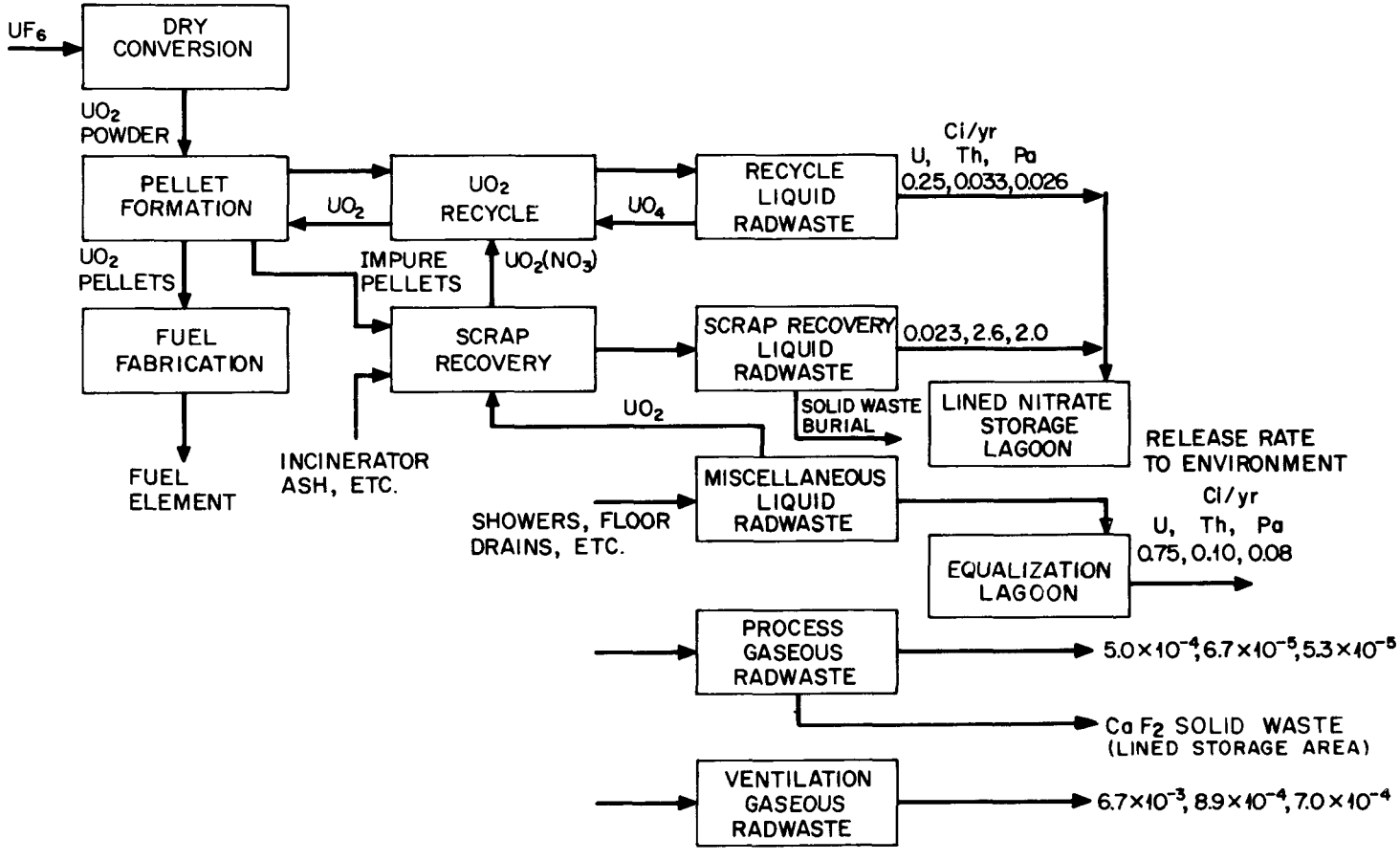


Fig. 4.23

ORNL-DWG 73-6505 R2

Process and Radwaste Systems for DC Plant

Case 2



ORNL-DWG 73-6513 R2

Fig. 4.24

DC Radwaste Treatment Systems-DC Process Gaseous Waste

Case 2

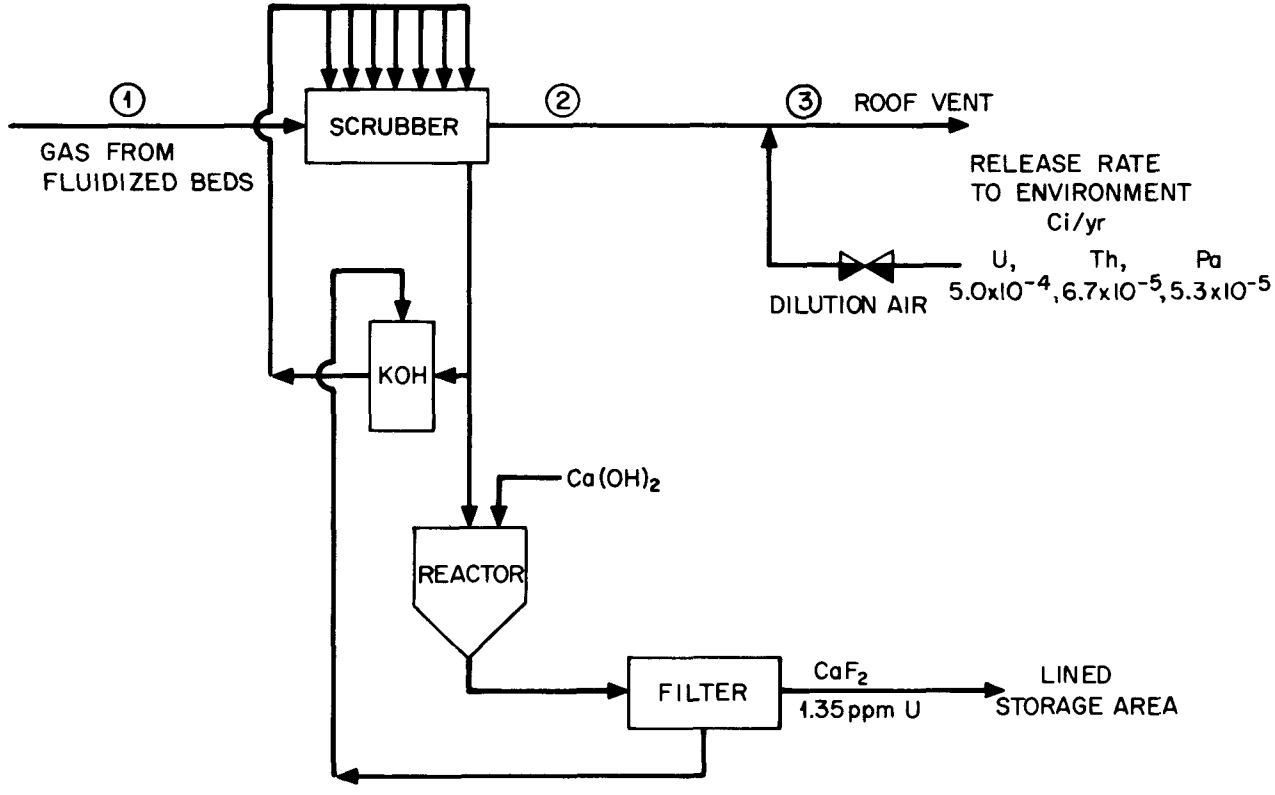
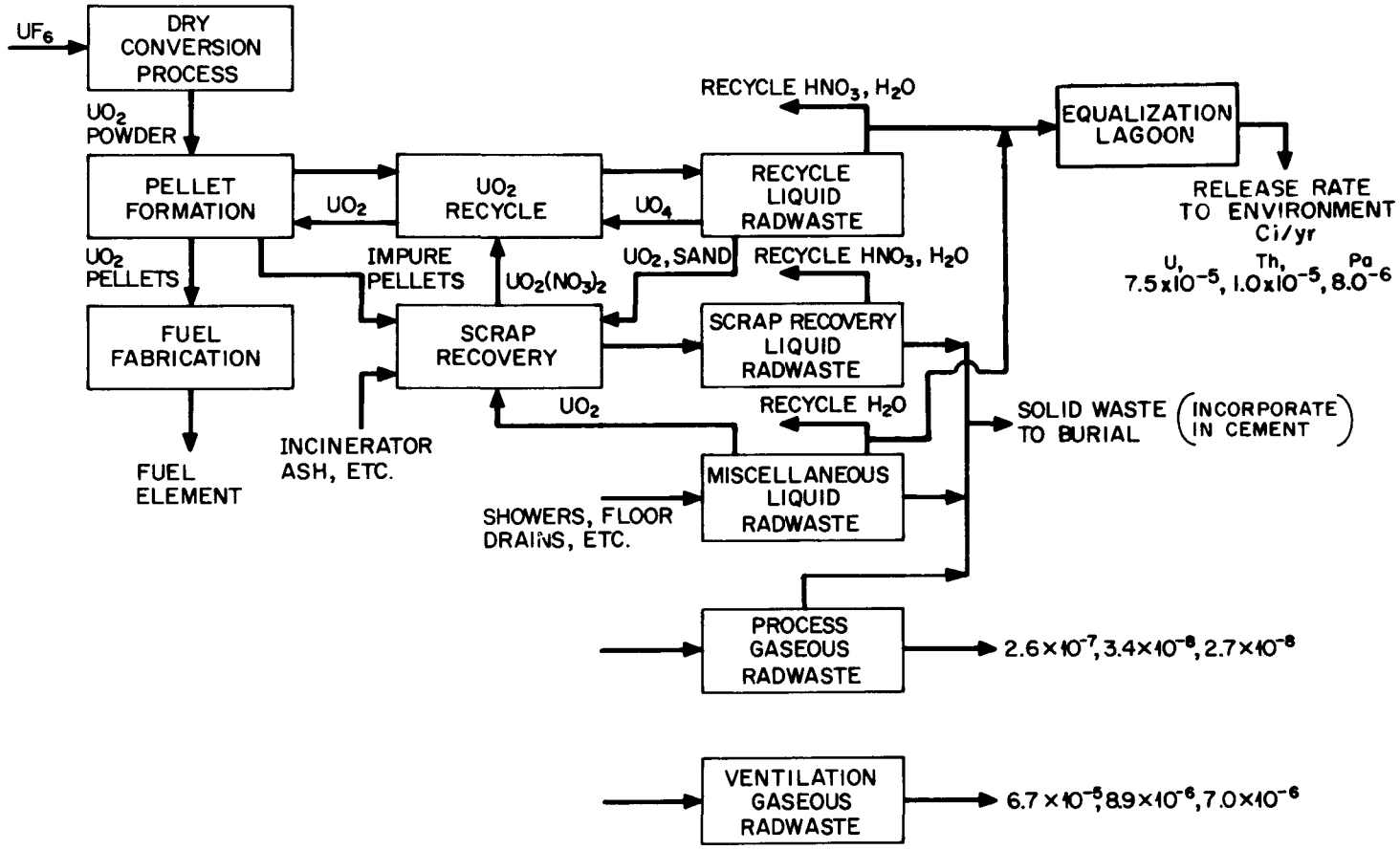


Fig. 4.25

ORNL-DWG 73-6506R3

Process and Radwaste Systems for DC Plant

Case 3



ORNL-DWG 73-6523 R2

Fig. 4.26

DC Radwaste Treatment Systems – DC Process Gaseous Waste

Case 3

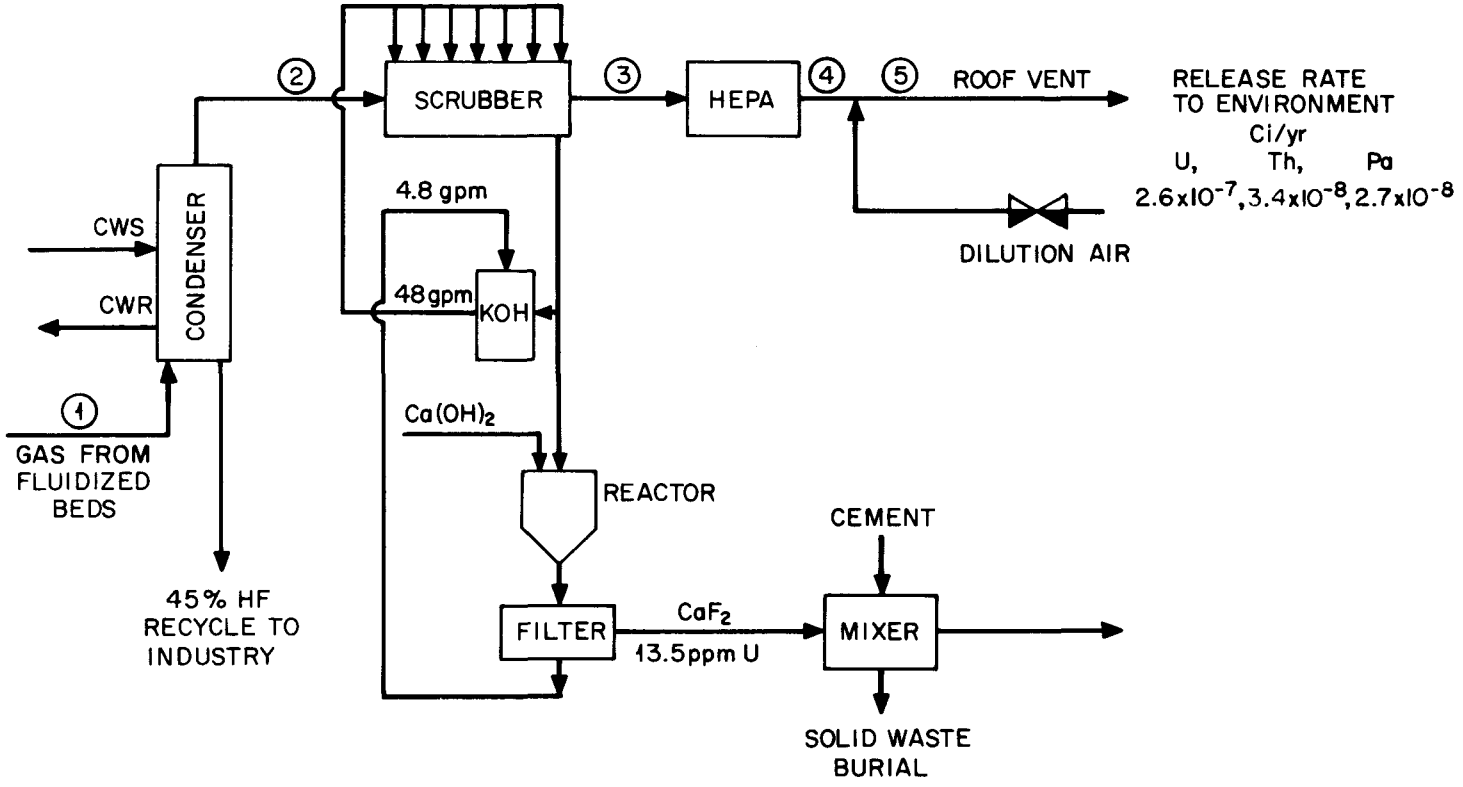
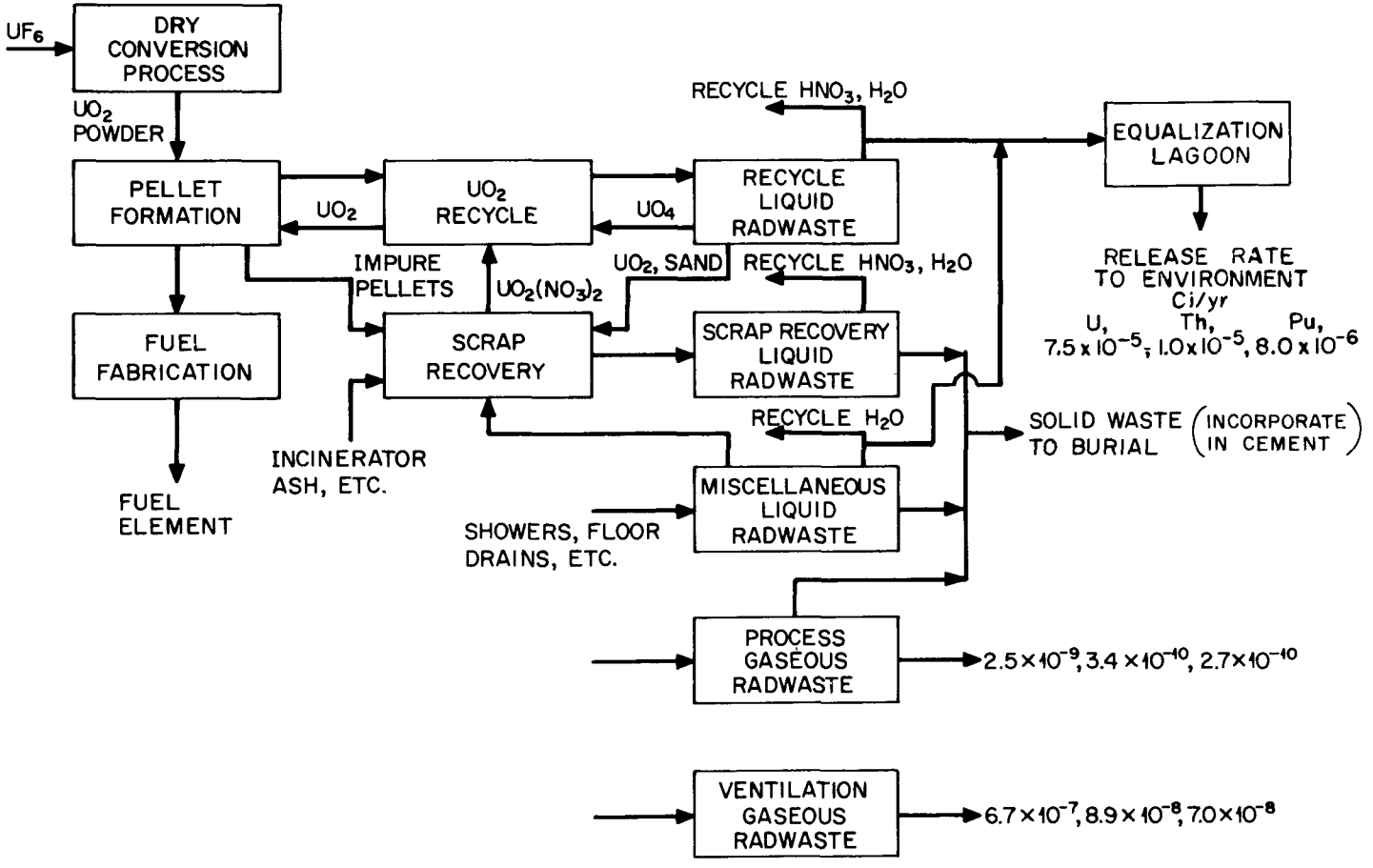


Fig. 4.27

ORNL-DWG 73-6507R2

Process and Radwaste Systems for DC Plant

Case 4

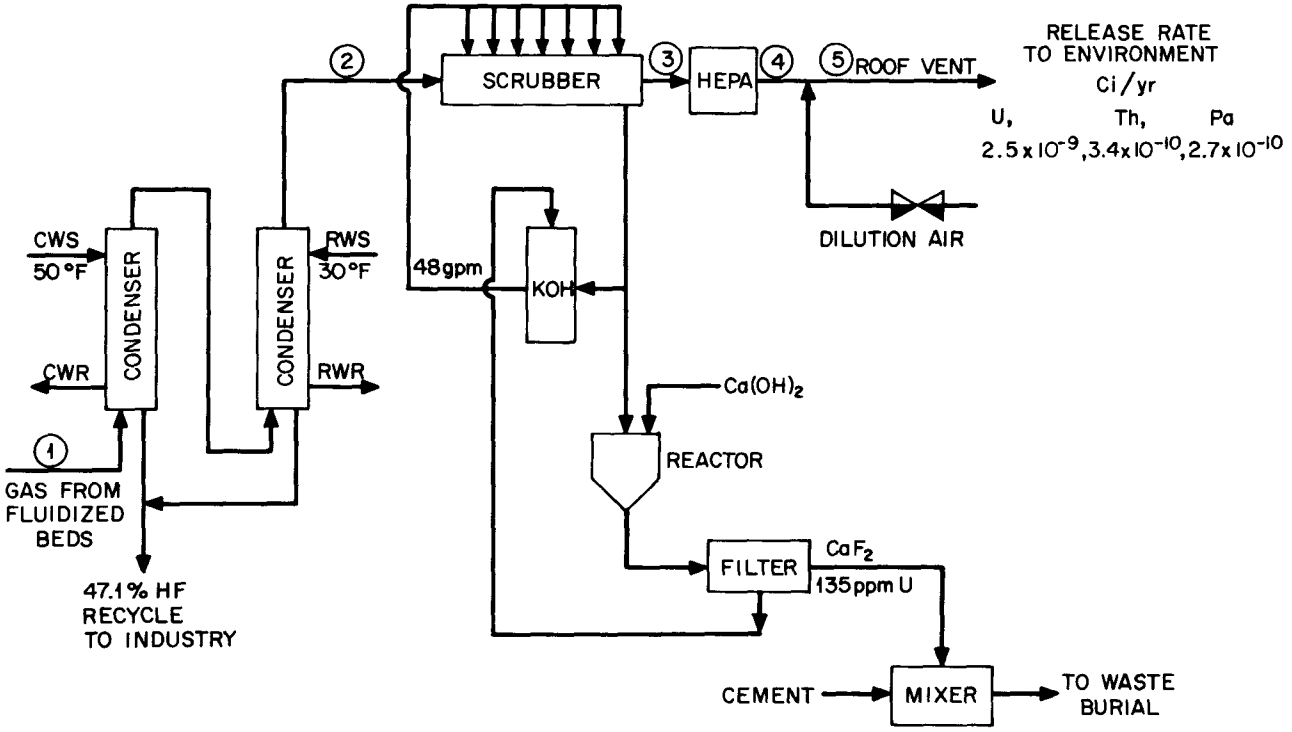


ORNL-DWG 73-6524 R2

Fig. 4.28

DC Radwaste Treatment Systems – DC Process Gaseous Waste

Case 4



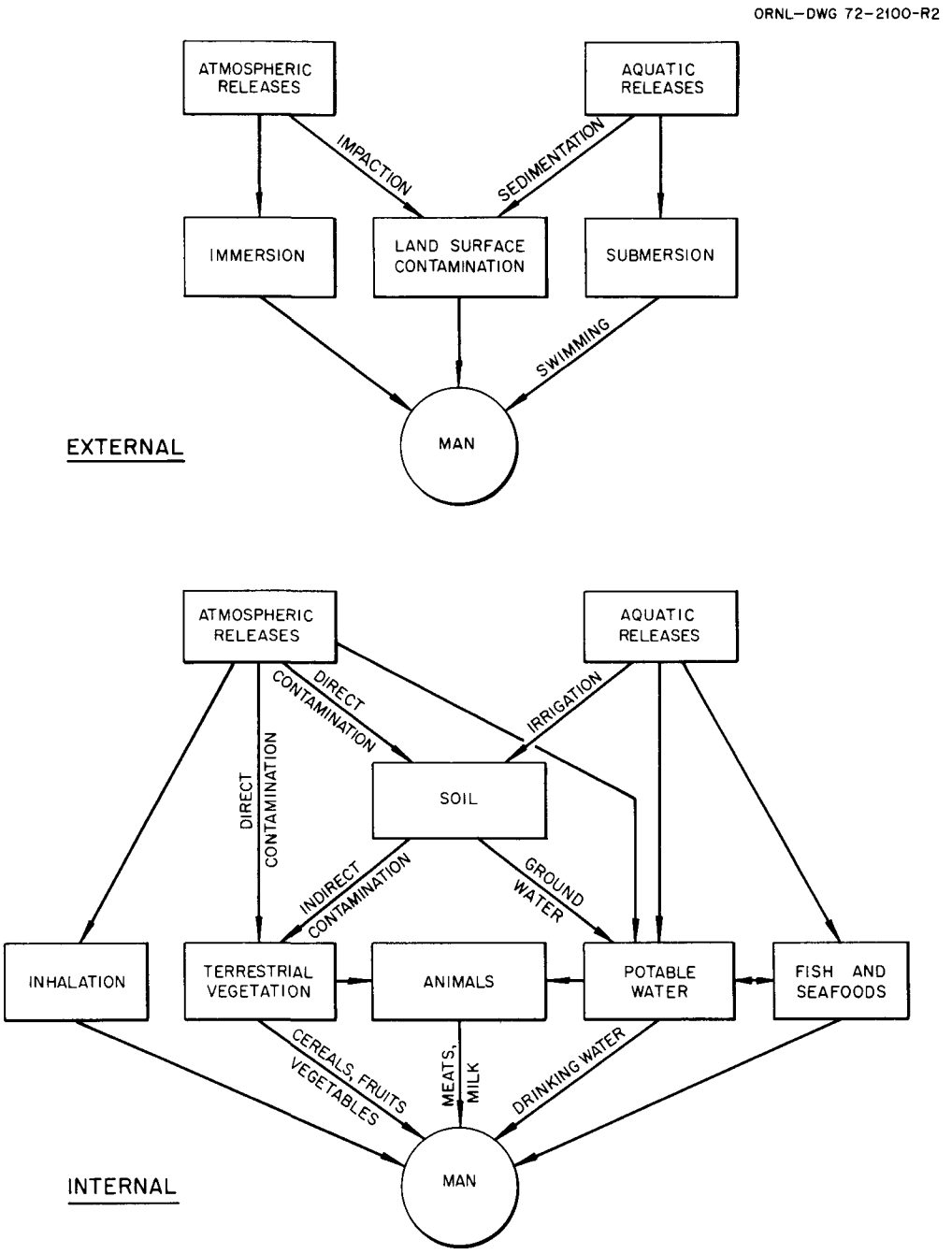


Fig. 7.1. Pathways for External and Internal Exposure of Man.

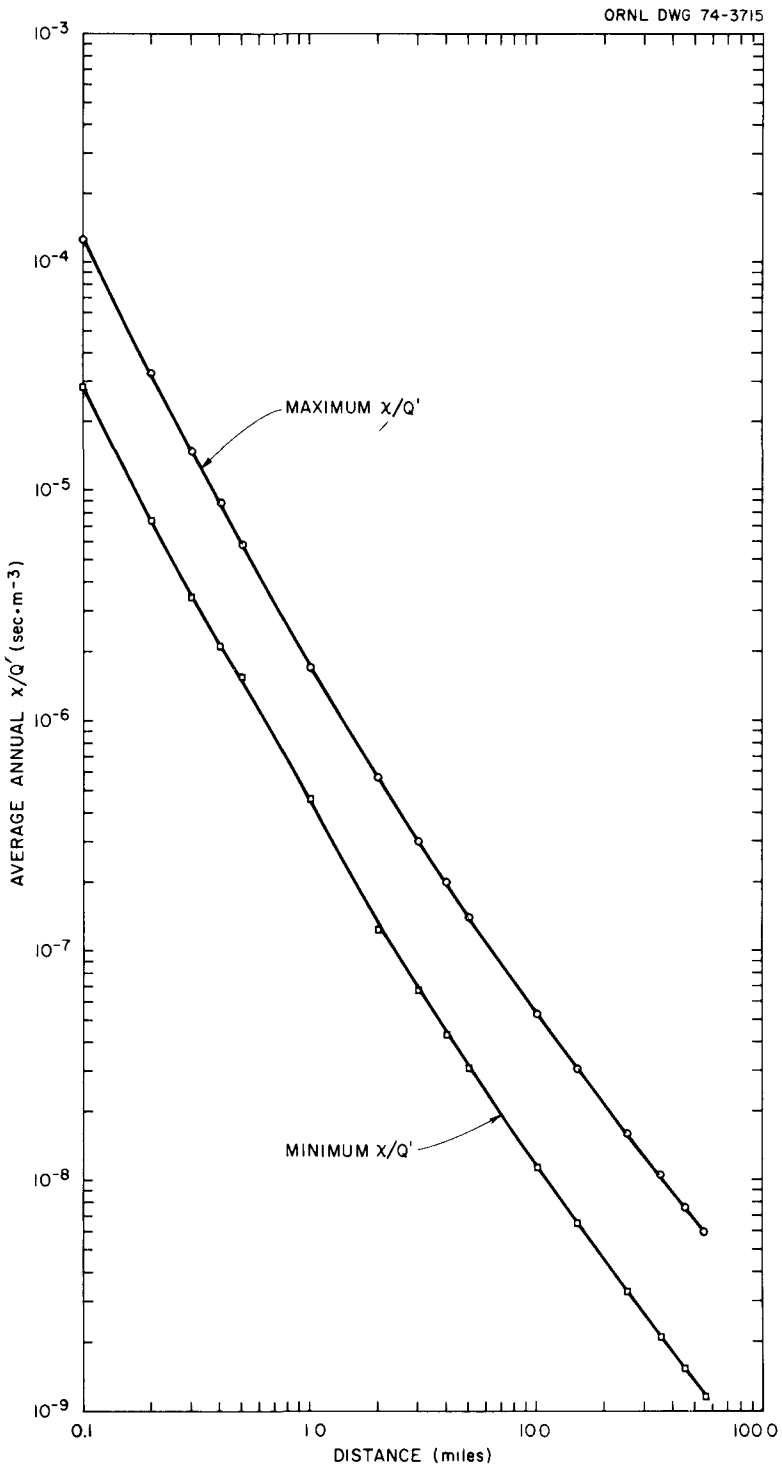


Fig. 7.2. Minimum and Maximum X/Q' for Ground Level Release at Midwestern Site. Average values of X/Q' for 16 sectors fall between these limits at respective distances.

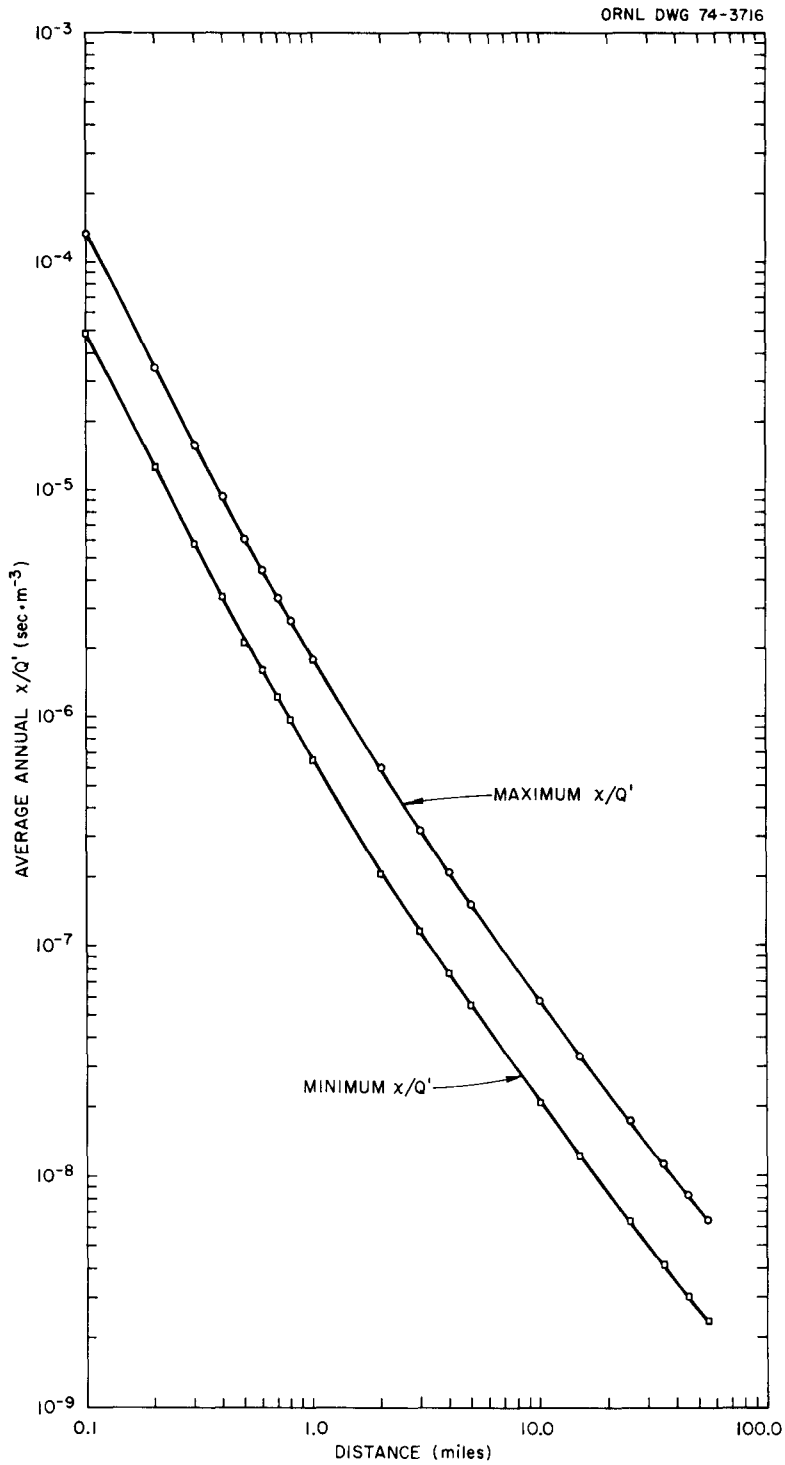


Fig. 7.3. Minimum and Maximum X/Q' for Ground Level Release at Coastal Plain Site. Average values of X/Q' for 16 sectors fall between these limits at respective distances.

ORNL DWG 74-5453

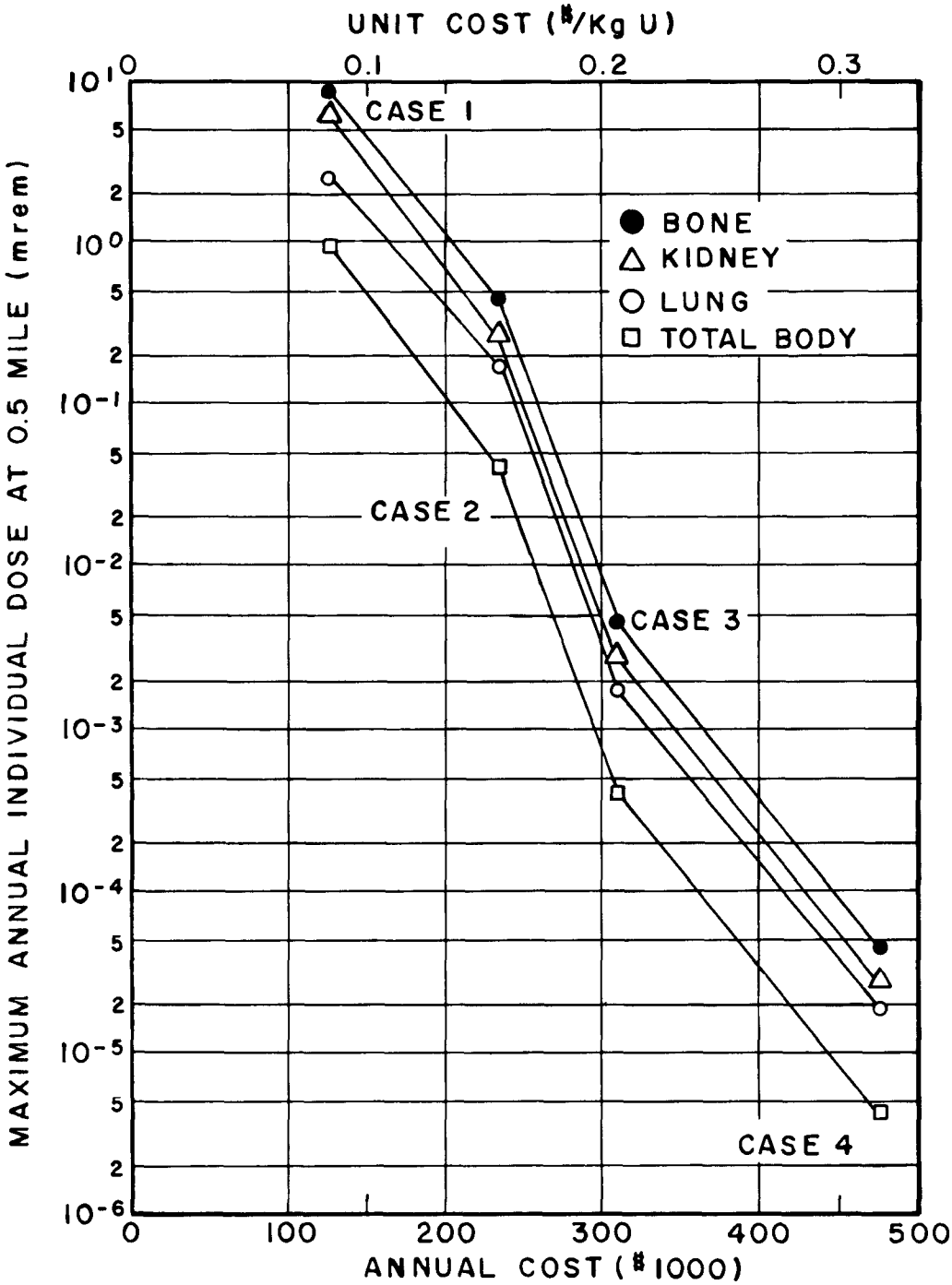


Fig. 8.1. Annual Cost for Reduction of Maximum Annual Dose from Gaseous Effluents at 0.5-mile Distance from Model ADU LWR Fuel Fabrication Plant. (Doses are not significantly different for coastal and midwestern locations.)

ORNL DWG 74-5456R1

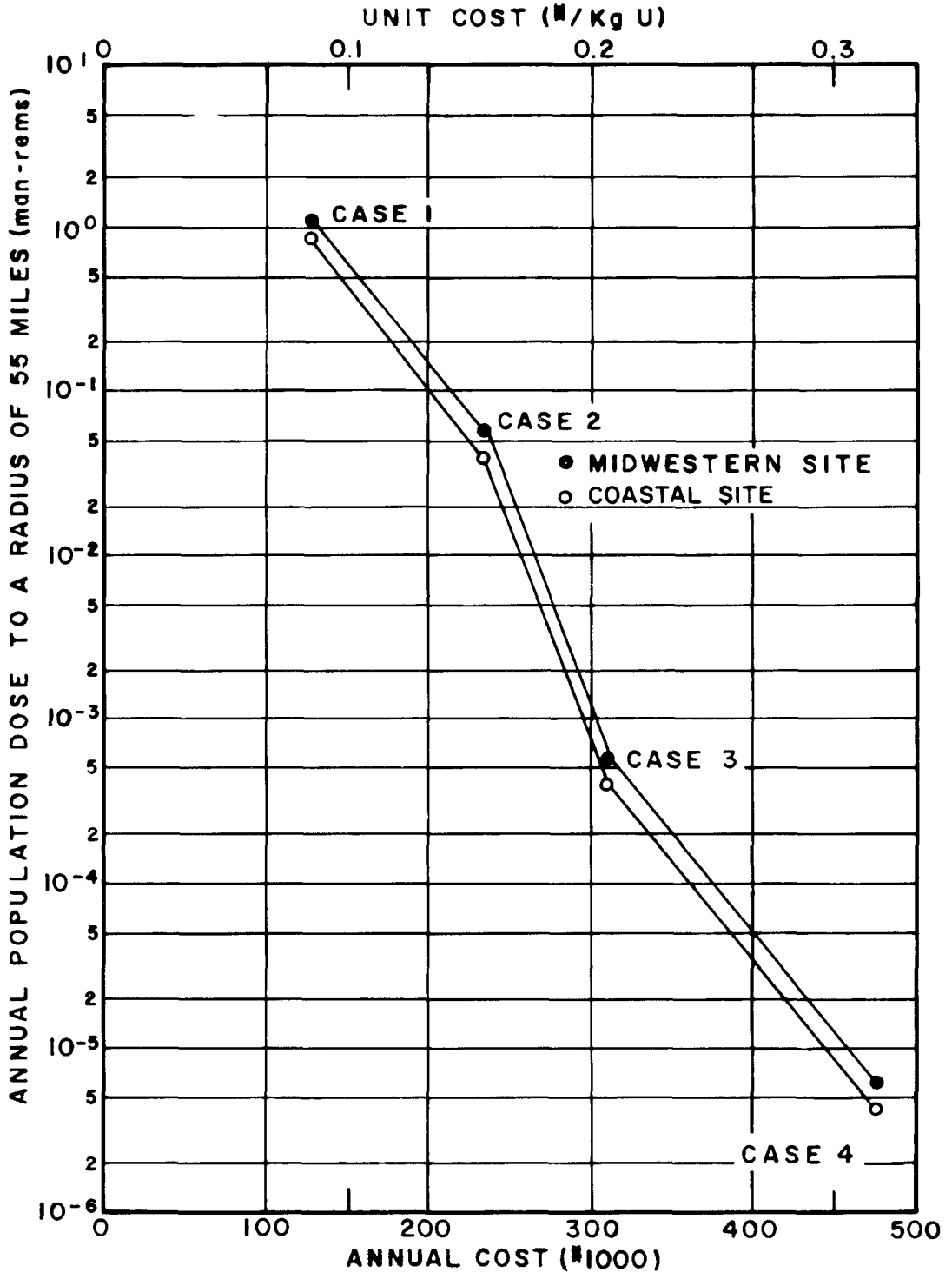


Fig. 8.2. Annual Cost for Reduction of Annual Population Dose to a Radius of 55 Miles from Gaseous Effluent from Model ADU LWR Fuel Fabrication Plant.

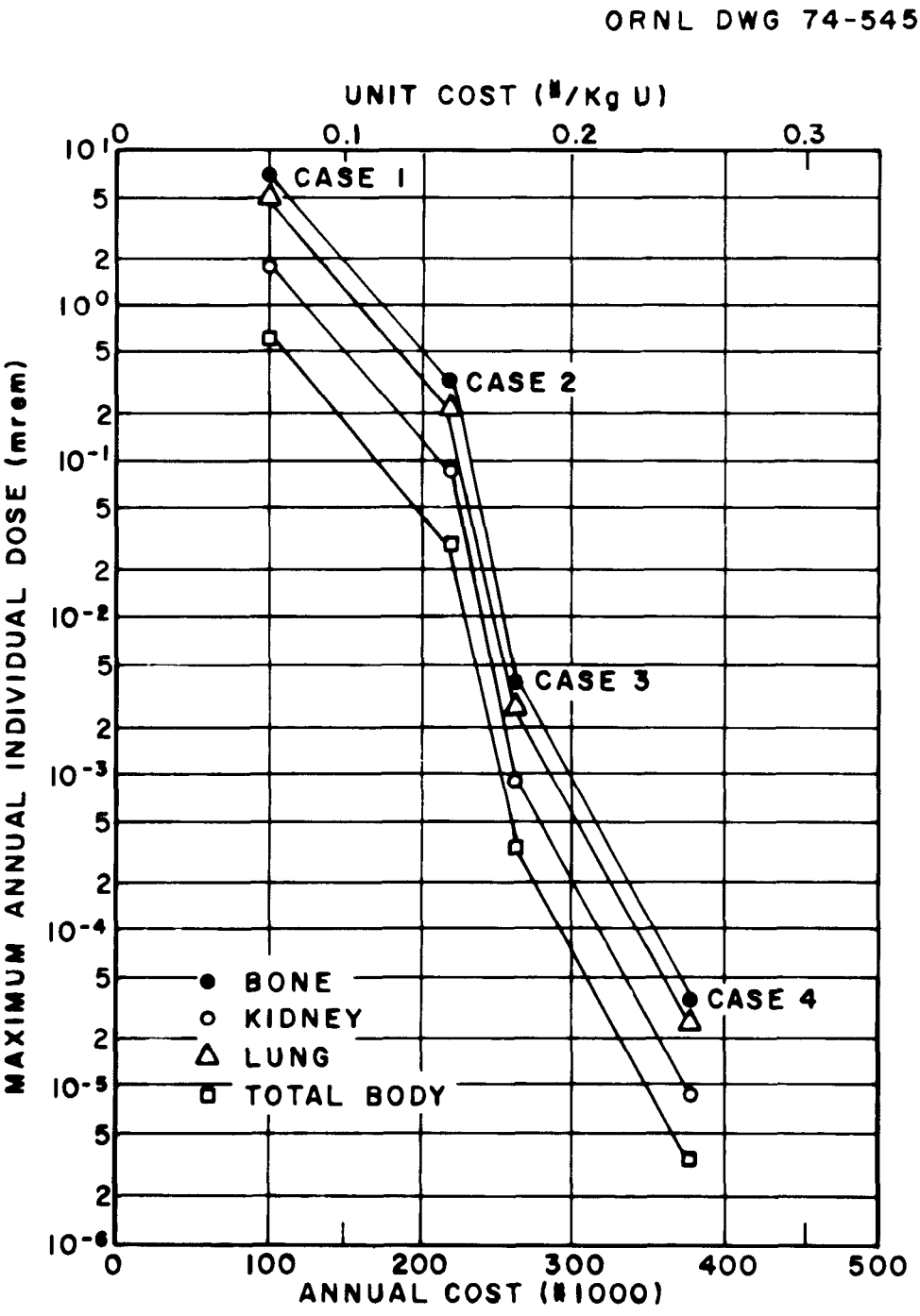


Fig. 8.3. Annual Cost for Reduction of Maximum Annual Dose from Gaseous Effluents at 0.5-Mile Distance from Model DC LWR Fuel Fabrication Plant. (Doses are not significantly different from coastal and midwestern locations.)

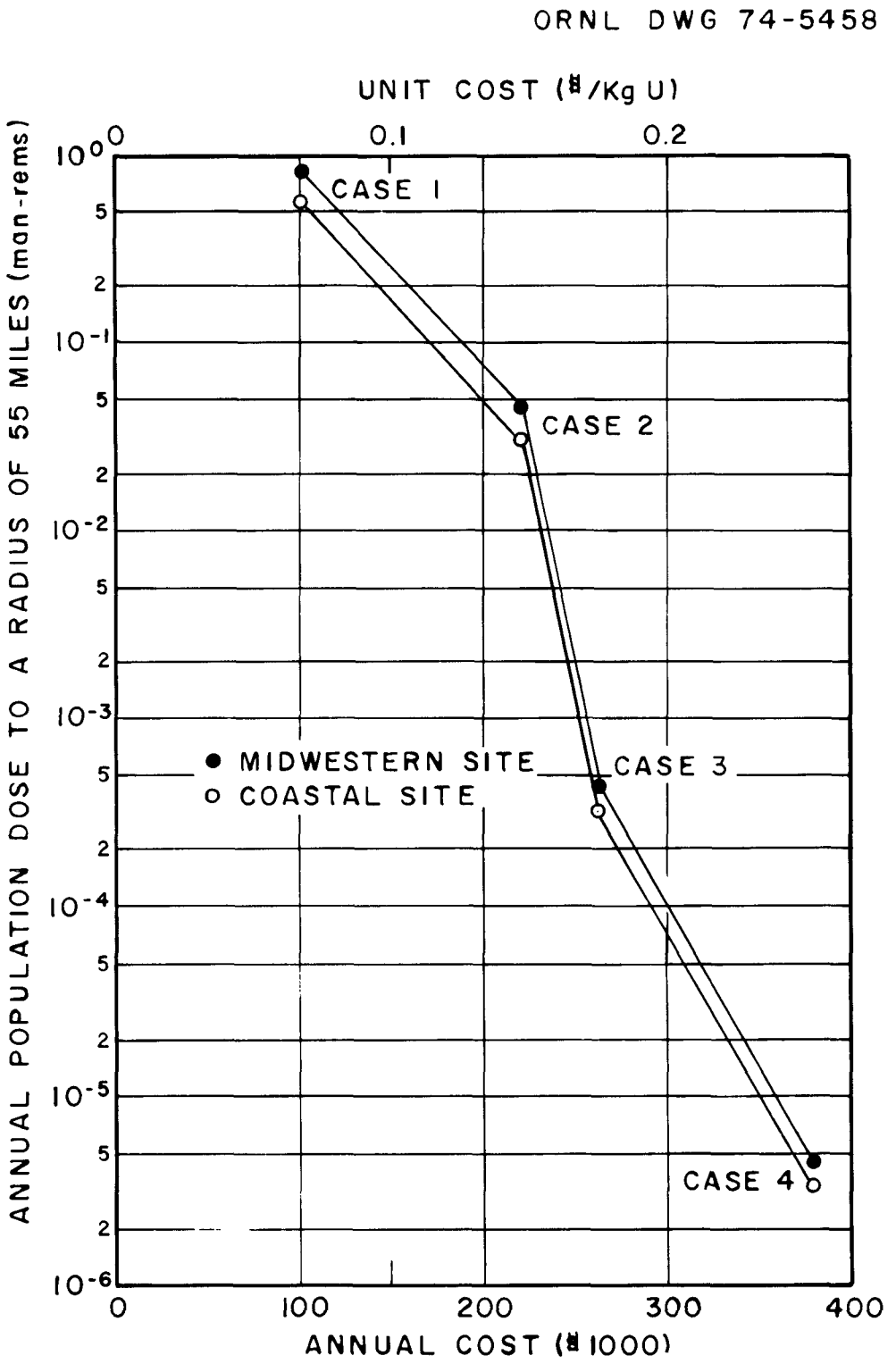


Fig. 8.4. Annual Cost for Reduction of Annual Population Dose to a Radius of 55 Miles from Gaseous Effluent from Model DC LWR Fuel Fabrication Plant.

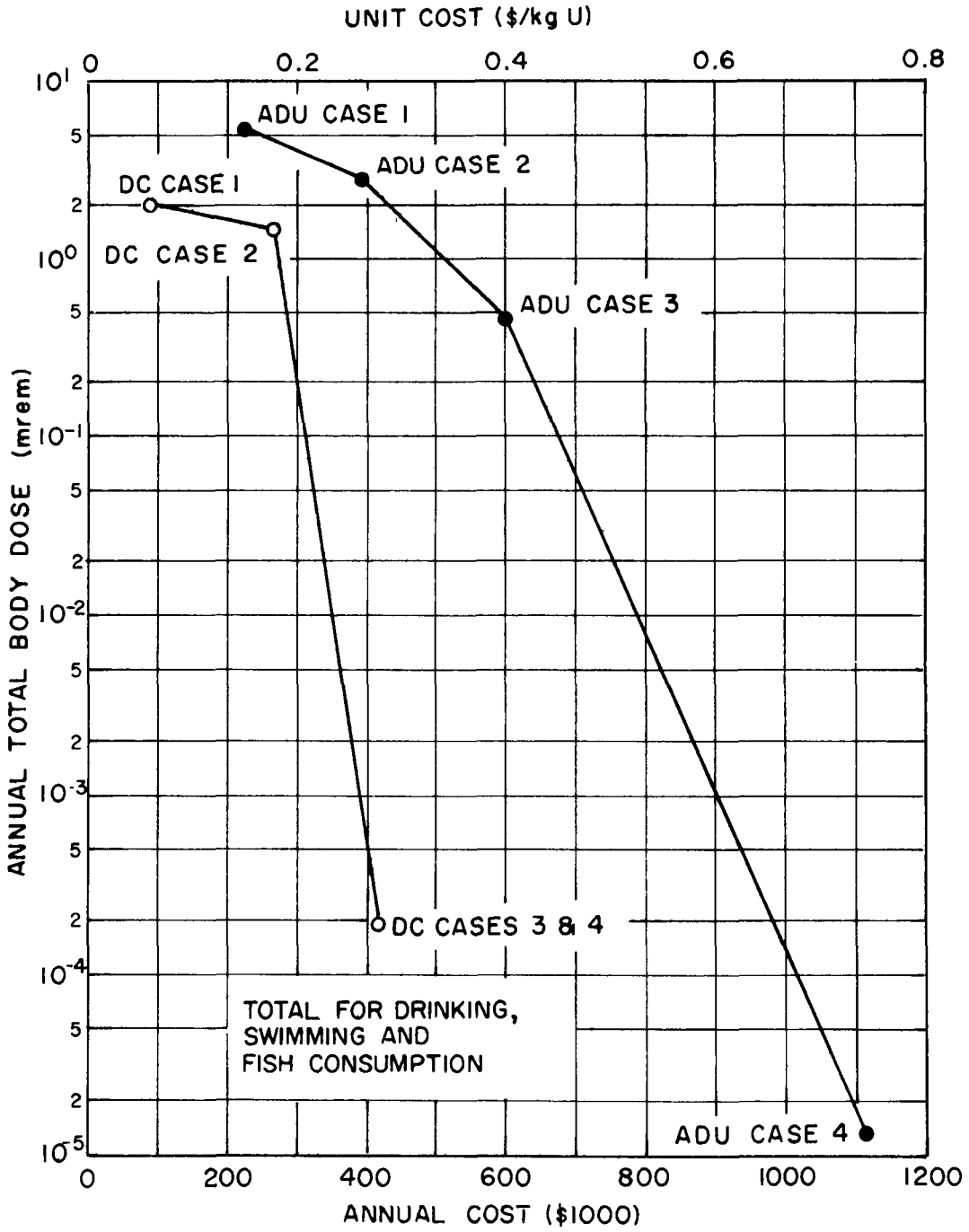


Fig. 8.5. Annual Cost for Reduction of Annual Total Body Dose from Liquid Effluents Diluted by 15-cfs Stream from Model ADU and DC LWR Fuel Fabrication Plant at Midwestern and Coastal Sites.

ORNL DWG 73-10476 R2

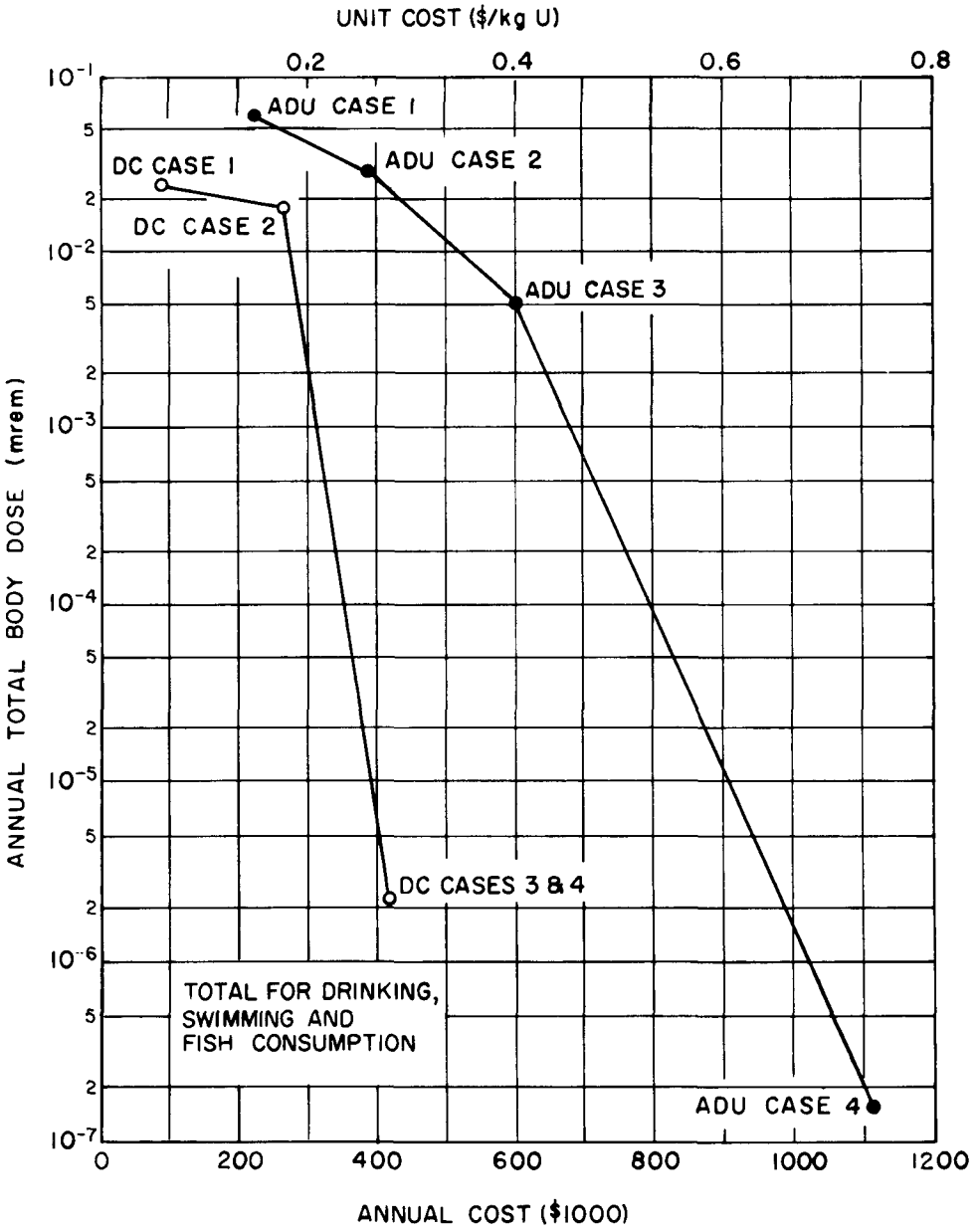


Fig. 8.6. Annual Cost for Reduction of Annual Total Body Dose from Liquid Effluents Diluted by 1300-cfs Stream from Model ADU and DC LWR Fuel Fabrication Plants at Midwestern Site.

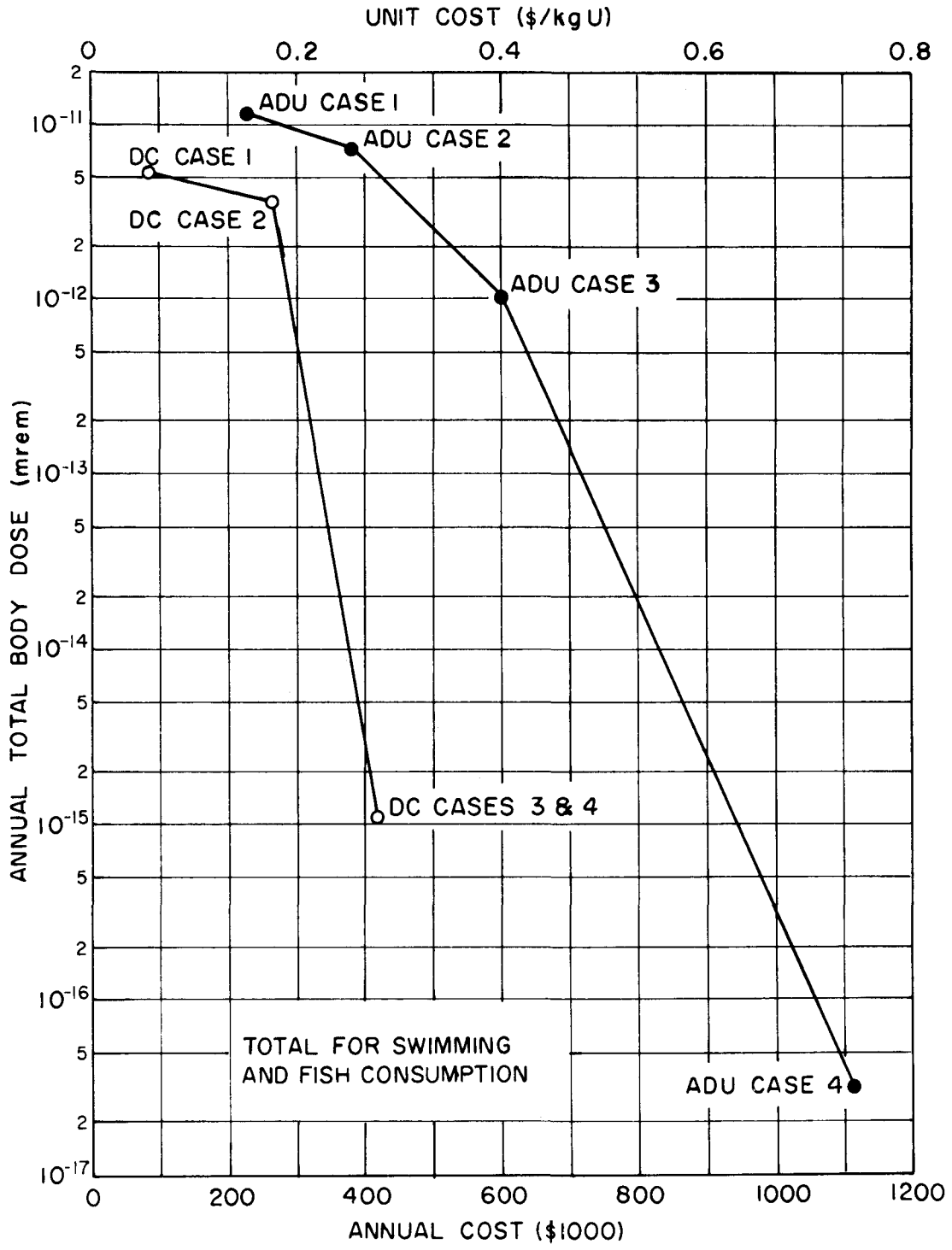


Fig. 8.7. Annual Cost for Reduction of Annual Total Body Dose from Liquid Effluents Diluted by Coastal Estuary from Model ADU and DC LWR Fuel Fabrication Plants at Coastal Site.

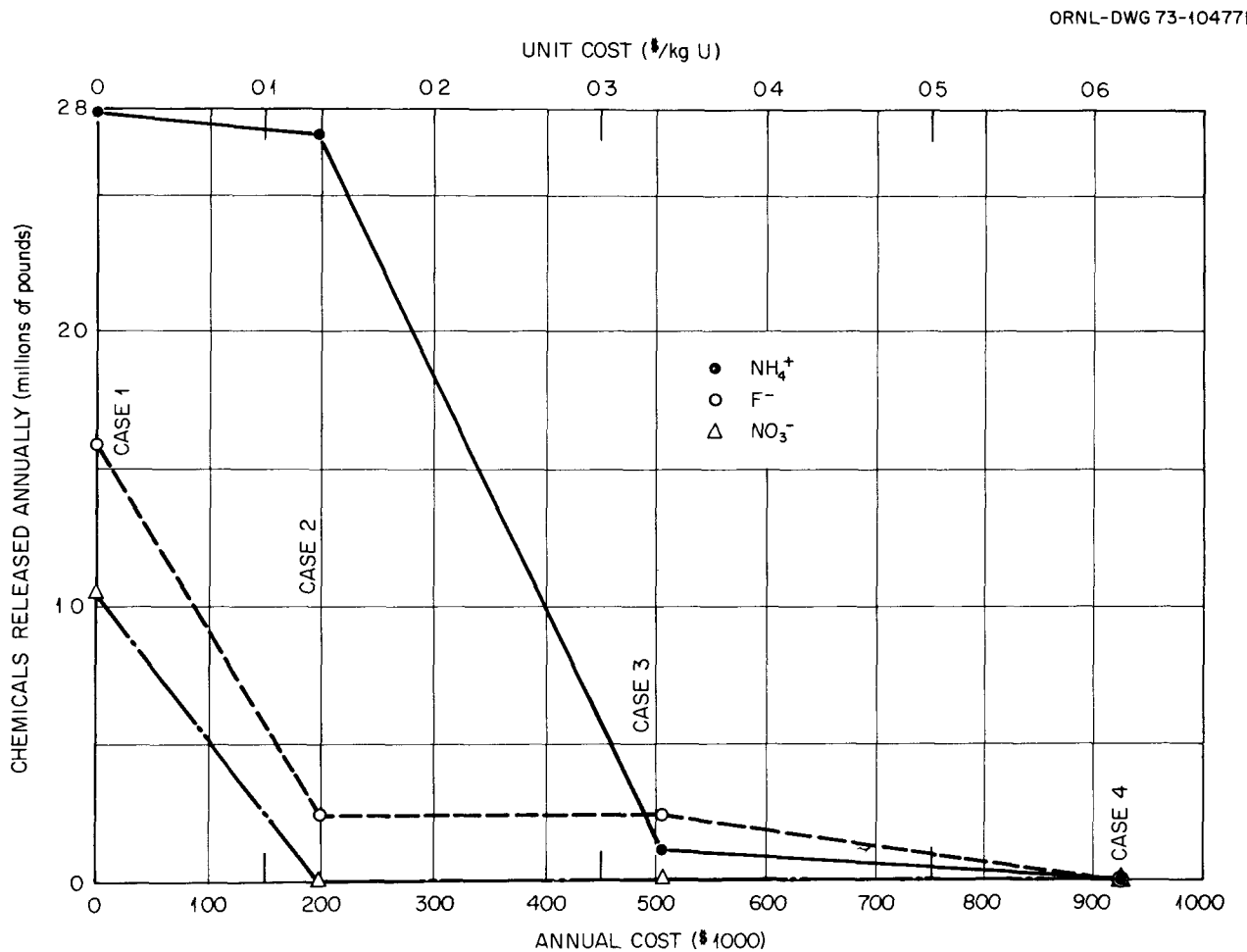


Fig. 8.8. Annual Cost for Reduction in Release of Chemical Wastes in the Liquid Effluent from Model ADU LWR Fuel Fabrication Plant.

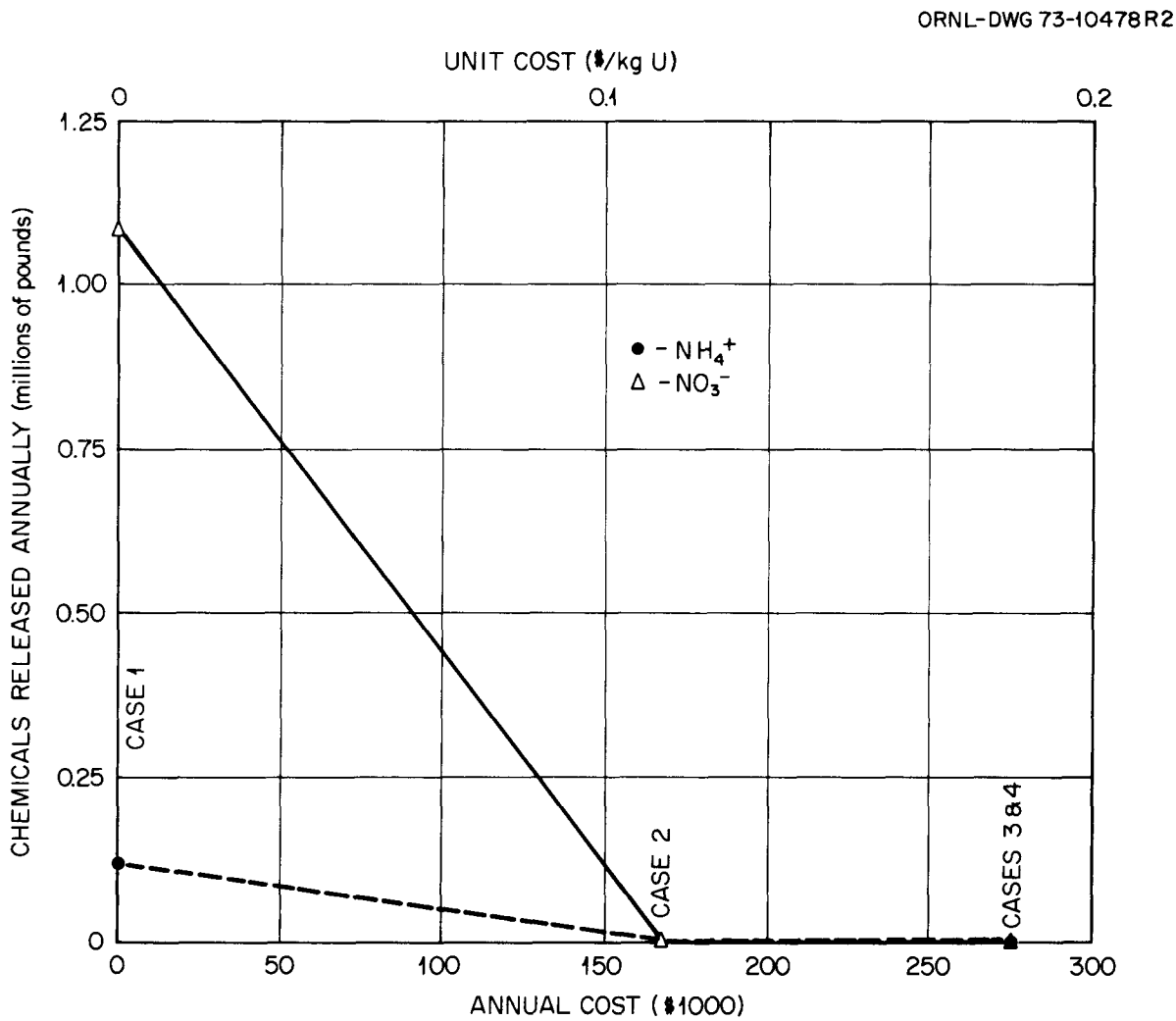


Fig. 8.9. Annual Cost for Reduction in Chemical Wastes in the Liquid Effluent from Model DC LWR Fuel Fabrication Plant.

APPENDIX A. PREPARATION OF COST ESTIMATES

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APPENDIX A. PREPARATION OF COST ESTIMATES — FABRICATION OF LIGHT-WATER REACTOR FUEL FROM ENRICHED URANIUM DIOXIDE

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1.0 INTRODUCTION

This Appendix presents the details of the methods used to estimate the capital costs of the installations required for treating the radioactive and chemical wastes from model enriched-uranium, light-water reactor fuel fabrication plants. The details of the methods used for estimating the annual fixed charges and annual operating costs are presented in Sect. 6.0 of the survey report. In summary, the total annual cost is obtained as the sum of the annual fixed charge (26% of the capital costs) and the annual operating cost (40% of the annual fixed charge). Additional operating costs are included to cover the cost of cement and the testing and replacing of HEPA filters. Operating costs are not included for operation of the lagoons or for ventilation ducts. This Appendix also describes the method used for prorating costs between the chemwaste and the radwaste treatment systems. Tables are included for each case which show the annual cost for decreasing the releases of F^-, NH_4^+, NO_3^- in the liquid and gaseous wastes for each equipment item.

The capital and annual costs for all of the radwaste treatment cases are summarized in Table A-1.

1.1 Capital Costs

The capital cost of the waste treatment cases is the sum of the direct 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 direct cost of the major equipment components was obtained for the most part from "Capital Cost Estimating" by K. M. Guthrie, Chemical Engineering, March 24, 1969.[1] The base cost for each equipment item

was obtained from the appropriate graph and multiplied by factors to allow for special design features, type of material, and the field installation factor for that type of equipment. The field installation factor includes material and labor for foundations, erection, normal piping, instruments, electrical, insulation, and paint. An escalation factor of 1.06 per year was used from 1968 to 1973.

1.1.2 Indirect Costs

Indirect costs are estimated as follows:

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

1.1.3 Method of Estimating Costs

The method used to estimate the cost of the individual equipment items is described for each treatment case. An equipment list, Tables A-2 to A-9, and flowsheet, Figures A-1 to A-8, are included for each case.

ADU Radwaste Treatment Case 1. — The flowsheet for ADU Case 1 is shown in Fig. A-1. The four systems, process, scrap recovery, recycle, and miscellaneous waste, consist of filtration and a lagoon for "holdup" of the liquid waste. Costs for the batching and sampling tanks were obtained from the storage tank graph in ref. 1. A factor of 1.85 was used for field installation. The pump costs were obtained from the centrifugal pump graph in ref 1. A factor of 2.41 was applied for field installation.

The rotary drum filter costs were obtained from the special equipment graph[1] using a unit cost of $\$1400/ft^2$, a size exponent of 0.63, and a field installation factor of 1.60.

The cost of the lagoons is based on the recent (1973) experience of the General Engineering Division at Oak Ridge National Laboratory.[2] The lagoons are constructed on flat land by removal of top soil, additional excavation and formation of embankments from the excavation material. ORNL costs are for lined and unlined lagoons of 1×10^6 gallon capacity. The costs that are used are based on volume factors.

Ventilation air flows were estimated to be 57,000 cfm from the process scrubber (2 ducts), 9000 cfm from the recycle scrubber, 1000 cfm from the scrap recovery scrubber, 1000 cfm from the incinerator, and 87,500 cfm (2 ducts) from the UO_2 pellet building. Case 1 does not include filtration. Ducts were assumed to be 100 ft long and costs were based on 1973 ORNL General Engineering Division experience.[2] Blower costs were obtained from the special equipment graph in ref. 1 using a unit cost of $\$7/ft^3$, a size exponent of 0.68, and a field installation factor of 1.59.

ADU Radwaste Treatment Case 2. — The flowsheet for ADU Case 2 is shown in Fig. A-2. In addition to Case 1 equipment, this case uses lime handling equipment, centrifuges, and HEPA filters. The lime conveyor costs were obtained from the special equipment graph in ref. 1 using a unit cost of \$230/ft, a size exponent of 0.90, and a field installation factor of 1.59. The centrifuge costs were also obtained from the special equipment graph using a unit cost of \$140/diam in., a size exponent of 1.25, and a field installation factor of 1.57.

The HEPA filter installation used in this case is of standard construction. Costs are based on 1973 ORNL General Engineering Division experience.[2] The cost of \$1000/1000 cfm includes leak testing of the filter housing. It is estimated that the filters would be replaced and tested with DOP twice each year. DOP testing would require 2 man-hours or \$30 per bank.[3] Filter replacement costs include labor and filter cost. Filter cost is \$38 per 1000-cfm unit. Labor costs are \$60 (4 man-hours) for 1000 cfm and \$480 (32 man-hours) for 50,000 cfm.[4]

This case also includes a lined, nitrate, storage lagoon for recycle and scrap recovery waste. There is no discharge from this lagoon. The cost of a new lagoon every 6 months is shown as an operating expense.

ADU Radwaste Treatment Case 3. — The flowsheet for ADU Case 3 is shown in Fig. A-3. In addition to equipment used in the two previous cases, ADU Case 3 includes ion exchange columns, an ammonia still and condenser, an acid evaporator and fractionating tower, a water evaporator and fluid bed calciner, a nitrate digestion plant, and a cement plant. A more efficient HEPA filter installation is specified.

The pressure vessel graph in ref. 1 is used to estimate the cost for the four ion exchange columns using a factor of 2.5 for stainless steel and 3.04 for field installation. The special equipment graph in ref. 1 is used for the ammonia still with a unit cost of $\$1200/ft^2$, a size exponent of 0.53, and a field installation factor of 1.90. The cost of the condensers is obtained from the heat-exchanger graph in ref. 1, with factors of 2.5 for stainless steel and 2.34 for field installation. The cost of the acid evaporator is obtained from the special equipment graph in ref. 1, using a unit cost of $\$1200/ft^2$, a size exponent of 0.53, and factors of 2.5 for stainless steel and 1.9 for field installation, respectively. The nitric acid fractionating tower used in the scrap recovery waste treatment system and recycle system was sized using Perry's Chemical Engineering Handbook, 4th Edition, Section 18, page 6. For 12-in. plate spacing, a maximum vapor velocity of 6 ft/sec was calculated. A 27-in.-diam tower is required for the $1400\text{-}ft^3/min$ water vapor flow rate from the two systems. The shell cost was obtained from the pressure vessel graph in ref. 1, using factors of 3.67 for stainless steel and 3.03 for field installation. The tray cost was estimated from the tray graph in ref. 1, using factors of 1.7 for stainless steel and 1.4 for 18-in. instead of 24-in. spacing of the trays. The water evaporator cost was obtained from the special equipment graph in ref. 1, using a unit cost of $\$1200/ft^2$, a size exponent of 0.53, and a field installation factor of 1.90.

The fluid bed calciner is a scale-up of the waste calciner used at the Idaho Chemical Processing Plant.[5] The same liquid feed rate per cross-sectional area and the same height-to-diameter ratio was used. The cost of the $3500\text{-}ft^2$ heat exchanger tubes was obtained from the heat exchanger graph in ref. 1, less the cost of an 8-ft-high shell. Factors

used for the tubes were 3.75 for stainless steel and 2.34 for the field installation. Factors of 3.67 for stainless steel and 3.03 for field installation were used for the 8-ft-diam by 21-ft-high shell.

The nitrate digestion plant consists of lime storage, conveyors, mixing tanks, two pumps, and a dilution and a digestion tank. Costs were obtained from the appropriate graphs in ref. 1.

The cement plant consists of a small, separate building, a cement storage tank, cement weigher, sludge hold tank, and a concrete mix tank with agitator. The plant is designed to handle 300 lbs of solid waste per day. The 1968 operating costs of \$250 per m^3 of waste (50% water) are based on costs at Los Alamos[6] which are somewhat higher than costs for the French and British plants.[6]

A high-efficiency HEPA filter installation is used in this case. A cost[2] of \$1500/1000 cfm was used to cover the cost of additional extensive leak testing and weld inspection. Additional operating costs of \$2100 are included to allow for monthly instead of semi-annual filter testing. An additional 50 ft of duct is also provided downstream of the filters to obtain improved gas mixing and increase the accuracy of sampling.

ADU Radwaste Treatment Case 4. — The flowsheet for ADU Case 4 is shown in Fig. A-4. ADU Case 4 is the same as ADU Case 3 with the exception that a centrifuge is used for removing the CaF_2 as a solid instead of storing it in a lined lagoon and the size of the cement plant is increased to handle this material (from 300 to 12,145 lbs/day). In addition, a second bank of HEPA filters is included in series with the first bank. Additional ductwork is required between the two banks. Testing and filter change costs are calculated in the same manner as in ADU Case 3.

DC Radwaste Treatment Case 1. — The flowsheet for DC Case 1 is shown in Fig. A-5. The scrap recovery, recycle, and miscellaneous waste systems are the same as in ADU Case 1. A $CaCO_3$ dry tower is used to remove HF and particulates from the off-gas. The superficial velocity of the gas is 1 ft/sec. The pressure vessel graph in ref. 1 is used to obtain the cost of the 2-ft-diam by 15-ft tower. The hydrogen burner cost was estimated by C. E. Sanders (ORNL). Ventilation costs are the same as ADU Case 1 less the cost of the process blowers and ducts (57,000 cfm).

DC Radwaste Treatment Case 2. — The flowsheet for DC Case 2 is shown in Fig. A-6. The scrap recovery, recycle, and miscellaneous waste systems are the same as for ADU Case 2. Gas from the process passes through a KOH scrubber to remove HF and uranium fluoride particulates. A decontamination factor of 82 is required in order to reduce the uranium concentration in the off-gas to the Radiation Concentration Guideline.[a] Assuming an efficiency of 50% per stage, a DF of 2 per stage would be required.

$$\frac{\ln 82}{\ln 2} = \frac{4.4}{0.7} = 6.3 \text{ stages}$$

A 7-stage scrubber is specified. Allowing 1 ft per stage and 5 ft for baffles and disengagement, a 12-ft-long Monel unit is required. A 12-in.-diam scrubber provides the same noncondensable gas residence time as the scrubber used in the ORNL Volatility Pilot Plant development work.[7] The pressure vessel graph from ref. 1 was used to estimate the costs with factors of 6.34 for Monel and 3.03 for field installation. The ventilation costs are the same as in ADU Case 1 less the cost of the ducts, blowers, and filters for the ADU process. An additional cost of $4000 is added for a duct and blower for air to dilute the hydrogen below the explosive limit. There are no HEPA filters in the process gas stream.

DC Radwaste Treatment Case 3. — The flowsheet for DC Case 3 is shown in Fig. A-7. The scrap recovery, recycle, and miscellaneous waste systems are the same as for ADU Case 3. The process gas treatment includes a Karbate condenser upstream of the scrubber to remove 90% of the HF prior to scrubbing. The condenser is the same as that used at the Paducah feed plant[8] for HF recovery. The required capacity is 600,000 Btu/hr vs 1,000,000 Btu/hr for the specified unit. The cost was obtained from the National Carbon Company and a factor of 2.34 was applied for field installation.

The HF concentration in the gas stream from the scrubber is low enough to permit the use of HEPA filters. HF-resistant filters made of silica are specified at about double the cost of the regular HEPA filters. Hydrogen is diluted with air as in DC Case 2.

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[a] Federal Code of Regulations, Title 10, Part 20, Appendix B, Table 2, Column 1.

Removal of the bulk of the HF before scrubbing reduces the amount of CaF_2 produced and the cost of disposal of the solid waste.

DC Radwaste Treatment Case 4. – The flowsheet for DC Case 4 is shown in Fig. A-8. The scrap recovery, recycle, and miscellaneous waste systems are the same as for ADU Case 4. The process gas stream passes through two Karbate condensers in series before the scrubber. The second condenser is cooled by a 2-ton refrigeration unit. The gas stream leaving the second condenser is cooled to 30°C and 99% of the HF is removed. The HF concentration in the gas stream from the scrubber is very low ($\sim 10^{-3}$ ppm). Consequently, the service life of the HEPA filters is expected to be significantly longer than in DC Case 3. The amount of CaF_2 produced is reduced from about 600 lbs/hr in DC Case 2 to 6 lb/hr in Case 4.

1.2 Cost Proration of Annual Costs

The costs for the waste treatment systems are divided into the cost for removal of radioactive materials and the cost for removal of noxious chemicals from the wastes. The cost of removing the radioactive materials from the wastes is further divided into the cost for treatment of the gaseous and liquid radwastes, and the cost for removal of the noxious chemicals is divided into costs for removal of fluoride, ammonia, and nitrate. The total annual costs have been prorated to the above categories, as shown in Tables A-10 through A-17, by assigning the costs associated with each equipment item to one or several of the objectives. All tanks are charged to radwaste treatment on the premise that they represent a redundancy not common to chemical operations. The cost of other equipment contributing to both chemwaste and radwaste treatment is apportioned 50% to radwaste and 50% to chemwaste. Chemwaste treatment costs are further prorated to the various species (NH_4^+, F^-, NO_3^-) on the basis of the relative weight of each species entering the system.

1.3 References

1. K. M. Guthrie, "Capital Cost Estimating," Chemical Engineering, March 24, 1969, pp. 114-42.
2. C. O. Kirby, General Engineering Division, ORNL, private communication, May 1973.
3. J. J. Smith, Inspection Engineering, ORNL, private communication, May 1973.
4. G. Johnstone, Plant and Equipment Maintenance Service, ORNL, private communication, May 1973.
5. G. E. Lohse and M. P. Hales, Second Processing Campaign in the Waste Calcining Facility, IN-1344 (March 1970).
6. Treatment of Low and Intermediate-Level Radwaste Concentrates, Technical Report Series No. 82, IAEA, Vienna, 1968, Appendix I-16, p. 98.
7. J. B. Ruch, UPP - Design Criteria for an Installation to Remove Hydrogen Fluoride and Fluorine from the Cells 1 and 2 Ventilation Gases Prior to Filtration, ORNL-CF-60-4-38 (April 1960).
8. Earl Richardson, Plant Engineering Department, Paducah Gaseous Diffusion Plant.

Table A-1. Summary of Capital and Annual Costs for Model Fuel Fabrication Plant Radwaste Treatment Cases ADU 1-4 and DC 1-4

	Cost ($1000)							
	ADU Case				DC Case			
	1	2	3	4	1	2	3	4
Direct Cost								
Process equipment	155	264	1128	1308	112	213	798	804
Ventilation	168	327	432	691	111	210	292	472
Lagoons	115	56	56	14	14	14	14	14
Building	12	29	66	66	7	29	66	66
Total direct cost	450	676	1682	2079	244	466	1170	1356
Indirect cost	631	943	2355	2911	342	653	1638	1898
Total capital	1081	1619	4037	4990	586	1119	2808	3254
Annual fixed charges	281	421	1050	1297	153	291	730	846
Annual operating and maintenance	59	391	365	1218	49	368	264	284
Total annual	340	812	1415	2515	202	659	994	1130

Table A-2. Installed Cost of Equipment for Waste Treatment System - ADU Case 1

Item No.	Item	Cost ($1000) Direct	Capital[a]
1	Batching tank, 90,000 gal	37	89
2	Centrifugal pump, 150 gpm	4	10
3	Rotary drum filter, 1/2 ft^2	2	5
4	Liquid waste pipeline, 12-in. diam, PV	16	38
5	Batching tank, 10,000 gal	17	41
6	Centrifugal pump, 12 gpm	2	5
7	Sump pump, 15 gpm	2	5
8	Sampling tanks (2), 25,000 gal	35	84
9	Centrifugal pump, 15 gpm	2	5
10	Rotary drum filter, 1 ft^2	3	7
11	Liquid waste pipeline, 1-in. diam, SS	10	24
12	Tank, 250 gal, SS	8	19
13	Centrifugal pump, 5 gpm, SS	3	7
14	Lagoon, unlined, holding, 1.2×10^7 gal	115	276
15	Lagoon, unlined, equalization, 3.6×10^5 gal	14	34
16	Processing building, 25 ft x 25 ft	12	29
17	Ventilation - Ducts	83	199
18	Blowers	85	204
	TOTAL	450	1081

[a]Capital cost is sum of direct and indirect costs.

Table A-3. Installed Cost of Equipment for Waste Treatment System - ADU Case 2

Item No.	Item	Cost ($1000) Direct	Capital[a]
1	Batching tank, 90,000 gal	37	89
2	Hold tank, 90,000 gal	40	96
3	Batching tank, 10,000 gal	17	41
4	Sampling tanks (2), 25,000 gal	35	84
5	Tank, 250 gal, SS	8	19
6	Hold tank, 10,000 gal	20	48
7	Centrifugal pump, 150 gpm	4	10
8	Centrifugal pump, 12 gpm	2	5
9	Centrifugal pump, 75 gpm	3	7
10	Sump pump, 15 gpm	2	5
11	Centrifugal pump, 15 gpm	2	5
12	Centrifugal pump, 5 gpm, SS	3	7
13	Centrifuge, 24 in.	21	50
14	Centrifuge, 20 in.	17	36
15	Rotary drum filter, 1/2 ft^2 (2)	4	10
16	Rotary drum filter, 1 ft^2	3	7
17	Liquid waste pipeline, 12-in. diam, PV	16	38
18	Liquid waste pipeline, 1-in. diam, SS	10	24
19	Lime storage tank, 750 ft^3	10	24
20	Lime screw conveyors (2)	6	15
21	Lime mix tanks (2)	4	10
22	Lagoon, lined, fluoride precipitation, 1.4×10^6 gal	42	100
23	Lagoon, unlined, equalization, 3.6×10^5 gal	14	34
24	Processing building, 40 ft x 40 ft	29	70
25	Ventilation - Ducts	83	199
26	Blowers	85	204
27	HEPA filters	159	382
28	Lagoons, lined, storage, 1.4×10^6 gal[b]	0	0
	TOTAL	676	1619

[a]Capital cost is the sum of direct and indirect costs.

[b]Cost of a new lagoon every six months ($141,300) is considered as an operating cost and is shown in Tables A-10 through A-17.

Table A-4. Installed Cost of Equipment for Waste Treatment System - ADU Case 3

Item No.	Item	Cost ($1000) Direct	Capital[a]
1	Batching tank, 90,000 gal	37	89
2	Hold tank, 90,000 gal	40	96
3	Batching tank, 10,000 gal	17	41
4	Hold tank, 10,000 gal	20	48
5	Sampling tanks, 25,000 gal (2)	35	84
6	Acid tanks, 250 gal, SS (2)	16	38
7	Centrifugal pump, 150 gpm	4	10
8	Centrifugal pump, 75 gpm	3	7
9	Centrifugal pump, 12 gpm (2)	4	10
10	Centrifugal pump, 15 gpm	2	5
11	Centrifugal pumps, 5 gpm, SS (2)	6	14
12	Sump pump, 15 gpm	2	5
13	Centrifuge, 24 in.	21	50
14	Centrifuge, 20 in.	17	36
15	Rotary drum filters, 1/2 ft^2 (2)	4	10
16	Rotary drum filter, 1 ft^2	3	7
17	Liquid waste pipeline, 12 in. PV	16	38
18	Lime storage tank, 750 ft^3	10	24
19	Lime screw conveyor	3	7
20	Lime mix tank	2	5
21	Ion exchange columns, 11 in. diam x 20 ft, SS (4)	48	115
22	Ammonia still, 10 ft^2, SS	185	444
23	Condenser, 125 ft^2	8	19
24	Condensers, 50 ft^2, SS (2)	30	72
25	Fluidized bed calciner, 8 ft diam x 21 ft, SS	351	842
26	Air blowers, 675 scfm, 3 psi (2)	3	7
27	Cyclone separator	2	5
28	Water evaporator, 200 ft^2	55	132
29	Acid evaporator, 70 ft^2, SS	90	216
30	Acid fractionating tower, 27 in. diam x 40 ft, SS	57	137
31	Lagoon, lined, fluoride precipitation, 1.4×10^6 gal	42	100
32	Lagoon, unlined, equalization, 3.6×10^5 gal	14	34
33	Cement plant	12	29
34	Nitrate digestion plant	25	61
35	Processing building, 60 ft x 60 ft	66	158
36	Ventilation - Ducts	107	257
37	Blowers	85	204
38	HEPA filters	240	576
	TOTAL	1682	4037

[a]Capital cost is sum of direct and indirect costs.

Table A-5. Installed Cost of Equipment for Waste Treatment System - ADU Case 4

Item No.	Item	Cost ($1000) Direct	Capital[a]
1	Batching tank, 90,000 gal	37	89
2	Hold tank, 90,000 gal	40	96
3	Batching tank, 10,000 gal	17	41
4	Hold tank, 10,000 gal	20	48
5	Sampling tanks, 25,000 gal (2)	35	84
6	Acid tanks, 250 gal, SS (2)	16	38
7	Centrifugal pump, 150 gpm	4	10
8	Centrifugal pump, 75 gpm	3	7
9	Centrifugal pumps, 12 gpm (2)	4	10
10	Centrifugal pump, 15 gpm	2	5
11	Centrifugal pumps, 5 gpm, SS (2)	6	14
12	Sump pump, 15 gpm	2	5
13	Centrifuge, 24 in. (very dilute slurry)	21	50
14	Centrifuge, 20 in. (very dilute slurry)	17	36
15	Rotary drum filters, 1/2 ft^2 (2)	4	10
16	Rotary drum filter, 1 ft^2	3	7
17	Lime storage tank, 750 ft^3	10	24
18	Lime screw conveyor	3	7
19	Lime mix tank	2	3
20	Ammonia still, 200 ft^2, SS	185	443
21	Condensers, 50 ft^2, SS (2)	30	72
22	Water evaporator, 1000 ft^2	122	293
23	Water evaporator, 200 ft^3	55	132
24	Condenser, 500 ft^2	19	46
25	Centrifuge (1.7% slurry - Westinghouse cost)	50	120
26	Cement plant	20	48
27	Fluidized bed calciner, 8 ft diam x 21 ft, SS	351	842
28	Air blowers, 675 scfm, 3 psi (2)	3	7
29	Cyclone separator	2	5
30	Condenser, 125 ft^2	8	19
31	Nitrate digestion plant	25	61
32	Acid fractionating tower, 27 in. diam x 40 ft, SS	57	137
33	Acid evaporator, 70 ft^2, SS	90	216
34	Ion exchange columns, 11 in. diam x 20 ft, SS (4)	48	115
35	Lagoon, unlined, equalization, 3.6 x 10^5 gal	14	34
36	Processing building, 60 ft x 60 ft	66	158
37	Ventilation - Ducts	129	309
38	Blowers	85	204
39	HEPA filters	477	1145
	TOTAL	2079	4992

[a]Capital cost is sum of direct and indirect costs.

Table A-6. Installed Cost of Equipment for Waste Treatment System - DC Case 1

Item No.	Item	Cost ($1000) Direct	Capital[a]
1	Limestone tower, 2 ft diam x 15 ft	8	19
2	Hydrogen burner	4	10
3	Batching tank, 10,000 gal	17	41
4	Sampling tanks, 25,000 gal (2)	35	84
5	Acid tank, 250 gal, SS	8	19
6	Centrifugal pump, 12 gpm	2	5
7	Centrifugal pump, 15 gpm	2	5
8	Centrifugal pump, 5 gpm, SS	3	7
9	Sump pump, 15 gpm	2	5
10	Rotary drum filter, 1/2 ft^2	2	5
11	Rotary drum filter, 1 ft^2	3	7
12	Liquid waste pipeline, 12 in. diam, PV	16	38
13	Liquid waste pipeline, 1 in. diam, SS	10	24
14	Lagoon, unlined, equalization, 3.6 x 10^3 gal	14	34
15	Processing building, 20 ft x 20 ft	7	17
16	Ventilation - Ducts	50	120
17	Blowers	61	146
	TOTAL	244	586

[a]Capital cost is sum of direct and indirect costs.

Table A-7. Installed Cost of Equipment for Waste Treatment System - DC Case 2

Item No.	Item	Cost ($1000) Direct	Capital[a]
1	HF scrubber, 1 ft diam x 12 ft, Monel	15	36
2	KOH tanks, 750 gal, steel (2)	16	38
3	Lime storage tank, 500 ft^3	9	22
4	Centrifugal pump, 50 gpm, 60 psig	3	7
5	Centrifugal pumps, 50 gpm, 30 psig (2)	4	10
6	Lime conveyor (2)	6	14
7	Lime mix tank, 2000 gal	5	12
8	Agitator, 5 hp	2	5
9	Batching tank, 10,000 gal	17	41
10	Sampling tanks, 25,000 gal (2)	35	84
11	Tank, 250 gal, SS	8	19
12	Hold tank, 10,000 gal	20	48
13	Centrifugal pump, 12 gpm	2	5
14	Sump pump, 15 gpm	2	5
15	Centrifugal pump, 15 gpm	2	5
16	Centrifugal pump, 5 gpm, SS	3	7
17	Centrifuge, 20 in.	17	40
18	Rotary drum filter, 1/2 ft^2	2	5
19	Rotary drum filter, 1 ft^2	3	7
20	Rotary drum filter, 10 ft^2	14	34
21	Liquid waste pipeline, 12 in. PV	16	38
22	Liquid waste pipeline, 1 in. SS	10	24
23	Lime mix tank	2	5
24	Lagoon, unlined, equalization, 3.6 x 10^6 gal	14	34
25	Processing building, 40 ft x 40 ft	29	70
26	Ventilation - Ducts	50	120
27	Blowers	58	139
28	HEPA filters	102	245
29	Lagoon, lined, storage, 1.4 x 10^6 gal[b]	0	0
	TOTAL	466	1118

[a]Capital cost is sum of direct and indirect costs.

[b]Cost of a new lagoon every six months ($141,300) is considered as an operating cost and is shown in Tables A-10 to A-17.

Table A-8. Installed Cost of Equipment for Waste Treatment System - DC Case 3

Item No.	Item	Cost ($1000) Direct	Capital[a]
1	HF scrubber, 1 ft diam x 12 ft, Monel	15	36
2	HF condenser, 115 ft^2, Karbate	6	14
3	HF tanks, 500 gal, lead-lined (2)	10	24
4	KOH tanks, 750 gal, steel (2)	16	38
5	Centrifugal pump, 50 gpm, 60 psig	3	7
6	Centrifugal pump, 50 gpm, 30 psig	2	5
7	Centrifugal pump, 5 gpm, 30 psig	2	5
8	Lime storage tank, 50 ft^3	3	7
9	Lime conveyor	3	7
10	Lime mix tank, 200 gal	3	7
11	Agitator, 1 hp	1	2
12	Rotary drum filters, 1 ft^2 (2)	6	14
13	Batching tank, 10,000 gal	17	41
14	Hold tank, 10,000 gal	20	48
15	Sampling tanks, 25,000 gal (2)	35	84
16	Acid tank, 250 gal, SS	8	19
17	Centrifugal pumps, 12 gpm (2)	4	10
18	Centrifugal pump, 15 gpm	2	2
19	Sump pump, 15 gpm	2	5
20	Centrifugal pump, 5 gpm, SS	3	7
21	Centrifuge, 20 in.	17	41
22	Rotary drum filter, 1/2 ft^2	2	5
23	Fluidized bed calciner, 8 ft diam x 21 ft, SS	351	842
24	Air blowers, 675 scfm, 3 psi (2)	3	7
25	Cyclone separator	2	5
26	Condenser, 50 ft^2, SS	15	36
27	Condenser, 125 ft	8	19
28	Water evaporator, 200 ft^2	55	132
29	Acid evaporator, 70 ft^2	90	216
30	Acid fractionating tower, 27 in. diam x 40 ft, SS	57	137
31	Nitrate digestion plant	25	61
32	Cement plant	12	29
33	Lagoon, unlined, equalization, 3.6 x 10^6 gal	14	34
34	Processing building, 60 ft x 60 ft	66	158
35	Ventilation - Ducts	66	158
36	Blowers	58	139
37	HEPA filters	168	404
	TOTAL	1170	2808

[a]Capital cost is sum of direct and indirect costs.

Table A-9. Installed Cost of Equipment for Waste Treatment System - DC Case 4

Item No.	Item	Cost ($1000) Direct	Capital[a]
1	HF scrubber, 1 ft diam x 12 ft, Monel	15	36
2	HF condensers, 115 ft^2, Karbate (2)	12	29
3	Refrigeration unit, 2 ton with brine tank and pump	5	12
4	HF tanks, 500 gal, lead-lined (2)	10	24
5	KOH tanks, 750 gal, steel (2)	16	38
6	Centrifugal pump, 50 gpm, 60 psig	3	7
7	Centrifugal pump, 50 gpm, 30 psig	2	5
8	Centrifugal pump, 1 gpm, 30 psig	1	2
9	Lime storage, 5 ft^3	2	5
10	Lime conveyor	3	7
11	Lime mix tank with agitator	2	5
12	Rotary drum filters, 1/2 ft^2 (2)	4	10
13	Batching tank, 10,000 gal	17	41
14	Hold tank, 10,000 gal	10	48
15	Sampling tanks, 25,000 gal (2)	35	84
16	Acid tank, 250 gal, SS	8	19
17	Centrifugal pumps, 12 gpm (2)	4	10
18	Centrifugal pump, 15 gpm	2	5
19	Centrifugal pump, 5 gpm, SS	3	7
20	Sump pump, 15 gpm	2	5
21	Rotary drum filter, 1 ft^2	3	7
22	Centrifuge, 20 in.	17	41
23	Fluidized bed calciner, 8 ft diam x 21 ft, SS	351	842
24	Air blowers, 675 scfm, 3 psi (2)	3	7
25	Cyclone separator	2	5
26	Condenser, 50 ft^2, SS	15	36
27	Water evaporator, 200 ft^2	55	132
28	Condenser, 125 ft^2	8	19
29	Acid evaporator, 70 ft^2	90	216
30	Acid fractionating tower, 27 in. diam x 40 ft, SS	57	137
31	Nitrate digestion plant	25	60
32	Cement plant	12	29
33	Lagoon, unlined, equalization, 3.6×10^6 gal	14	34
34	Processing building, 60 ft x 60 ft	66	158
35	Ventilation - Ducts	81	194
36	Blowers	58	139
37	HEPA filters	333	800
	TOTAL	1356	3254

[a]Capital cost is sum of direct and indirect costs.

Table A-10. Annual Cost for Treatment of Chemwaste and Radwaste - ADU Case 1

Equipment Item (Table A-2)	Chemwaste Cost ($1000)				Radwaste Cost ($1000)			Total Cost ($1,000)
	Fluoride	Ammonia	Nitrate	Total	Liquid	Gaseous	Total	
1	0	0	0	0	29	0	29	29
2	0	0	0	0	4	0	4	4
3	0	0	0	0	2	0	2	2
4	0	0	0	0	13	0	13	13
5	0	0	0	0	14	0	14	14
6	0	0	0	0	2	0	2	2
7	0	0	0	0	2	0	2	2
8	0	0	0	0	14	0	14	14
9	0	0	0	0	14	0	14	14
10	0	0	0	0	2	0	2	2
11	0	0	0	0	2	0	2	2
12	0	0	0	0	8	0	8	8
13	0	0	0	0	7	0	7	7
14	0	0	0	0	2	0	2	2
15	0	0	0	0	9	0	9	9
16	0	0	0	0	90	0	90	90
17	0	0	0	0	0	52	52	52
18	0	0	0	0	0	74	74	74
Total	0	0	0	0	214	126	340	340

Table A-11. Annual Cost for Treatment of Chemwaste and Radwaste - ADU Case 2

Equipment Item (Table A-3)	Chemwaste Cost ($1000)				Radwaste Cost ($1000)			Total Cost ($1,000)
	Fluoride	Ammonia	Nitrate	Total	Liquid	Gaseous	Total	
1	0	0	0	0	34	0	34	34
2	0	0	0	0	38	0	38	38
3	0	0	0	0	15	0	15	15
4	0	0	0	0	15	0	15	15
5	0	0	0	0	15	0	15	15
6	0	0	0	0	7	0	7	7
7	2	0	0	2	2	0	2	4
8	0	1	1	2	1	0	1	3
9	1	0	0	1	1	0	1	2
10	0	0	0	0	2	0	2	2
11	0	0	0	0	2	0	2	2
12	0	0	1	1	1	0	1	2
13	0	0	0	0	19	0	19	19
14	0	0	0	0	13	0	13	13
15	0	0	0	0	4	0	4	4
16	0	0	0	0	3	0	3	3
17	5	0	0	5	8	0	8	13
18	0	0	4	4	4	0	4	8
19	4	0	0	4	4	0	4	8
20	1	0	0	1	3	0	3	4
21	1	0	2	3	2	0	2	5
22	17	0	0	17	33	0	33	50
23	0	0	0	0	8	0	8	8
24	8	0	1	9	15	0	15	24
25	0	0	0	0	0	51	51	51
26	0	0	0	0	0	72	72	72
27	0	0	0	0	0	112	112	112
28	0	20	119	139	140	0	140	279
Total	39	21	128	188	389	235	624	812

Table A-12. Annual Cost for Treatment of Chemwaste and Radwaste — ADU Case 3

Equipment Item (Table A-4)	Chemwaste Cost ($1000)				Radwaste Cost ($1000)			Total Cost ($1000)
	Fluoride	Ammonia	Nitrate	Total	Liquid	Gaseous	Total	
1	0	0	0	0	32	0	32	32
2	0	0	0	0	35	0	35	35
3	0	0	0	0	15	0	15	15
4	0	0	0	0	18	0	18	18
5	0	0	0	0	31	0	31	31
6	0	0	0	0	14	0	14	14
7	1	1	0	2	2	0	2	4
8	1	0	0	1	1	0	1	2
9	0	1	2	3	2	0	2	5
10	0	0	0	0	2	0	2	2
11	0	0	3	3	3	0	3	6
12	0	0	0	0	2	0	2	2
13	0	0	0	0	18	0	18	18
14	0	0	0	0	13	0	13	13
15	0	0	0	0	4	0	4	4
16	0	0	0	0	3	0	3	3
17	7	0	0	7	7	0	7	14
18	2	3	0	5	4	0	4	9
19	0	1	0	1	1	0	1	2
20	0	0	0	0	1	0	1	1
21	0	0	0	0	42	0	42	42
22	0	166	0	166	0	0	0	166
23	0	7	0	7	0	0	0	7
24	0	0	7	7	20	0	20	27
25	0	24	139	163	153	0	153	316
26	0	0	1	1	1	0	1	2
27	0	0	1	1	1	0	1	2
28	0	0	0	0	48	0	48	48
29	0	0	42	42	39	0	39	81
30	0	4	23	27	25	0	25	52
31	16	0	0	16	18	0	18	34
32	0	0	0	0	11	0	11	11
33	6	0	0	6	8	0	8	14
34	0	0	24	24	0	0	0	24
35	8	13	2	23	27	0	27	50
36	0	0	0	0	0	67	67	67
37	0	0	0	0	0	74	74	74
38	0	0	0	0	0	168	168	168
Total	41	220	244	505	601	309	910	1415

Table A-13. Annual Cost for Treatment of Chemwaste and Radwaste — ADU Case 4

Equipment Item (Table A-5)	Chemwaste Cost ($1000)				Radwaste Cost ($1000)			Total Cost ($1000)
	Fluoride	Ammonia	Nitrate	Total	Liquid	Gaseous	Total	
1	0	0	0	0	32	0	32	32
2	0	0	0	0	35	0	35	35
3	0	0	0	0	15	0	15	15
4	0	0	0	0	18	0	18	18
5	0	0	0	0	31	0	31	31
6	0	0	0	0	14	0	14	14
7	1	1	0	2	2	0	2	4
8	0	0	0	0	1	0	1	2
9	0	1	2	3	2	0	2	5
10	0	0	0	0	2	0	2	2
11	0	0	3	3	3	0	3	6
12	0	0	0	0	2	0	2	2
13	0	0	0	0	18	0	18	18
14	0	0	0	0	13	0	13	13
15	0	0	0	0	2	0	2	0
16	0	0	0	0	3	0	3	3
17	0	3	0	3	4	0	4	7
18	0	1	0	1	1	0	1	2
19	0	0	0	0	1	0	1	1
20	0	166	0	166	0	0	0	166
21	0	0	0	0	20	0	20	20
22	17	0	0	17	63	0	63	80
23	0	0	0	0	48	0	48	48
24	3	0	0	3	17	0	17	20
25	39	0	0	39	0	0	0	0
26	380	0	0	380	450	0	450	450
27	0	24	139	163	153	0	153	316
28	0	0	1	1	1	0	1	2
29	0	0	1	1	1	0	1	2
30	0	7	7	14	0	0	0	14
31	0	0	24	24	0	0	0	24
32	0	4	23	27	25	0	25	52
33	0	0	42	42	44	0	44	86
34	0	0	0	0	42	0	42	42
35	13	0	0	13	21	0	21	34
36	7	13	2	22	30	0	30	52
37	0	0	0	0	0	67	67	67
38	0	0	0	0	0	74	74	74
39	0	0	0	0	0	336	336	336
Total	460	220	244	924	1114	477	1591	2515

Table A-14. Annual Cost for Treatment of Chemwaste and Radwaste — DC Case 1

Equipment Item (Table A-6)	Chemwaste Cost ($1000)				Radwaste Cost ($1000)			Total Cost ($1000)
	Fluoride	Ammonia	Nitrate	Total	Liquid	Gaseous	Total	
1	3	0	0	3	0	4	4	7
2	0	0	0	0	0	4	4	4
3	0	0	0	0	13	0	0	13
4	0	0	0	0	26	0	26	26
5	0	0	0	0	7	0	7	7
6	0	0	0	0	2	0	2	2
7	0	0	0	0	2	0	2	2
8	0	0	0	0	2	0	2	2
9	0	0	0	0	2	0	2	2
10	0	0	0	0	2	0	2	2
11	0	0	0	0	2	0	2	2
12	0	0	0	0	14	0	14	14
13	0	0	0	0	9	0	9	9
14	0	0	0	0	8	0	8	8
15	0	0	0	0	6	0	6	6
16	2	0	0	2	0	34	34	36
17	3	0	0	3	0	57	57	60
Total	8	0	0	8	95	99	194	202

Table A-15. Annual Cost for Treatment of Chemwaste and Radwaste — DC Case 2

Equipment Item (Table A-7)	Chemwaste Cost ($1000)				Radwaste Case ($1000)			Total Cost ($1000)
	Fluoride	Ammonia	Nitrate	Total	Liquid	Gaseous	Total	
1	3	0	0	3	0	10	10	13
2	3	0	0	3	0	11	11	14
3	2	0	0	2	0	6	6	8
4	1	0	0	1	0	2	2	3
5	1	0	0	1	0	2	2	3
6	1	0	0	1	0	3	3	4
7	1	0	0	1	0	3	3	4
8	0	0	0	0	0	1	1	1
9	0	0	0	0	15	0	15	15
10	0	0	0	0	31	0	31	31
11	0	0	0	0	7	0	7	7
12	0	0	0	0	18	0	18	18
13	0	0	1	1	1	0	1	2
14	0	0	0	0	2	0	2	2
15	0	0	0	0	2	0	2	2
16	0	0	1	1	1	0	1	2
17	0	0	0	0	14	0	14	14
18	0	0	0	0	2	0	2	2
19	0	0	0	0	2	0	2	2
20	4	0	0	4	8	0	8	12
21	5	0	0	5	8	0	8	13
22	0	0	4	4	5	0	5	9
23	0	0	1	1	1	0	1	2
24	0	0	0	0	4	0	4	4
25	5	0	0	5	5	15	20	25
26	0	0	0	0	0	34	34	34
27	0	0	0	0	0	57	57	57
28	0	0	0	0	0	75	75	75
29	0	20	134	154	127	0	127	281
Total	26	20	141	187	253	219	472	659

Table A-16. Annual Cost for Treatment of Chemwaste and Radwaste – DC Case 3

Equipment Item (Table A-8)	Chemwaste Cost ($1000)				Radwaste Cost ($1000)			Total Cost ($1000)
	Fluoride	Ammonia	Nitrate	Total	Liquid	Gaseous	Total	
1	3	0	0	3	0	10	10	13
2	2	0	0	2	0	3	3	5
3	3	0	0	3	0	6	6	9
4	4	0	0	4	0	9	9	13
5	1	0	0	1	0	1	1	2
6	1	0	0	1	0	1	1	2
7	1	0	0	1	0	1	1	2
8	1	0	0	1	0	1	1	2
9	1	0	0	1	0	1	1	2
10	1	0	0	1	0	1	1	2
11	0	0	0	0	0	1	1	1
12	2	0	0	2	0	3	3	5
13	0	0	0	0	15	0	15	15
14	0	0	0	0	17	0	17	17
15	0	0	0	0	30	0	30	30
16	0	0	0	0	7	0	7	7
17	0	0	2	2	2	0	2	4
18	0	0	0	0	2	0	2	2
19	0	0	0	0	2	0	2	2
20	0	0	2	2	1	0	1	3
21	0	0	0	0	15	0	15	15
22	0	0	0	0	2	0	2	2
23	0	20	139	159	150	0	150	309
24	0	0	1	1	1	0	1	2
25	0	0	1	1	1	0	1	2
26	0	0	7	7	7	0	7	14
27	0	7	0	7	0	0	0	7
28	0	0	0	0	48	0	48	48
29	0	0	42	42	39	0	39	81
30	0	4	23	27	23	0	23	50
31	0	0	24	24	0	0	0	24
32	0	0	0	0	7	3	10	10
33	5	0	0	5	30	0	30	35
34	5	0	3	8	28	14	42	50
35	0	0	0	0	0	41	41	41
36	0	0	0	0	0	51	51	51
37	0	0	0	0	0	115	115	115
Total	30	31	244	305	427	262	689	994

Table A-17. Annual Cost for Treatment of Chemwaste and Radwaste — DC Case 4

Equipment Item (Table A-9)	Chemwaste Cost ($1000)				Radwaste Cost ($1000)			Total Cost ($1000)
	Fluoride	Ammonia	Nitrate	Total	Liquid	Gaseous	Total	
1	3	0	0	3	0	10	10	13
2	4	0	0	4	0	7	7	11
3	2	0	0	2	0	4	4	6
4	3	0	0	3	0	6	6	9
5	4	0	0	4	0	11	11	15
6	2	0	0	2	0	1	1	3
7	1	0	0	1	0	1	1	2
8	1	0	0	1	0	0	0	1
9	1	0	0	1	0	1	1	2
10	2	0	0	2	0	1	1	3
11	1	0	0	1	0	1	1	2
12	2	0	0	2	0	3	3	5
13	0	0	0	0	15	0	15	15
14	0	0	0	0	17	0	17	17
15	0	0	0	0	30	0	30	30
16	0	0	0	0	7	0	7	7
17	0	0	2	2	2	0	2	4
18	0	0	0	0	2	0	2	2
19	0	0	2	2	1	0	1	2
20	0	0	0	0	2	0	2	2
21	0	0	0	0	2	0	2	2
22	0	0	0	0	15	0	15	15
23	0	20	139	159	150	0	150	309
24	0	0	1	1	1	0	1	2
25	0	0	1	1	1	0	1	2
26	0	0	7	7	7	0	7	14
27	0	0	0	0	48	0	48	48
28	0	7	0	7	0	0	0	7
29	0	0	42	42	39	0	39	81
30	0	4	23	27	23	0	23	50
31	0	0	24	24	0	0	0	24
32	0	0	0	0	7	3	10	10
33	5	0	0	5	30	0	30	35
34	9	0	3	12	28	15	43	55
35	0	0	0	0	0	41	41	41
36	0	0	0	0	0	51	51	51
37	0	0	0	0	0	232	232	232
Total	40	31	244	315	427	388	815	1130

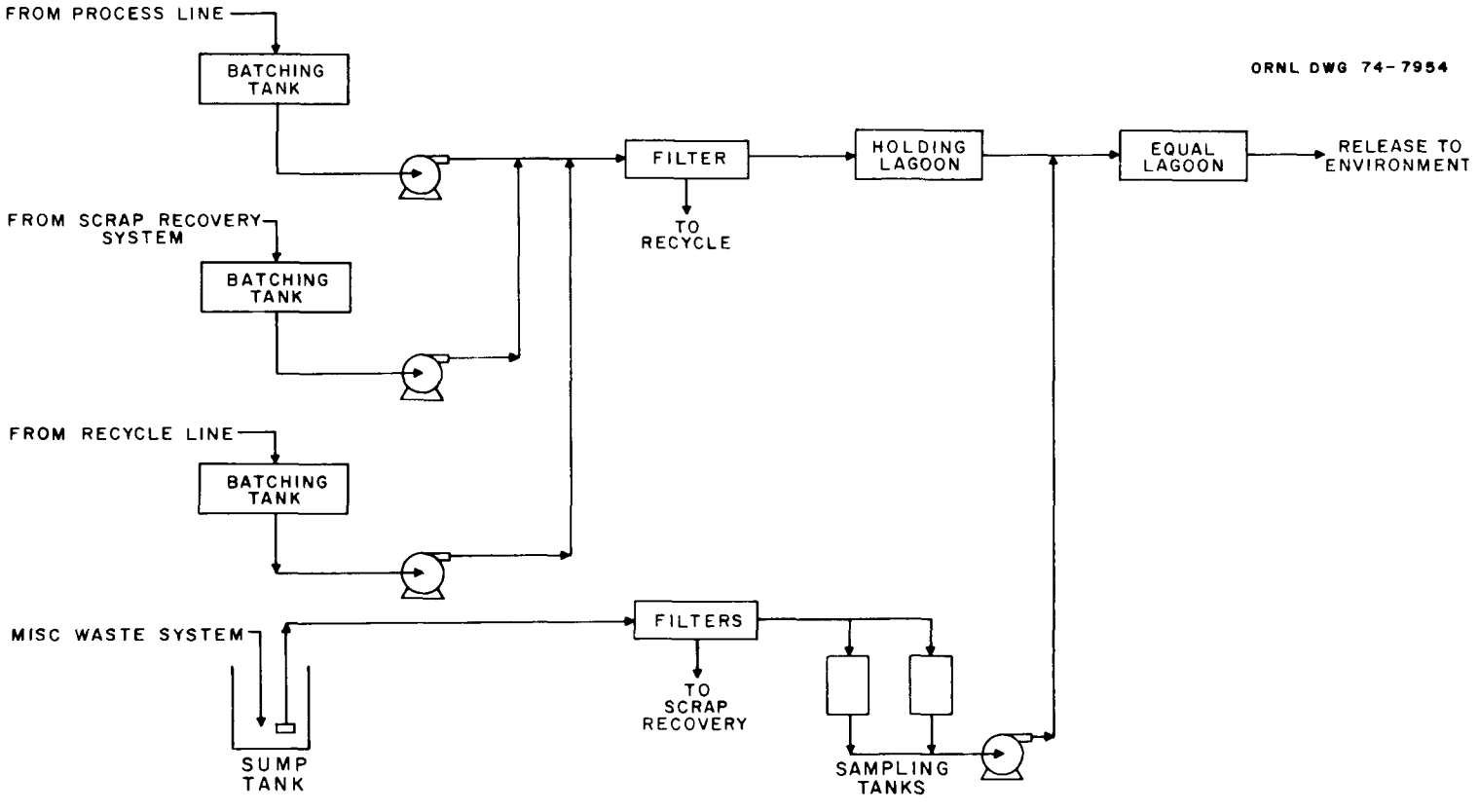

Fig. A-1. ADU Radwaste Treatment System - Case 1.

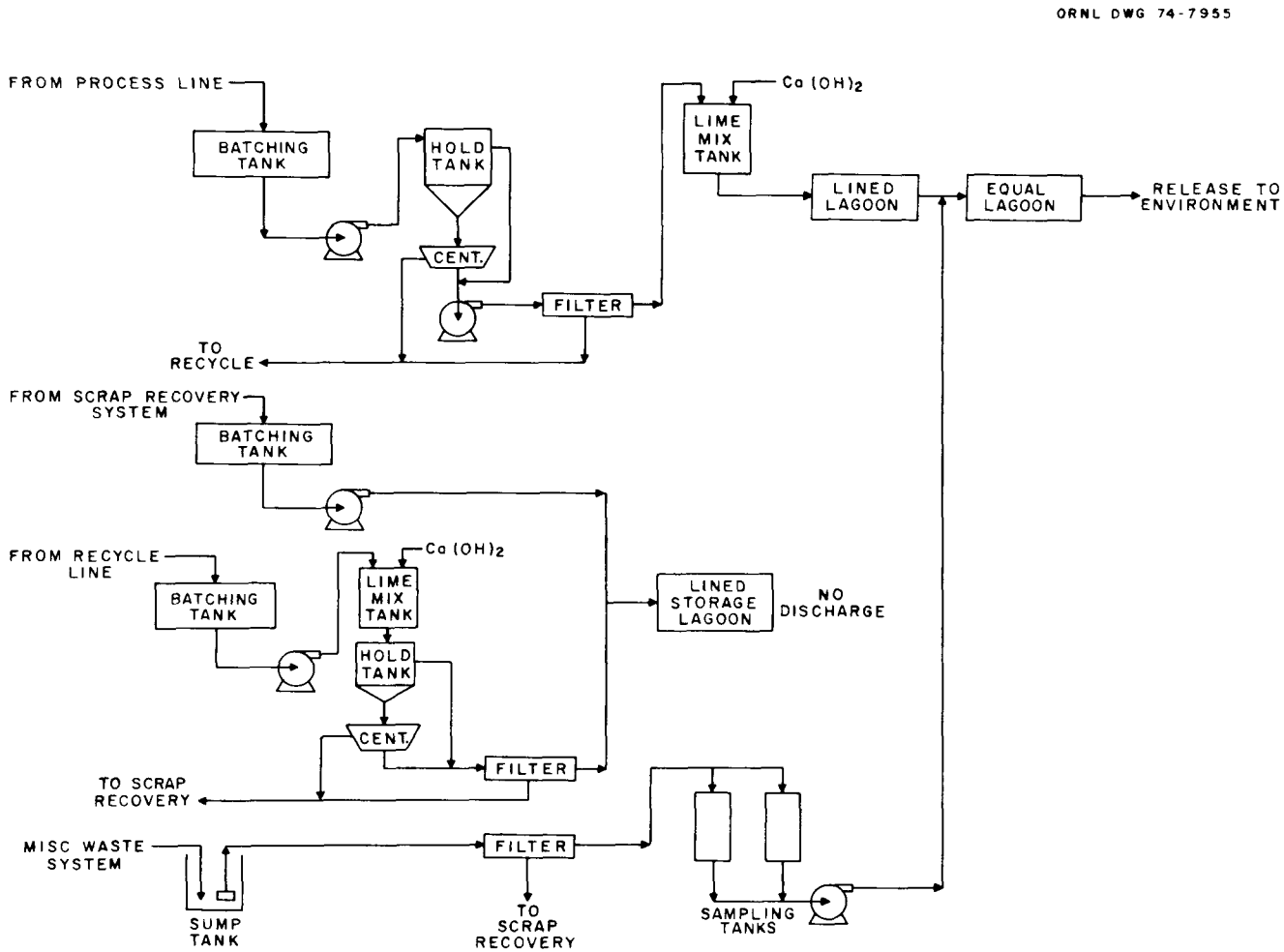

Fig. A-2. ADU Radwaste Treatment System - Case 2.

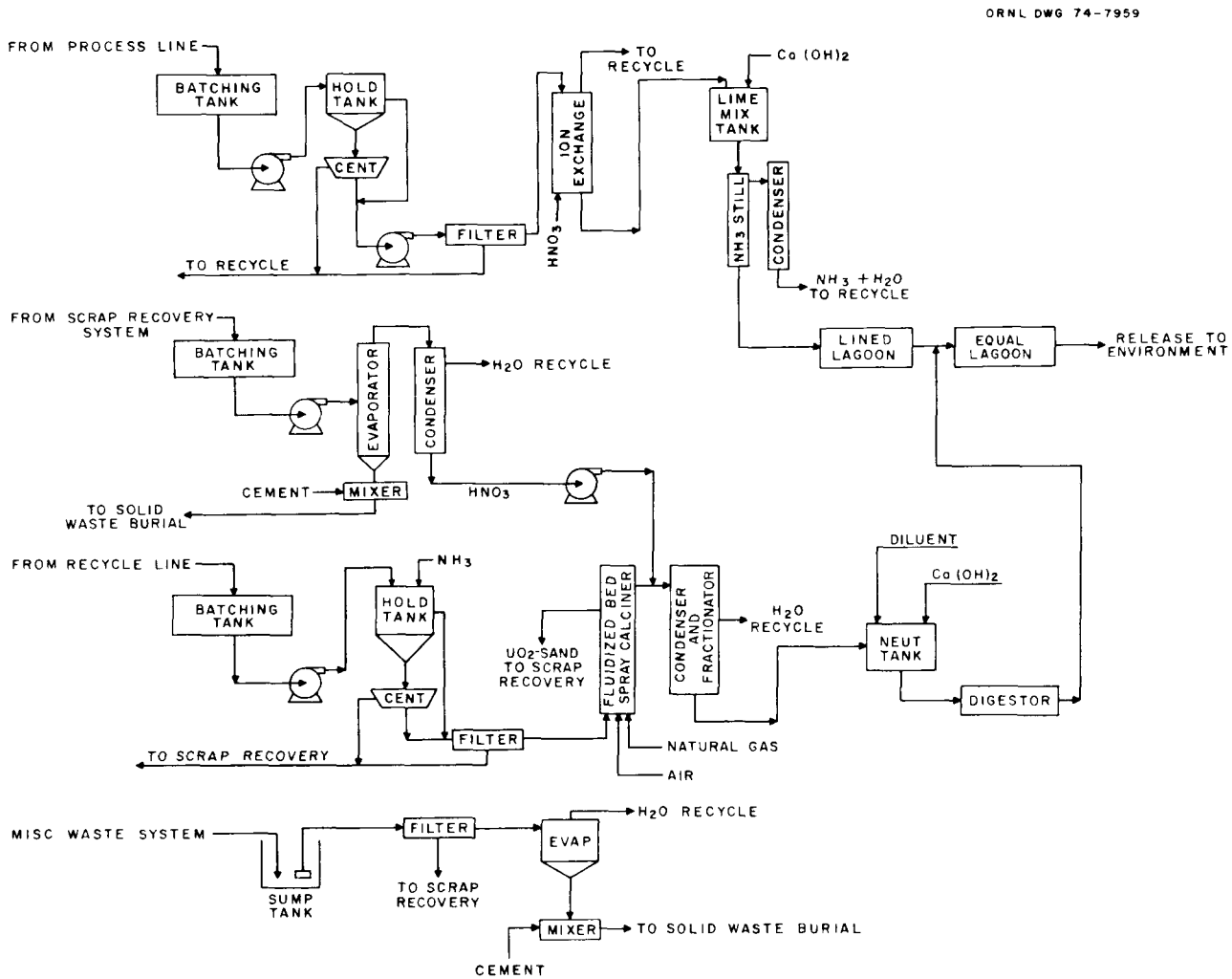

Fig. A-3. ADU Radwaste Treatment System - Case 3.

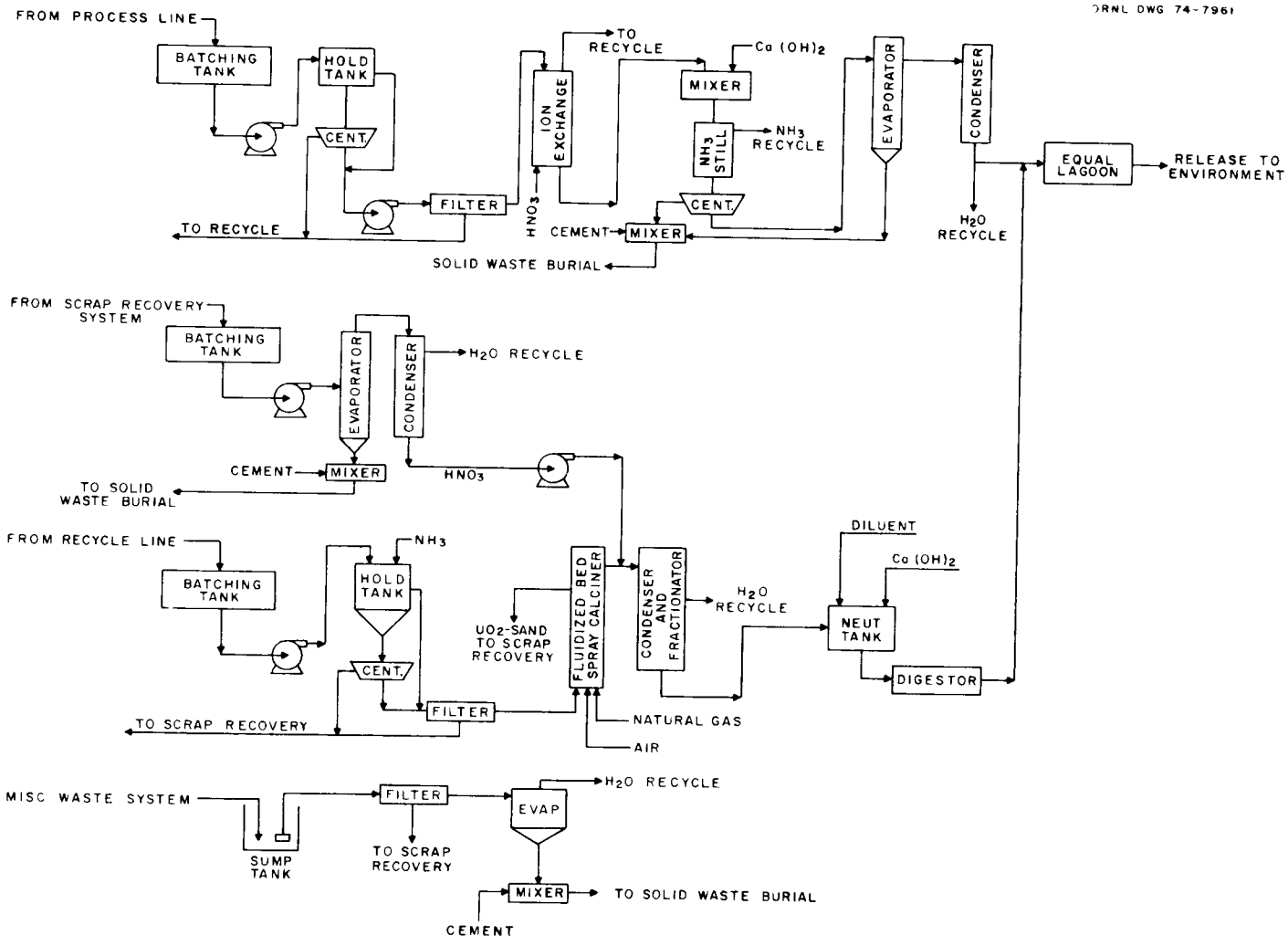

Fig. A-4. ADU Radwaste Treatment System - Case 4.

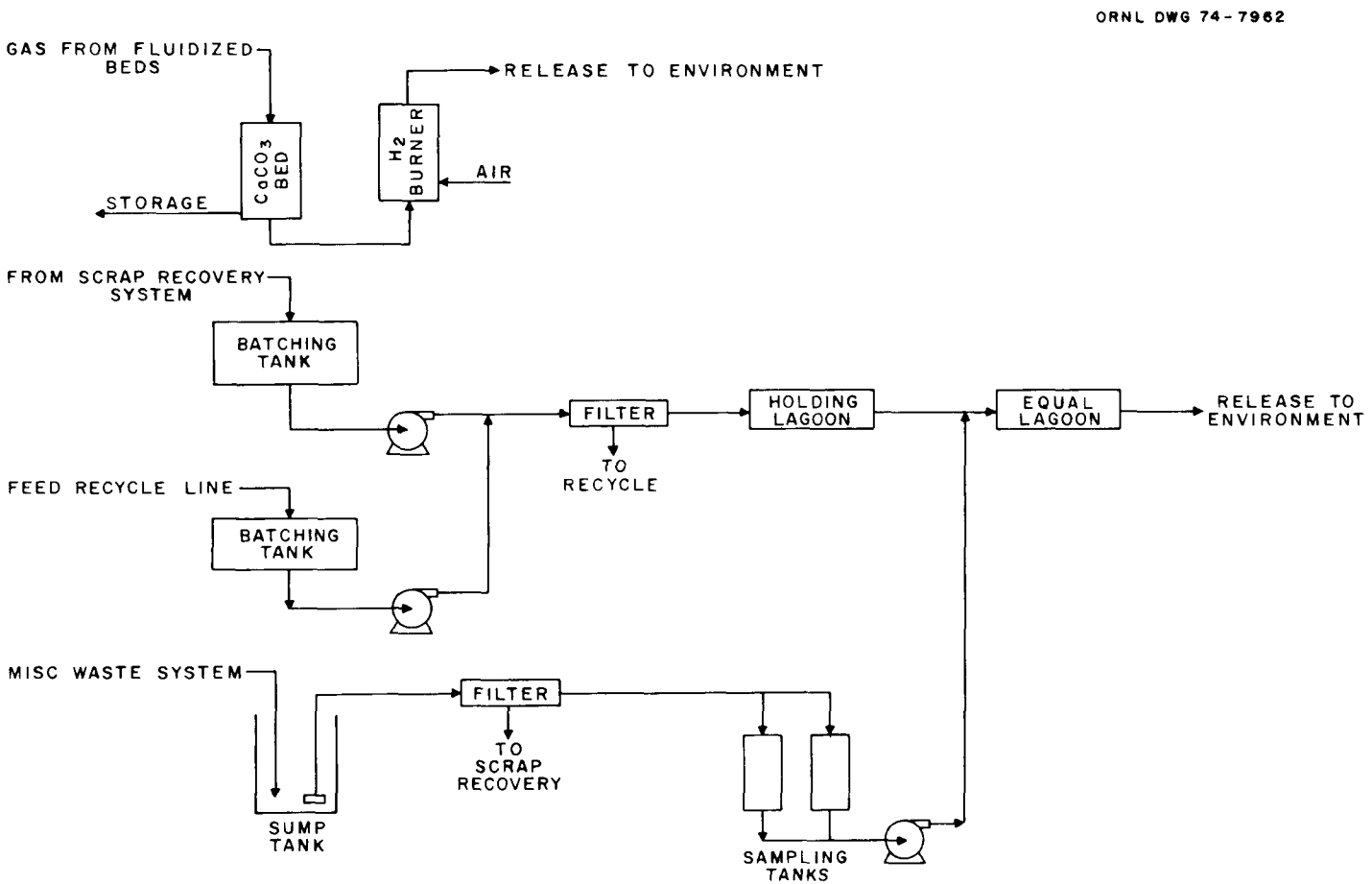

Fig. A-5. DC Radwaste Treatment System - Case 1.

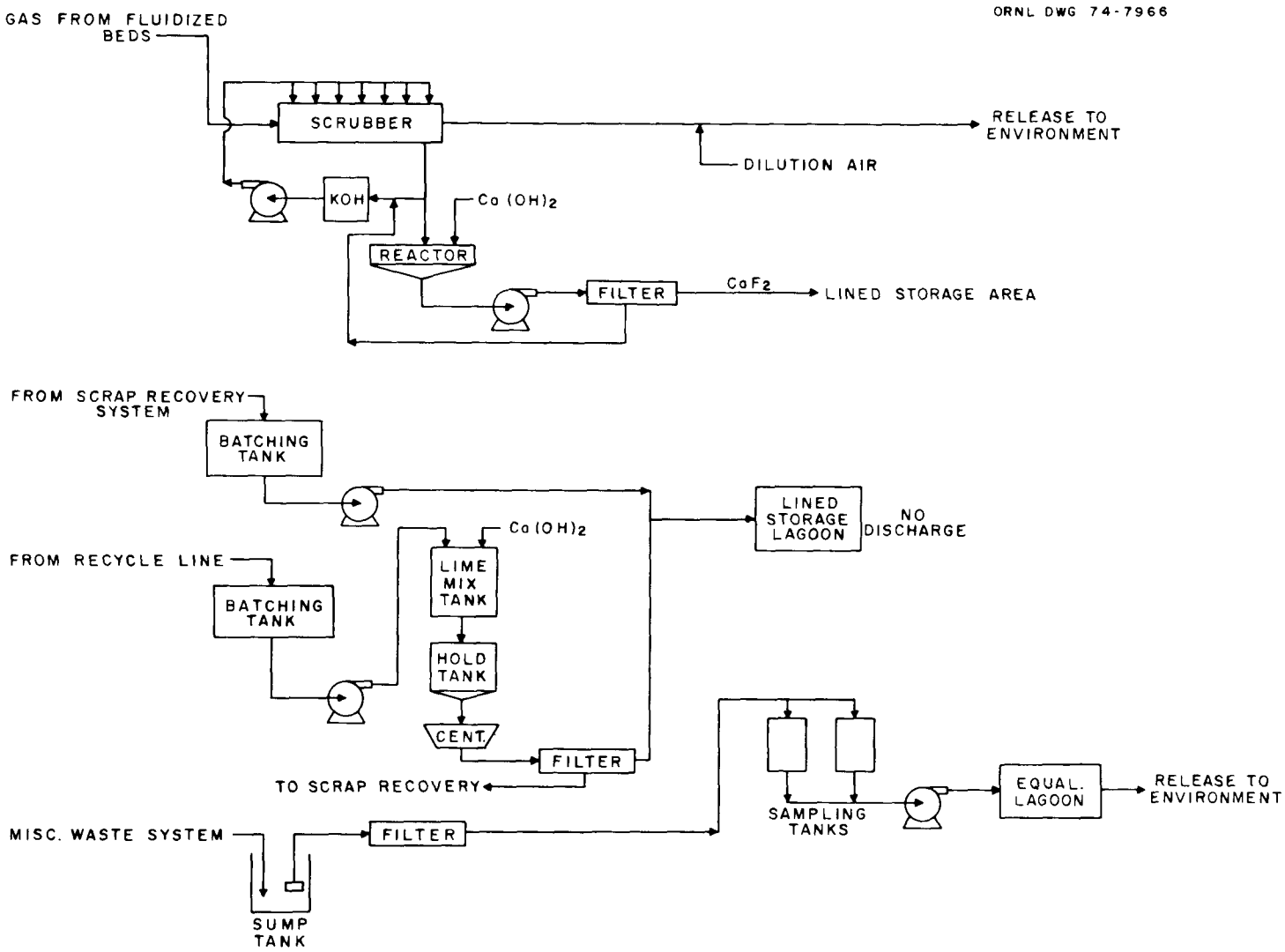

Fig. A-6. DC Radwaste Treatment System - Case 2.

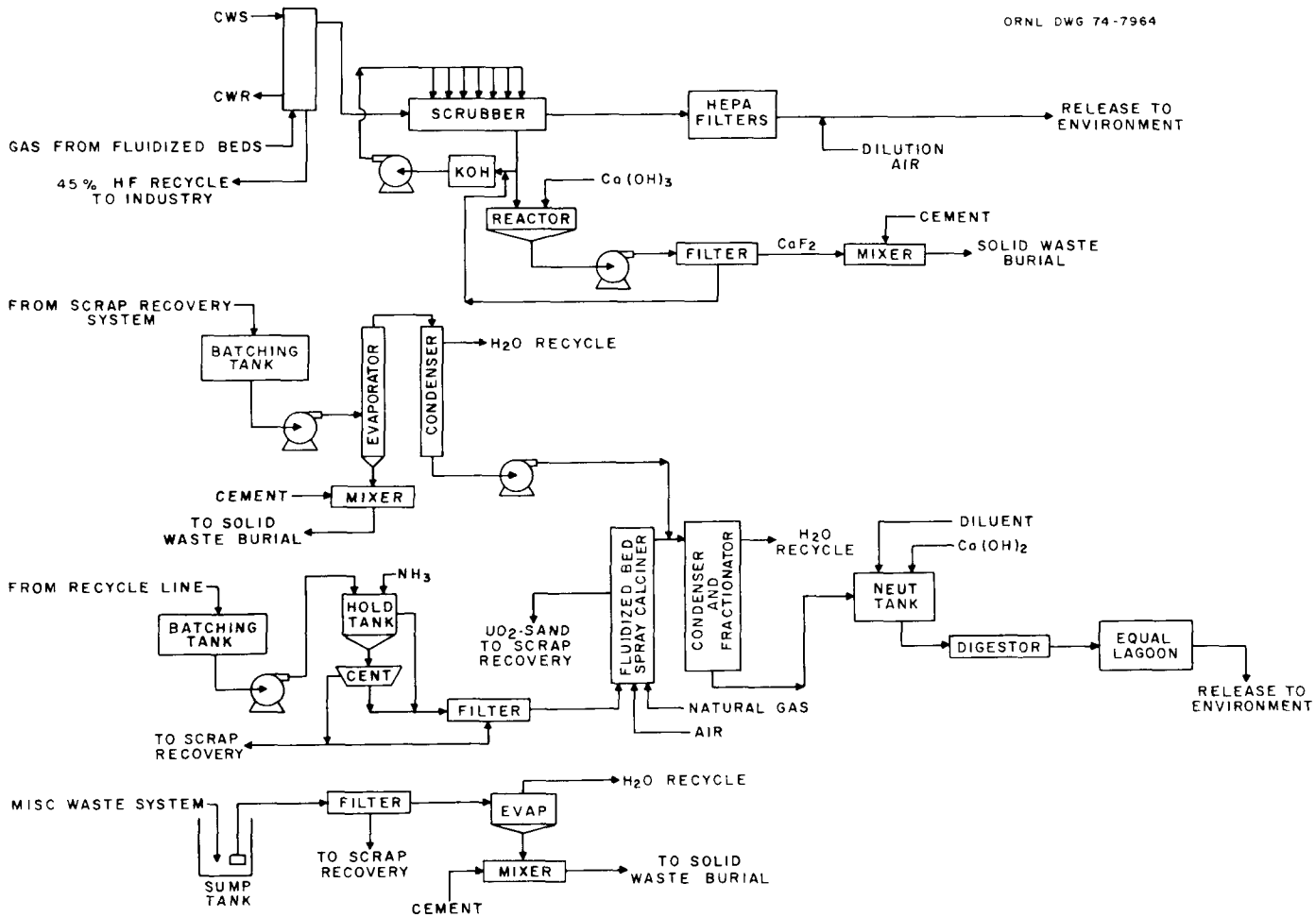

Fig. A-7. DC Radwaste Treatment System - Case 3.

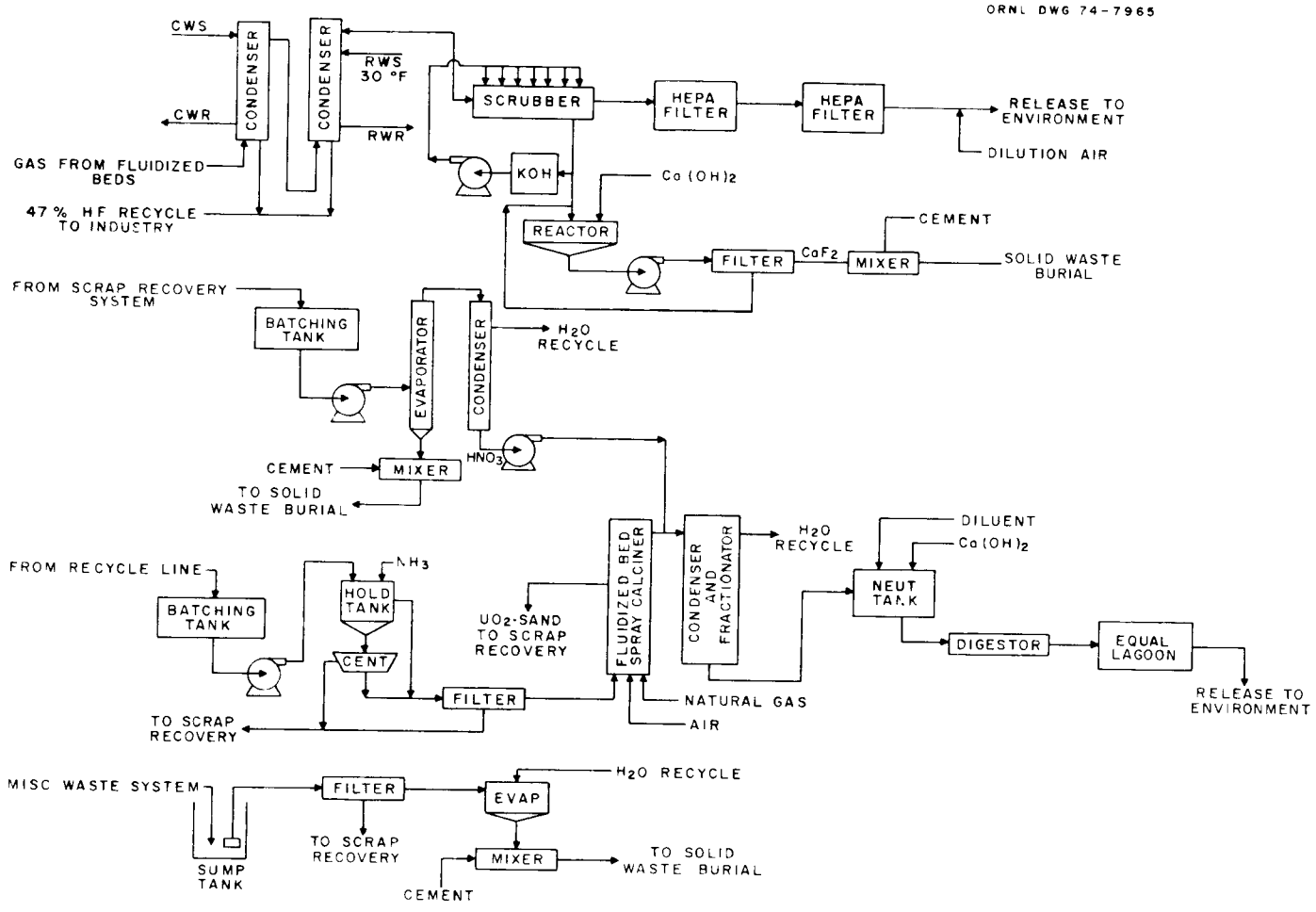

Fig. A-8. DC Radwaste Treatment System - Case 4.

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