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**Correlation of Radioactive Waste
Treatment Costs and the Environmental
Impact of Waste Effluents in the Nuclear
Fuel Cycle—Fabrication of
High-Temperature Gas-Cooled Reactor
Fuel Containing Uranium-233 and Thorium**

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MASTER

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OAK RIDGE NATIONAL LABORATORY

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CHEMICAL TECHNOLOGY DIVISION

CORRELATION OF RADIOACTIVE WASTE TREATMENT COSTS AND THE
ENVIRONMENTAL IMPACT OF WASTE EFFLUENTS IN THE NUCLEAR FUEL
CYCLE - FABRICATION OF HIGH-TEMPERATURE GAS-COOLED REACTOR
FUEL CONTAINING URANIUM-233 AND THORIUM

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ABSTRACT

A cost/benefit study was made to determine the cost and effectiveness of various radioactive waste (radwaste) treatment systems for decreasing the release of radioactive materials from model High-Temperature Gas-Cooled (HTGR) fuel fabrication plants and to determine the radiological impact (dose commitment) of the released materials on the environment. The study is designed to assist the U.S. Nuclear Regulatory Commission in defining the term "as low as reasonably achievable" as it applies to these nuclear facilities. The base cases of the two model plants, a fresh fuel fabrication plant and a refabrication plant, are representative of current proposed commercial designs or are based on technology that is being developed to fabricate uranium, thorium, and graphite into fuel elements. The annual capacities of the fresh fuel plant and the refabrication plant are 450 and 245 metric tons of heavy metal (where heavy metal is uranium plus thorium), as charged to about fifty 1000-MW(e) HTGRs. Additional radwaste treatment systems are 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 capital and annual costs for the added waste treatment operations and the corresponding reductions in dose commitments are calculated for each case. In the final analysis, the cost/benefit of each case, calculated as additional cost of radwaste system divided by the reduction in dose commitment, is tabulated or the dose commitment is plotted with cost as the variable. The status of each of the radwaste treatment methods used in the case studies is discussed. Much of the technology included in the advanced case studies has been utilized in either pilot-plant or industrial-scale operations, although no existing fabrication plant has used all of the treatment methods. The methodology used in estimating the costs is presented in Appendix A.

1.0 SUMMARY AND CONCLUSIONS

A study was made to determine the cost and effectiveness of radioactive waste (radwaste) treatment systems for decreasing the release of radioactive materials from model High-Temperature Gas-Cooled Reactor (HTGR) fuel fabrication plants and to determine the radiological impact (dose commitment) of the released radioactive materials on the

environment. The model plants are representative of current proposed commercial designs or are based on technology that is being developed to fabricate uranium, thorium, and graphite into fuel elements. Two model plants are required for the fuel fabrication operations. The fresh fuel fabrication plant converts uranium hexafluoride (UF_6), containing 93% uranium-235, into ceramic uranium dicarbide (UC_2) particles and converts thorium nitrate [$\text{Th}(\text{NO}_3)_4$] into ceramic thorium dioxide particles (ThO_2). The uranium dicarbide particles are coated with a buffer low-density carbon coating and then two layers of pyrolytic carbon which are separated by one layer of silicon carbide. The thorium dioxide particles are coated with two layers of pyrolytic carbon. These two types of particles are mixed and are formed into fuel rods. The rods are then inserted into hexagonal blocks of graphite to produce fuel elements. The recycle fuel fabrication (refabrication) plant converts uranyl nitrate [$\text{UO}_2(\text{NO}_3)_2$], containing either bred uranium-233 (bred from thorium-232) or recycled uranium-235, into coated uranium oxide-carbide particles. The coatings on these particles are the same as those described for the fresh fuel particles. The methods for formation of the recycle fuel rods and fuel elements are also the same as those for the fresh fuel except that operations with uranium-233 must be performed remotely behind shielding because of the radiation from the daughters of uranium-232. The annual capacity of the model fresh fuel fabrication plant is 450 metric tons of uranium and thorium (as metal) per year, i.e., a nominal 1.5-ton-per-day throughput on a 300-day-per-year basis. Approximately 52% of the ThO_2 particles are shipped to the refabrication plant for use in the manufacture of recycle fuel elements. It is assumed that the fresh fuel plant and the refabrication plant are separate units and are located at different sites. The refabrication plant processes 245 metric tons of uranium and thorium per year (a nominal 0.81-ton-per-day plant operation, 300 days per year), including about 22 metric tons as recycle uranium. The ^{233}U and recycle ^{235}U are received from an adjacent HTGR fuel reprocessing plant, and the capacity of the refabrication plant corresponds to the processing rate of ^{233}U and ^{235}U in the reprocessing plant. The radionuclides entering the fabrication plants in the uranium and thorium feed are discussed in Sect. 4.2. The radionuclides indicated in Table 4.11 are considered in the radiological impact studies. The airborne waste effluents from the plants are treated to remove radioactive materials and noxious chemicals (fluoride, chloride, and nitrate), and the airborne effluents are then released to the environment. The liquid wastes are treated to recover uranium and remove radioactive materials, and the treated liquids are released through a system of lagoons for the fresh fuel fabrication plant Case 1 study. No liquids containing radioactivity are released in the advanced cases of this plant or in any of the case studies for the refabrication plant. The model plants are evaluated at 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. The Case 1 study for the HTGR fresh fuel fabrication plant is the base case representing the lowest cost and currently conceived treatment technology. In each succeeding case, radwaste treatment equipment is added or modified to accomplish specific objectives. The release of liquids containing radioactivity is eliminated in Cases 2, 3, and 4. In Cases 3 and 4 process changes are made to improve the airborne radwaste treatment system, and nitric acid and water are reclaimed and recycled. The Case 1 study for the refabrication plant represents the lowest cost and is based on a current ERDA development program and on

the experience of other fuel fabrication plants utilizing similar operations. One of the roughing filter systems is replaced with a bank of High Efficiency Particulate Air (HEPA) filters in Case 2. Process changes are incorporated in Case 3 to reduce the releases of uranium and thorium daughters. In Case 4 the treatment systems for the process off-gas and cell ventilation air are redesigned to recycle 95% of the gas stream and to include the addition of two supplementary stages of HEPA filters for the final blowdown effluent stream. All of the equipment added in the case studies is presently available, although no existing fabrication plant has used some of the treatment methods selected for the advanced cases. The case studies and cost estimates for the model plants are based on the design and construction of new plants. Backfitting of existing plants is not evaluated. The efficiency of a treatment system or plant for retention of radioactive material is expressed as a decontamination factor (DF), i.e., the ratio of the amount of material entering a plant to that released to the environment. The general plan for the studies is summarized in Tables 4.15 and 4.16.

The annual amounts of radioactive materials released (the source terms), the capital, annual, and contribution to power costs, and the radiological impact are calculated for each case and for each plant. The dose commitments for each case were calculated for: (a) the maximum annual individual total body, GI tract, bone, thyroid, lungs, muscle, kidneys, liver, spleen, testes, and ovaries at 0.5 mile from the fresh fuel plant and 1.5 miles from the refabrication plant (factors are provided to project the dose to lesser or greater distances); (b) the incremental maximum annual individual dose which represents the difference in dose between a given case and the preceding case; and (c) the annual population total-body dose (person-rem) out to a distance of 55 miles. Typical population densities are used for the 55-mile radii circles around each plant to estimate population dose from radioactive airborne releases.

Liquid radwastes are released only in the Case 1 study for the fresh fuel plant and, therefore, the incremental costs between Case 1 and other cases reflect the effect of eliminating the discharge of this stream. The Case 2 study demonstrates a temporary solution to liquid radwaste treatment where the effluents are discharged to a lined lagoon for concentration via solar evaporation. In the Case 3 and Case 4 studies, the liquid effluents are concentrated via evaporators, and water, nitric acid, and ammonia are recycled where feasible. The excess water is evaporated and released to the atmosphere, and the excess nitrate and ammonia are converted to nitrogen by anaerobic digestion. The radioactive materials in the residues are incorporated in cement and packaged in drums for disposal. No economic credit is taken for the recycle streams. Dose commitments from liquid effluents from the fresh fuel fabrication Case 1 study are compared with treatment costs on two bases, i.e., annual individual total-body doses (millirem) from aquatic pathways after dilution in a 15-cfs stream and after the 15-cfs stream flows into a 1300-cfs river 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 small size. Population dose (person-rem) is not estimated for liquid effluents, since it is not practical to predict a population distribution along a river. However, comparison of dose from airborne and liquid effluents can be made. For example, for the midwestern fresh fuel plant, the maximum annual individual total body dose from the model plant in Case 1 is 0.14 millirem from airborne

effluents at a distance of 0.5 mile. This compares with an individual total body dose of 0.016 millirem from aquatic pathways in the 1300-cfs river, i.e., about 11% of the maximum airborne dose. If 33 thousand people are exposed to aqueous pathways from the river, the population dose is 0.524 person-rem, which is equal to the population dose from airborne effluents to the 3.6 million people living in a 55-mile radius around the midwestern plant.

Internal exposure to radiation through inhalation and ingestion of radionuclides from airborne effluents accounts for 60% of the total body dose to individuals and population around the fresh fuel plant while these pathways contribute only 17% for the refabrication plant. The major contribution near the refabrication plant is from contaminated ground (83%). The principal radionuclides contributing to this dose are ^{230}Th , ^{234}U , and ^{235}U for the fresh fuel plant and ^{232}U for the refabrication plant. Estimated annual maximum total body doses from airborne effluents do not exceed 1 millirem to individuals living within 0.5 to 1 mile from the base Case 1 plants at either site. Maximum dose to individuals is slightly higher at the midwestern site than at the coastal site because of meteorological differences. Population dose commitments for the fresh fuel plant (0.524 person-rem for the midwestern site and 0.304 person-rem for the coastal site) and for the refabrication plant (7.54 and 2.68 person-rem, respectively) represent only a fractional percent of the population dose received from background radiation (100 to 170 millirem per year). The fuel refabrication plant of the combined reprocessing-refabrication operations contributes less than 1% of the individual total-body organ dose, or population total-body dose commitment of the reprocessing plant.

The long-term annual total body doses from airborne effluents to individuals living within 55 miles of the model plants (in Case 1) for the period of time after the plants have been closed until a significant decay of all radionuclides occurs are estimated to be about 1.1×10^{-4} millirem for the fresh fuel plant and 4.9×10^{-3} millirem for the refabrication plant. These estimates are based on the assumptions that all of the radioactive material is deposited within 55 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 total body dose is based on conservative assumptions which tend to maximize the estimated dose.

The radwaste treatment costs and the radiation dose from the airborne effluents from the fresh fuel plant and from the refabrication plant are shown in Tables 8.1 and 8.5, respectively. These costs are given in terms of 1973 dollars to maintain consistency with previous reports in this series (refs. 2.6 to 2.9). Factors are provided to convert to 1975 dollars (Sect. 6.0). The doses from airborne effluents in Case 4 are about a factor of 1600 times lower (fresh fuel plant) and 7000 times lower (refabrication plant) than in Case 1. In both model plants the largest dose is for bone, followed by lung, muscle, and other organs. For the midwestern site, the total body dose from the fresh fuel plant airborne effluents decreases from 0.14 millirem in Case 1 to 8.5×10^{-5} millirem in Case 4 for an additional annual cost of \$2.26 million. Similarly, the annual dose to the population at the midwestern site decreases from 0.524 person-rem in Case 1 to 3.21×10^{-4} person-rem in Case 4 for the same additional cost (Fig. 8.2). The total body dose at the same site for the refabrication plant decreases from 0.15 millirem in Case 1 to 2.1×10^{-5} millirem in Case 4 for an additional annual cost of \$966 thousand. The annual dose to the population decreases from 7.54 person-rem in Case 1 to 1.09×10^{-3} person-rem in Case 4 for the same additional cost.

The incremental costs and doses between the case studies for the fresh fuel plant at the midwestern site indicate the cost/benefit ratio, in terms of dollars per millirem reduction of maximum annual total body dose from airborne effluents at 0.5 mile, increases from \$5.76 million for the Case 1 (or Case 2)/Case 3 increment to \$50.2 million for the Case 3/Case 4 increment. The cost/benefit ratio for the initial Case 1 treatment, i.e., the increment from no final off-gas treatment to Case 1, is \$1.23 thousand per millirem. Thus, a cost/benefit ratio increase by a factor of 4700 occurs from Case 2 to Case 3, and by a factor of 8.7 for Case 3 to Case 4, indicating that Case 1 offers the optimum cost/benefit ratio.

The incremental costs and doses between the case studies for the refabrication plant indicate the cost/benefit ratio, in terms of dollars per millirem reduction of maximum annual total body dose from airborne effluents at 1.5 miles, increase from \$178 thousand for the Case 1/Case 2 increment to \$112 million for the Case 2/Case 3 increment, and decrease to \$59.3 million for the Case 3/Case 4 increment. Case 3 illustrates the effectiveness of a feed cleanup step in reducing the dose to the bone. This purification step has little effect on the total body dose but reduces the bone dose by approximately 35% (Table 8.5).

The radwaste treatment costs and the radiation dose from the liquid effluents from the fresh fuel plant are presented in Table 8.3 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. In Case 1, the doses are essentially the same for the midwestern and coastal sites from the 15-cfs stream, but the doses for the river and for the estuary are not exactly comparable because the estuary is not a source of drinking water. The maximum annual individual dose from aquatic pathways associated with the 15-cfs stream is 1.4 millirem, which is ten times higher than the maximum individual dose of 0.14 millirem from the airborne effluent from the fresh fuel fabrication plant at 0.5 mile. However, the more realistic annual dose associated with the 1300-cfs river at the midwestern site is 0.016 millirem, about nine times lower than the dose from the airborne effluent at 0.5 mile and about 90 times lower than that from the 15-cfs stream case. In Cases 2 through 4, the annual doses are reduced to zero by eliminating the discharge of the liquid radwaste stream.

The incremental costs and doses between the Case 1/Case 2 study, in terms of dollars per millirem decrease in annual total-body dose for the 15-cfs stream, amount to \$149 thousand at the midwestern site (Table 8.4). The Case 3 (or Case 4) study illustrates the cost of a permanent solution to the handling of liquid wastes via (a) recycling of several chemical components, (b) conversion of nonreusable chemical materials to innocuous compounds, and (c) incorporation of residual radioactive material in cement and packaging in drums for disposal. The cost/benefit ratio for the increment Case 1/Case 3 (or Case 4) is \$329 thousand per millirem for the 15-cfs stream at the midwestern site. For comparison, the treatment system in the basic model plant (Case 1) involving dilution in a 15-cfs stream achieves a dose reduction of 60 at an annual cost of \$22 thousand to provide a cost/benefit ratio of \$262 per millirem at the midwestern site. The cost/benefit ratio for the cases involving dilution in the 1300-cfs river increases from \$13.1 million for the Case 1/Case 2 increment to \$28.8 million for the Case 1/Case 3 (or Case 4) increment.

If the fresh fuel and refabrication plants are considered as a single unit, the estimated capital cost for the Case 1 plants is \$450 million. This includes a \$14.0 million cost for the airborne radwaste treatment system. The total annual cost of the off-gas treatment of \$5.21 million in Case 1 corresponds to a contribution to the power cost of 0.014 mill/kWhr. Capital

costs for the airborne radwaste treatment systems in advanced cases range from \$14.7 to \$24.1 million, or up to about 5.4% of the capital cost of the base complex. The annual charges associated with advanced cases of airborne radwaste treatment range from \$5.46 to \$8.90 million and are equivalent to contribution to power costs of 0.014 and 0.024 mill/kWhr, respectively. All of these values are less than about 0.4% of an estimated total power generation cost of 7 to 10 mills/kWhr. Thus, while the absolute dollar costs for advanced airborne radwaste treatment systems are high, the percentage of the total capital cost and the contribution to total power generation costs are low.

2.0 INTRODUCTION

This study was performed to determine the cost and the effectiveness of radioactive waste (radwaste) treatment systems that are used, or could be used, at plants which fabricate uranium-thorium-bearing fuels for High-Temperature Gas-Cooled Reactors (HTGR) in order 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 material releases on the environment. The effectiveness of the alternate radwaste treatment systems under consideration is measured by comparing the quantities of radioactive materials released by the various systems and the relative impact of each release on the environment. The amount of radioactive material released in each case is designated "the source term," since these values are used in evaluating the impact of radioactive releases on the environment. The impact on the environment is assessed and compared with the radwaste treatment costs as the basis for a cost/benefit analysis.

The manufacturing process for HTGR fuel involves complexities which are different from those for the fabrication of Zircaloy-clad uranium oxide pellet fuel for Light-Water Reactors (LWRs). The fuel used in the HTGR is in the form of ceramic kernels, coated with pyrolytic carbon and silicon carbide to form particles, which are bonded into fuel rods that fit into the fuel holes of a hexagonal block of graphite approximately 31 in. long and 14 in. across the flats (Figs. 2.1, 2.2, and 2.3).¹⁻⁴ The multiple coatings of specific composition and characteristics on the kernels retain the volatile fission products inside the particles and prevent their spread into the helium flow of the reactor system. An inner layer (the buffer coating) of low-density pyrolytic carbon is applied to all kernels to provide voids for the accumulation of volatile fission products and to protect the outer coating from fission recoil damage. The outer layer, which may be either a single layer of high-density pyrolytic carbon (for the fertile or "BISO" coated particles) or a layer of silicon carbide sandwiched between two layers of high-density pyrolytic carbon (for the fissile or "TRISO" coated particles), acts as a pressure vessel to contain the volatile fission products. The silicon carbide coating serves as an effective diffusion barrier to some fission products, and also keeps fissile particles intact during early stages of head-end reprocessing. A summary listing of the components and purposes of each coating layer is shown in Table 2.1.⁵

Three types of hexagonal fuel blocks (also called fuel elements) are used which are similar in design with respect to geometry and dimensions. These three elements, classified by the type of particles they contain, are: (a) the IM element, which contains ^{235}U and thorium and is used in initial and makeup (IM) fuel loadings; (b) the 23R recycle element, which contains ^{233}U and thorium and is used as the major recycle element; and (c) the 25R recycle element, which contains recycled ^{235}U and thorium and is used when it is desirable to pass ^{235}U through the reactor more than once. The 23R and 25R terminology has been developed to specify the recycling (R) of uranium with an atomic number of 92 and a mass number of either 233 or 235. Any combination of these elements may be used in any given reactor core. Also, fuel element loadings from block to block may vary due to differences in uranium fissile content or in neutronic core requirements. The IM elements are fabricated in a conventional "direct contact" plant since the radiation levels are low. This type of plant is called the fresh fuel

fabrication plant in this report. Both the 23 recycle elements and the 25 recycle elements must be fabricated remotely in a separate refabrication plant because of their high radiation levels. It is expected that refabrication plants will be located adjacent to HTGR reprocessing plants.

Several types of particles are used to maintain separation of spent ^{235}U (containing ^{236}U) from ^{233}U and to reduce the fabrication costs. Particles containing thorium or fresh ^{235}U , which have low levels of radiation, can be fabricated in direct contact facilities. The costs for fabrication of these types of fuel particles will be much lower than for ^{233}U and recycle ^{235}U particles, which have high levels of radiation and which require remote processing behind heavy shielding. The four particle types are one fertile particle containing thorium and three fissile particles containing uranium, i.e., (a) a fissile particle containing new ^{235}U with both pyrolytic carbon and silicon carbide coatings, (b) a recycle fissile ^{235}U particle containing recycled ^{235}U coated with both pyrolytic carbon and silicon carbide, and (c) a recycle ^{233}U particle containing ^{233}U coated with both pyrolytic carbon coatings and silicon carbide. Only one type of fissile particle is used in any one fuel element. Fissile particles and fertile particles are mechanically blended and formed into a fuel rod. One other particle that is used in the fuel rod is a nonradioactive shim particle. These particles are graphite granules which are blended with the fuel particles to fill the balance of the 58-60% close-packed volume of the fuel rods. They are nominally 0.02 to 0.04 in. in diameter. A summary of the properties of the fissile and fertile kernels is given in Fig. 2.3.

The radioactive materials entering the fresh fuel fabrication plant consist of isotopes of uranium, thorium, and their daughter products. In addition to these materials, the refabrication plant will also receive fission products and transuranium materials which have not been separated completely from the recycle uranium. A small fraction of the radioactive materials is suspended in the airborne waste streams from processing areas as dust or aerosols. Liquid waste streams also contain small amounts of these materials. Treatment systems are used to minimize the release of these materials in the airborne and liquid effluents from the plants. In the most advanced case, liquid waste treatment systems are used to recover uranium, thorium, 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 nitrate, ammonia, and fluoride.

Since the fuel elements for an HTGR are of two separate types, i.e., those of low specific radioactivity which may be handled with little shielding and those of high specific radioactivity which must be shielded and confined, two model plants which are typical of current designs for HTGR fuel fabrication plants are used as the base cases in this study to represent a plant fabricating fresh fuel (the IM element) and a plant fabricating recycle fuel (the 23R recycle element and the 25R recycle element). The radiological impacts of these two plants, the fresh fuel fabrication plant and the recycle fuel fabrication plant, are considered at two typical sites, i.e., a midwestern location 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 are 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 currently proposed 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" (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.

This report is one of a series of studies on the nuclear fuel cycle. Other reports in this series are concerned with reprocessing LWR fuels,⁶ milling uranium ores,⁷ fabricating LWR fuels containing enriched uranium,⁸ and fabricating LWR fuels containing plutonium.⁹

2.1 References

1. R. C. Dahlberg, R. F. Turner, and W. V. Goeddel, *HTGR Fuel and Fuel Cycle Summary Description*, General Atomic Company, Gulf-GA-A-12801(Rev.) (Jan. 21, 1974).
2. R. C. Dahlberg, K. Asmussen, D. Lee, L. Brooks, and R. K. Lane, "HTGR Fuel and Fuel Cycle," Nucl. Eng. Des. 26, 58 (1974).
3. G. M. Insch, "The High Temperature Reactor," J. Inst. Nucl. Eng. 16, 3 (1975).
4. Editors, "HTGR Fuel Fabrication, Reprocessing Units Being Developed," Nucl. Ind. 21(6), 26 (1974).
5. O. M. Stansfield, *HTGR Fuel Design and Performance*, General Atomic Company, Gulf-GA-A-13072 (July 12, 1974).
6. 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).
7. 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, Vols. 1 and 2 (May 1975).
8. 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).

9. 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).

3.0 OBJECTIVES AND ASSUMPTIONS

3.1 Objectives

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

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

3.2 Selection of the Model Plants

An HTGR requires two types of fuel elements, i.e., those of low specific radioactivity containing fresh ^{235}U and natural thorium, and those of high specific radioactivity containing either bred ^{233}U or recycled ^{235}U and natural thorium. In this study, the two types of fuel elements are assumed to be manufactured in two separate plants. The fuel elements containing low specific radioactivity are produced in the fresh fuel fabrication plant, and the fuel elements containing high specific radioactivity are produced in the recycle fuel fabrication (refabrication) plant. The manufacturing steps in the production of fresh and recycle HTGR fuel elements are shown schematically in Fig. 3.1.

3.2.1 Fresh Fuel Fabrication Plant

The model fresh fuel fabrication plant selected for the Case 1 study is similar to and has features of an existing pilot plant² and a commercial plant³ to be built in the late 1970s. The commercial plant represents an advanced design dedicated solely to the HTGR economy. An artist's conception of this plant is presented in Fig. 3.2. The major structures consist of three large rectangular buildings for the process activities and an office building to house the administrative functions of the plant. Minor buildings house the waste treatment facilities, the matrix and shim particle facility, the receiving and storage facility, the service functions, and miscellaneous fabrication functions.

The main features of the plant are the three large process structures; the fertile building, the fissile building, and the fuel rod and element manufacturing building. These three structures have floor spaces of approximately 30,000 ft², 50,000 ft², and 65,000 ft², respectively. Recovery of uranium from process reject material is performed in the fissile building, and the recovered material is reused in the production process.

The annual capacity of the model plant is 450 metric tons of heavy metal (MTHM) per year, i.e., a nominal 1.5-MTHM-per-day plant operating 300 days per year. This facility produces about 98 IM fuel elements per day. Approximately 52% (by weight) of the fertile particle production is sent to the refabrication plant for use in the manufacture of recycle fuel elements.

The processes can be considered to consist of the production of fissile particles, fertile particles, matrix material, and fuel rods and elements. The individual processes consist of:

- (a) conversion of uranium hexafluoride (UF₆) feed to uranium dioxide, conversion to the dicarbide, spheroidization, and the formation of carbon and silicon carbide coatings on the fissile kernels to produce fissile particles;
- (b) conversion of thorium nitrate feed to thoria kernels and the formation of carbon coatings on the fertile kernels to produce fertile particles;
- (c) mixing of the coated fissile and fertile particles;
- (d) fabrication into graphite matrix fuel rods;
- (e) assembly of the rods into graphite fuel elements; and
- (f) packaging of the fuel elements for shipment.

All processing steps which involve radioactive materials are carried out inside equipment located within enclosures (glove boxes) maintained at negative pressures relative to the adjacent areas of the manufacturing building. The pressure differentials are maintained so that air flows from noncontaminated areas into areas of potentially higher contamination levels, thus limiting the spread of radioactivity. The equipment forms the first level of confinement, the enclosures form the second level of confinement, and the manufacturing building forms the third level. Pressure differentials are maintained by automatically controlled zoned ventilation systems. Spare ventilation fans and required controls are provided and are connected to independent or installed emergency power systems in the event of loss of normal plant power, to provide assurance that the required pressure differentials are maintained.

The airborne effluents or off-gases from the processing steps each receive a separate pretreatment. The treated process gases and enclosure ventilation air are combined with the ventilation air from personnel operating areas for final treatment. Several types of liquid radwaste are produced, i.e., aqueous scrubber radwaste, sol-gel process radwaste, the scrap recovery process radwaste, and the miscellaneous radwaste. Approximately 47% of the uranium feed is processed through the scrap recovery system.

3.2.2 *Recycle Fuel Fabrication Plant (Refabrication Plant)*

The design of the model refabrication plant is based on technology that is being developed at ORNL and the General Atomic Company for the fabrication of HTGR recycle fuels, and includes concepts for pilot plants which are being constructed to demonstrate these processes at ORNL.⁴ Construction of a commercial recycle fuel fabrication plant has not been proposed, and construction of an industrial-scale plant is not expected until the mid-1980s. The model refabrication plant is located adjacent to a reprocessing plant which processes HTGR fuels, and the filtered airborne effluents from both plants are combined and discharged through a 100-meter stack. The source terms and doses are evaluated separately for each plant and also for the combined plants in this report.

The annual capacity of the model refabrication plant is 245 MTHM per year (a nominal 0.81-ton-per-day plant operating 300 days per year), including about 22 MT as recycle uranium. The refabrication facility produces about 72 23R fuel elements and 5.5 25R elements per day. All of the fertile material (approximately 740 kg/day) is supplied by the fresh fuel fabrication plant.

The individual manufacturing processes are the same basic operations as are used in the fresh fuel fabrication plant with the exception of the production of the recycle fissile particle. This particle is prepared by:

- (a) loading a purified uranium-233 or uranium-235 nitrate solution onto spherical weak-acid ion exchange resin particles;
- (b) conversion of the kernels to an oxide-carbide by high-temperature reduction; and
- (c) formation of carbon and silicon carbide coatings on the fissile particles.

The fuel rods are prepared as for the fresh fuel but are carbonized after being loaded into the fuel elements. The remaining steps are identical to those in the fresh fuel fabrication plant. The significant difference between the two plants is the fact that materials processed in the fuel refabrication operation have higher radiation levels and must be processed in a shielded, remotely-operated facility.⁵ Personnel radiation protection is provided via a 4-foot, normal-density, concrete shielding wall as a barrier between the operating equipment and operating personnel. Remote maintenance is accomplished by cranes and electrically-driven, remote-control manipulators. Visibility requirements for maintenance are met by remote video devices rather than by shielding windows. Redundant TV monitors (and transmission equipment) are provided for in-cell use. Particles are pneumatically transported from each manufacturing operation throughout the facility. Figures 3.3 and 3.4 provide a diagrammatic view of the cell structure that will be used in the ORNL pilot plant.⁴

3.2.3 Fuel Management Modes

The general flow of nuclear materials in the HTGR fuel cycle is shown in Fig 3.5. The initial core of an HTGR reactor contains fresh ^{235}U and thorium which is converted to ^{233}U via neutron capture by the series of reactions:

The fuel remains in the reactor until over 90% of the ^{235}U has fissioned. At this time (about four years), approximately 70 units of ^{233}U have been generated from the ^{232}Th (approximately 5% of original ^{232}Th consumed) and about half of this ^{233}U has already fissioned for each 100 units of ^{235}U initially loaded. The remaining ^{233}U (equivalent to about 30% of the ^{235}U initially charged) is recovered in the reprocessing plant and refabricated into 23R recycle fuel elements. The residual ^{235}U may be disposed of as waste, stored for future recovery, or reprocessed and refabricated into 25R recycle fuel elements. These modes of operation are schematically represented in Fig. 3.6.⁶⁻⁸

Several fuel management modes have been considered for HTGRs. However, in this survey it is assumed that the model 1000-MW(e) HTGR uses bred and unburned ^{233}U as part of the fissile material as well as recycled ^{235}U . Part of the ^{235}U is converted to ^{236}U instead of fissioning. Uranium-236 is not fissile but acts as a poison by absorbing some of the neutrons formed (prior to fissioning) and reduces the number of neutrons available to maintain the reactivity of the HTGR. Fresh ^{235}U is required in approximately the same quantity as is ^{233}U during equilibrium recycle.

The relative quantities of uranium and thorium in the feed to the fabrication plants are based on calculations of the lifetime average reload fuel requirement for a 1000-MW(e) HTGR.⁹ The overall radionuclide content of the feed is discussed in Sect. 4.2, and the 30-year lifetime average reloading and the equilibrium reloading (reached in approximately 8 to 10 years) are listed in Table 3.1.

3.2.4 Sampling Program

The manufacture of HTGR fuel elements is an intricate process. A typical HTGR core contains approximately 1×10^{11} coated UC_2 and ThO_2 kernels which have been bonded in a carbonaceous matrix to form about six million fuel rods which are then loaded into 4000 fuel blocks. Such a complex series of operations requires an excellent Sample Inspection System (SIS).

The SIS receives samples from all stages of processing in the manufacture of fuel elements (Fig. 3.7), determines the various required physical and chemical characteristics, transmits this information to the appropriate individuals, returns expended or unused sample material to scrap recovery or waste handling, and transfers suitably packaged archive material to storage. Several inspections are performed by the SIS on the coated kernels, including: radioassay, size, spheroidicity, surface contamination, density, carbon, oxygen, heavy metal content, and fraction of broken particles.

3.3 Management of Radioactive Wastes

The most complex flowsheets in this study illustrate very low, but not zero, release of radionuclides in the airborne radwaste effluents. Radioactive liquid effluents are released only for Case 1 for the fresh fuel fabrication plant. No liquid wastes containing radioactivity are released by the refabrication plant.

3.3.1 Airborne Effluents

Airborne effluents from process vessels and from processing cells or alpha enclosures (glove boxes) contain radioactive particles that are produced directly as solids or are formed from aerosols of process solutions that subsequently dry to become solids. The handling of thorium presents additional hazards as one of the isotopes in the decay chain of one of the thorium isotopes, ^{228}Th , is a gas, ^{220}Rn . On this basis, the source terms (Sect. 4.5.3) are calculated assuming that (a) the process off-gases are delayed in the plant before release for all processes involving thorium and recycled uranium, (b) six months have passed since the thorium feed material has been processed, and (c) ninety days have passed since the recycle uranium has been processed. Therefore, the ^{228}Th activity as well as the activities of its daughters are 80% of their equilibrium values. The treated gases from the fresh fuel fabrication plant are released through roof vents at a height of approximately 10 meters, and this height is assumed in the meteorological and radiological assessment of the impact of these releases (Sect. 7.0). The treated gases from the refabrication plant are released through a 100-meter stack which is shared with the fuel reprocessing plant.

3.3.2 Liquid Effluents

Liquid radwastes from process vessels and miscellaneous liquids from processing cells or alpha enclosures (glove boxes) contain dissolved and suspended compounds of uranium, thorium, and uranium and thorium daughter products. Consideration of the chemistry involved indicates that in most of the process systems the relative proportion of these materials in the liquid effluent will be the same as in the solids formed in a given operation. Exceptions occur in the production of any thorium product where the ^{220}Rn gaseous release will alter the quantity of daughter products. The amount of alteration depends upon the type of processing step and amount of thorium involved. The liquid radwaste effluents from the fresh fuel plant base case study are treated to recover the valuable constituents, and the residues containing small amounts of naturally-occurring radioactive materials are released to the environment in the plant effluent. No liquids containing radioactivity are released in the advanced cases of the fresh fuel plant or in any of the case studies for the refabrication plant.

In the advanced case studies, the liquid wastes containing radioactivity are evaporated. Part of the condensate is recycled for reuse, while the remainder is fixed in cement. The concentration of radioactive material in the condensate is lower by a factor of 10,000 than that of the original waste.¹⁰

3.3.3 Solid Waste

Most of the solid wastes are generated in the thorium processing steps (Sect. 4.1.1.2) at the fresh fuel fabrication plant and contain about 16 percent of the thorium that is processed. Smaller amounts of miscellaneous wastes are generated in other parts of both plants. 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 containing uranium are processed in the scrap recovery system to recover uranium. In this study, it is assumed that 47% of the uranium at the fresh fuel fabrication plant and 25% of the uranium at the refabrication plant are processed in the scrap recovery system annually (Sects. 4.1.1.5 and 4.1.2.4). In the initial case study for the fresh fuel plant, the residues from the scrap recovery system and other miscellaneous wastes are packaged in drums and stored on-site or shipped to a licensed burial ground. In the advanced case studies for the fresh fuel plant and for all cases in the refabrication plant, the miscellaneous wastes are incorporated in cement. The waste materials could also be incorporated in plasticizers or asphalt instead of cement. However, cement is selected to avoid the possibility of combustion in a fire during storage or shipment and to avoid excessive leaching of the plasticizer product in case the drum should fail and the solidified waste should be exposed to water.¹¹⁻¹²

3.4 Cost Parameters

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 an amortization period of 15 years, although the operating lifetime of the plant is assumed to be 20 years. The costs are based on new model plants, and no attempt is made to estimate backfitting costs for present plants. The capital costs of the model fresh fuel plant and the refabrication plant are set at \$50 million and \$400 million (1973 dollars), respectively, based on an extrapolation from the estimated costs of existing and proposed plants.¹³ These values will vary considerably with the type of facility constructed, i.e., direct maintenance, semi-remote maintenance, or completely remote maintenance. These costs represent a qualitative comparison with the incremental capital costs of the case studies. Complete details of the cost estimating procedure are listed in Sect. 6.0.

3.5 Equipment Operation

All radioactive wastes will be assumed to be treated by the radioactive waste treatment equipment; i.e., wastes will not bypass treatment systems and be discharged even though the radioactive content is lower than permissible licensing levels. The equipment is adequately sized

to ensure 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. This type of design provides extra assurance that radioactive releases will not exceed the calculated design levels.

3.6 Plant Siting

The model plants are 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 (Wilmington, N. C.) and midwestern (St. Louis, Mo.) 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 plants are estimated using the procedures which have been standardized for environmental impact statements for light-water-cooled, nuclear power stations by the USAEC-Directorate of Regulatory Standards.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 airborne 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-degree sectors using the site parameters listed in Sect. 3.6. Doses to individuals are calculated for the total body and individual organs. Population doses (person-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. E. Borders, General Atomic Company, private communication, September 10, 1974.
3. USAEC-Fuels and Materials Directorate of Licensing, *Draft Environmental Statement Concerning the Issuance of a Special Nuclear Material License to General Atomic Company in Connection with the Planned General Atomic Fuel Fabrication Facility*, Docket No. 70-1372 (January 1974).
4. *HTGR Fuel Refabrication Pilot Plant. Final Environmental Statement*, Oak Ridge National Laboratory, Oak Ridge, Tenn., WASH-1533(Final) (August 1974).
5. Shiaw-Der Su, "Shielding Aspects of HTGR Refueling," *Trans. Amer. Nucl. Soc.* 19, 474 (1974).
6. *Draft National HTGR Fuel Recycle Development Program as of August 1973, prepared by Oak Ridge National Laboratory, General Atomic Company, and Allied Chemical Corporation*, ORNL-4702, Rev. 1, August 1973.
7. R. C. Dahlberg, R. F. Turner, and W. V. Goeddel, *HTGR Fuel and Fuel Cycle Summary Description*, General Atomic Company, Gulf-GA-A-12801(Rev.), January 21, 1974, pp. 13-15.
8. R. C. Dahlberg, K. Asmussen, D. Lee, L. Brooks, and R. K. Lane, "HTGR Fuel and Fuel Cycle," *Nucl. Eng. Des.* 26, 58 (1974).
9. F. J. Homan, Oak Ridge National Laboratory, private communication, "Calculation of Heavy Metal Charges and Discharges from HTGR's," Oct. 15, 1974.
10. H. W. Godbee, *Use of Evaporation for the Treatment of Liquids in the Nuclear Industry*, ORNL-4790 (September 1973).
11. A. H. Kibbey and H. W. Godbee, *A Critical Review of Solid Radioactive Waste Practices at Nuclear Power Plants*, ORNL-4924 (March 1974).

12. R. M. Wallace, H. L. Hull, and R. F. Bradley, *Solid Forms for Savannah River Plant High-Level Waste*, DP-1335 (December 1973).
13. W. E. Thomas, Oak Ridge National Laboratory, private communication, June 18, 1975.

4.0 SOURCE TERMS FOR RADIOACTIVE RELEASES

4.1 Origin of the Radioactive Wastes in HTGR Fuel Fabrication Plants

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

4.1.1 Fresh Fuel Fabrication Plant

Fuel fabrication operations are conducted in the three main process buildings. The fuel consists of tiny spherical carbon-coated uranium dicarbide and thorium dioxide particles blended together and formed into rods by means of a matrix filler and binder. These fuel rods, along with boron carbide poison rods, are inserted into holes machined into graphite blocks and subsequently sealed by the addition of graphite plugs.¹ For simplicity of description, the process is divided into the steps shown schematically in Fig. 3.1. These include: production of fissile particles, fertile particles, matrix material, and fuel rods, followed by fuel element loading. Airborne effluents from each building are filtered independently before being exhausted through a single 10-meter stack. Liquid and solid waste are sampled and appropriately processed before release from the plant. Recovery of uranium and thorium (advanced cases) from process reject material is performed in the fissile building. The recovered material is reused in the production process.

4.1.1.1 Fissile Particle Production. - The fissile particles are coated uranium dicarbide (93% ²³⁵U) kernels (approximately 0.01 in. in diameter) which have been coated with a low-density pyrolytic carbon (PyC) buffer layer followed by two high-density PyC layers separated by a silicon carbide (SiC) coating (Fig. 2.3).² Production operations are conducted in the fissile building. The process sequence, shown schematically in Fig. 4.1, consists of three general steps; i.e., (a) uranium hexafluoride conversion, (b) uranium dicarbide kernel preparation, and (c) kernel coating. All operations with uranium dicarbide, which can ignite spontaneously when exposed to air, are performed in an inert atmosphere until the kernels are coated with pyrolytic carbon effectively encapsulating each fuel kernel. The amounts of material flowing through the process are listed in Table 4.1.

Uranium Hexafluoride Conversion. - The uranium hexafluoride (93% ²³⁵U) arrives at the manufacturing plant in NRC- and Department of Transportation-approved Type 5A cylinders shipped from an ERDA enrichment plant and is stored in a vault. Each cylinder is removed separately and placed in a hot air vaporization chamber. Several vaporization chests are available to permit continuous feed as cylinders are changed. All uranium hexafluoride lines are purged with dry nitrogen gas prior to admission of the fluoride gas. The temperature in the vaporization chamber and the pressure of the uranium hexafluoride are monitored continuously. Overtemperature or overpressure conditions will automatically remove electrical heater power, and the detection of excessive temperature, pressure, or uranium hexafluoride leakage will initiate chilldown of the chamber and the contained cylinder by means of CO₂ discharged into the chamber. The gaseous uranium hexafluoride continuously flows into a

fluid-bed conversion unit where the UF_6 combines with steam to form solid particles of uranyl fluoride. The reaction is:

The UO_2F_2 particles then overflow the reaction bed and are collected in hoppers. In a batch-type process, the uranyl fluoride powder is placed in a second fluid-bed reactor where it is reduced to uranium dioxide by the reaction with a fluidizing gas consisting of cracked ammonia. The second reaction is:

The uranium dioxide produced becomes the feed for the fissile kernel preparation line. The airborne effluent from the converter vessel passes through a sintered Monel metal filter in the top of the vessel before going to the airborne effluent treatment system, consisting of a KOH scrubber and bag filter in series, where HF and particulates are removed from the off-gas stream. The total airborne flow (process plus cell) is approximately 6000 cfm. Liquid from the scrubber is filtered, pumped to an equalization pond, and monitored before release.

Fissile Kernel Preparation. - In this step of the manufacturing process, the uranium dioxide is converted to uranium dicarbide which is subsequently spheroidized.³ The uranium feed material is mixed with carbon flour, ethyl cellulose, and methyl chloroform in batches. The slurry is then dried, ground, and screened to separate the material into various size fractions. Appropriately sized kernels are heated in a vacuum, causing a substitution reaction to occur. The granular uranium dicarbide is transferred from the conversion crucibles to feed hoppers for the spheroidization step. The converted kernels are spheroidized by dropping them through an induction-heated, high-temperature graphite drop furnace. The furnace is comprised of an upper feed zone, an intermediate heating zone, a lower cooling zone, and a bottom collection receptacle. The kernels are fed into the furnace from a vibrating screen. The heat absorbed by the falling kernels in the elongated heating zone initially causes degassing and completion of carburization, which prevents splattering or exploding of the kernels in the melting stage. After leaving the hot zone (2700 to 2900°C), the melted kernels enter the cooling zone, where they solidify to a spheroidal shape during the remainder of the fall before reaching the bottom of the collection receptacle. During operation, the furnace is purged with a gas flow of argon. The small quantities of effluents emanating from the processing steps are passed through a soot filter and a bag filter in series to remove the particulate material (UO_2 , UC_2 , and C). The predominant effluent in the process off-gas is argon.

Another method which shows considerable promise for the production of fissile kernels is the resin loading process (Sect. 4.1.2.1). This technique is undergoing considerable development both at GA and ORNL and may be available for the production of fresh fissile fuel. However, because of its proven ability, the fusion drop technology (as described above) has been selected as the reference method in this report.

Fissile Kernel Coating. - In order to retain fission products in the fuel particles under reactor conditions, the spherical uranium dicarbide kernels are coated with two PyC layers separated by a silicon carbide coating. There are four carbon coating layers. They are: (a) a

buffer, (b) a seal, (c) an inner isotropic coating, and (d) an outer isotropic coating. The first three coatings are applied in the first of three furnaces. In the coating operations, the kernels are levitated by a flowing inert gas. A hydrocarbon gas, such as acetylene or propylene, is added to the fluidizing gas (argon). The specific hydrocarbon utilized is determined by the coating properties desired.⁴⁻⁹ At the high temperature in the furnace (1400°C), the hydrocarbon dissociates, producing free carbon which deposits on the kernels as a PyC layer.

The kernels are transferred to a second furnace where a SiC layer is deposited, using methyltrichlorosilane as the source of SiC.¹⁰⁻¹² The final PyC coating is added in a third furnace. This coating operation is similar to the first PyC coating operation.

After the final coating step, the particles are washed with water containing a wetting agent (alcohol) to remove lightly adhering process dust from their surfaces, dried in an oven, and then inspected.

The airborne effluents from the coating operations contain large amounts of carboniferous material, hydrogen, HCl, and small quantities of SiC and UC₂. Carbon and hydrogen are converted to CO₂ and water by controlled combustion, and particulates are removed by two bag filters in series. The HCl produced by the SiC coating operation is removed by a NaOH scrubber, and the resulting liquid is filtered, pumped to an equalization pond, and monitored for radioactivity before release.

4.1.1.2 Fertile Particle Production. - The fertile particles are spherical thorium dioxide kernels (approximately 0.03 in. in diameter) which have been coated with a low-density buffer coating and a high-density PyC seal coating.¹³ Production operations are conducted in the fertile building. The process sequence, shown schematically in Fig. 4.2, consists of three general steps; (a) thorium nitrate conversion, (b) thorium dioxide kernel preparation, and (c) kernel coating. The amounts of material flowing through the process are listed in Table 4.2.

Thorium Nitrate Conversion. - The feed material for the production of the fertile kernels is reactor-grade thorium nitrate hydrate crystals purchased from commercial vendors. The conversion of thorium nitrate to a dispersible ThO₂ powder must be carried out under conditions that minimize the decomposition of nitrate into nitrogen oxides.¹⁴ The desired overall reaction is:

A thorium nitrate feed solution containing approximately 550 g of thorium per liter is fed into a preheated fluidized-bed denitrator containing a relatively coarse, dense, high-fired ThO₂ as seed material. This hydrothermal denitration is continued until the residual nitrate in the ThO₂ is less than 0.1 mole per mole of thorium. The ThO₂ product is carried out of the denitrator with the gases and collected on a filter. At this point, the ThO₂ can be almost completely dispersed (more than 99%, often 99.9%).^{15,16} Airborne effluents are purified by passing them through a NaOH scrubber system, radon retention tank, and a HEPA filtration system before being released to the environment. The scrubber liquor, which contains large quantities of NaNO₃ and much smaller quantities of thorium and its daughter products, is transported to a tank for radium removal by coprecipitation with BaSO₄. The liquor is then directed to an equalization pond, monitored, and then discharged to a nearby stream.

Fertile Kernel Preparation. - In this step of the manufacturing process, the thorium dioxide is spheroidized using a sol-gel technique.^{17,18} The ThO₂ sol is prepared by adding hydrothermally denitrated ThO₂ powder and nitric acid to water, with heat and agitation, to produce a sol (dispersion) having a ThO₂ concentration of about 2.5 M, a pH of 3.1 to 3.2, and a nitrate/thorium molar ratio of about 0.1. The sol is fed through orifices so that the output stream consists of small droplets which fall through a column containing ammonia gas which gels the surfaces. The ThO₂ microspheres are collected in a pool of 10% NH₄OH at the bottom of the column. They are carefully dried and then sintered at high temperature. The airborne effluents are passed through a soot filter, a radon retention tank, and a HEPA filtration system before release to the environment. The liquid effluents are passed through a filter, sent to a sump for radium removal, and then to an equalization pond where they are monitored before release to a nearby stream.

Fertile Kernel Coating. - After the thorium dioxide kernels have been sintered, sized, and shape classified, they are transferred to a fluidized-bed coating furnace identical in operation to the fissile particle coaters described above.¹³ A buffer coating followed by a single high-density isotropic coating of PyC is formed on the fertile kernels. The kernels are subsequently washed and dried. The carbonous material and hydrogen produced in the coating operation are converted into CO₂ and water by controlled combustion. The particulates are removed from the airborne effluents by a bag filtration system and a HEPA filtration system in series.

4.1.1.3 Production of Matrix Material. - The matrix material is used in the final forming of a fuel rod. It is a carbonaceous base material injected to fill the interstitial voids between the microspheres within the fuel rod, to improve thermal conductivity, and to provide the physical strength to hold the coated kernels together in the final fuel rod form. The process sequence is shown schematically in Fig. 4.3. One part of graphite flour is mixed with two parts of hot pitch; the resulting mixture is then cooled, ground, and sieved. No radioactive materials are handled or released in this operation. Consequently, solid wastes (e.g., cartons, bags, miscellaneous steel, and wooden items) may be disposed of under contract in a commercial (or municipal) operation. No liquid wastes are generated. The airborne effluents are filtered prior to being released to the atmosphere. These effluents consist of graphite, pitch, and SO₂ gas. The product powder is transferred to the fuel fabrication building.

4.1.1.4 Fuel Rod and Element Production. - In the fuel fabrication building, the coated particles and shim particles are blended together and the cylindrical fuel rods are formed. After various heat treatments, the rods are inserted into machined graphite blocks.^{19,20} The process sequence is shown schematically in Fig. 4.4, and the amounts of material flowing through the process are listed in Table 4.3.

Fuel Rod Manufacture. - The next step in the manufacture of HTGR fuel elements is to combine the coated fissile and fertile particles with carbon to form fuel rods. The matrix material is injected under high pressure around close-packed particles contained in a hot mold.^{21,22} After the matrix material has cooled and solidified, the matrix material is carbonized by heating in furnace boats packed with alumina. The cylindrical rods are approximately 5/8 inch in diameter and 2-1/2 inches long. The carbonized rods are then cleaned with HCl gas, which removes surface contamination resulting from particle fracture during rod production. The cured and cleaned rods are then heated to a high temperature so that all volatile materials

from the matrix material are removed. All neutral process airborne effluents are treated via soot filters and bag filters in series. The acidic HCl airborne waste stream from rod cleaning is neutralized in a NaOH scrubber, and any remaining particulates are removed by bag filtration prior to release of the treated effluent. The scrubber liquor is filtered, sent to the equalization pond, monitored, and discharged.

Fuel Element Fabrication. - The final step in the fuel fabrication process involves the insertion of the fuel rods into hexagonal graphite fuel blocks which measure 14 inches across the flats and 31 inches long. Boron carbide rods, which are shipped to the site from their place of manufacture, also are loaded into the graphite blocks. The ends of the fuel holes are plugged by a graphite piece coated with a high-temperature graphite cement. The loaded element is baked to cure the plug cement. The completed fuel elements²³ are loaded into Department of Transportation- and NRC-approved shipping containers and placed in storage to await shipment to a reactor site.

4.1.1.5 Scrap Recovery System. - Recovery and purification of unirradiated uranium are performed on uranium-bearing scrap materials accumulated from off-specification particles and fuel rod materials, scrap, graphite process equipment and wastes, ventilation filters, and liquid wastes from analysis and recovery processes. Figure 4.5 depicts scrap recovery operations which include the initial recovery of impure uranium (amounting to approximately 47% of the uranium feed) through dry processing operations and the purification of the recovered uranium by wet processing operations. In the base case, the assumption has been made that it is not economically feasible to recover scrap thorium (amounting to about 16% of the thorium feed) generated in the various processing steps.

In order to recover the fuel particles in reject fuel rods and elements, the reject rods and elements are burned in an air-atmosphere furnace to convert the matrix material and the outer carbon coating on the particles to carbon dioxide. The recovered bare thoria kernels are separated from the silicon carbide-coated uranium particles by screening.²⁴ The recovered fissile particles are then ground to break the remaining silicon carbide coating. The recovered uranium-bearing particles as well as other off-specification fissile kernels are burned, ground, and screened to reduce the material to ash, which is subsequently collected for recovery of the uranium. For the reclamation of the uranium adhering to graphite parts and the uranium contained in miscellaneous scrap such as filters, waste paper, and rags, the steps include segregation of scrap into furnace parts (liners, frits, crucibles, etc.) and high-level and low-level miscellaneous scrap. The carbonaceous and combustible materials are then burned, and the ash is screened and ground.

After the above preparatory recovery operations, the scrap is leached with nitric acid containing a small amount of hydrofluoric acid, and the resulting solution is filtered to remove insoluble impurities. The solution is processed in a solvent extraction system which is designed to achieve a high recovery of uranium and separation from thorium and nonextractable impurities.^{25,26} In this system, the adjusted dissolver solution, containing 150 g (U+Th)/liter, is passed countercurrent to a solvent containing 30 vol % tri-*n*-butyl phosphate (TBP) in an aliphatic hydrocarbon diluent using a 2-in.-diam by 20-ft-high pulsed column. The uranium is recovered from the solvent by contacting the solvent with approximately 0.01 *M* HNO₃ in a second solvent extraction contactor. The solvent is then reused. About once a year, the stripped solvent (approximately 300 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. The barren dissolver solution, or raffinate, contains a trace of the uranium and all of the thorium fed to solvent extraction. This solution is sent to an evaporator to concentrate the thorium for waste disposal. The airborne effluents are passed through a NaOH scrubber to remove HNO_3 and subsequently through a soot filter before release. The scrubber liquor is filtered, pumped to an equalization pond, monitored, and discharged.

The recovered uranium solution from the solvent stripping operation is neutralized, and the insoluble ammonium diuranate is precipitated using an aqueous strike solution containing approximately 3 wt % ammonia. The solids are collected in a centrifuge and clarifier, and then dried at a temperature of 180°C . A calciner is used to thermally decompose and reduce the solids at temperatures of 750 to 850°C to form UO_2 powder. The clarified liquid is filtered and then sent to the equalization pond for monitoring purposes before release. Off-gases are treated by sending them through a scrubber and then a soot filter before release. The amounts of material flowing through the scrap recovery system are listed in Table 4.4.

4.1.1.6 Scrubber Systems. - All chemical process airborne effluents are passed through spray-type water scrubbers before being released to the environment. The liquids from these scrubbers contain traces of uranium and thorium as well as nonradioactive chemical constituents. These wastes are combined with liquid radwastes from the process generating the particular airborne effluent. For example, the scrubbing liquids from the off-gas scrubbers in the fissile scrap recovery system are added to the scrap recovery system liquid radwaste stream.

4.1.1.7 Soot Filter System. - All dry process airborne effluents are passed through soot-type filters before being released to the environment. The gases to these filters contain traces of uranium, thorium, and daughter products as well as some nonradioactive chemical constituents. Those materials that are collected in the filters are sent to the fissile scrap recovery system for reprocessing.

4.1.1.8 Miscellaneous Liquid Wastes. - Miscellaneous liquid wastes are generated from the laundering of clothing, personnel showers, floor drains, laboratory drains, etc. Since all processing operations are carried out within cells or alpha enclosures, this liquid waste is normally free of radioactive contamination. The potential for contamination exists, however, and therefore a miscellaneous liquid waste treatment system exists to monitor and treat this waste. In this study, it is assumed that small amounts of naturally-occurring radioactive materials are released to the equalization pond from this stream.

4.1.1.9 Miscellaneous Solid Wastes. - Miscellaneous solid wastes, including glove-box gloves, cleaning materials, filters, etc., are separated into combustible and noncombustible types. An incinerator is used to reduce combustible wastes to a waste residue which is processed in the scrap recovery system. Radioactive materials in the incinerator off-gas are retained by a filter system attached to the incinerator unit that is considered to be part of the base plant. Thus, it is common to all of the case studies. Noncombustible wastes are mechanically compacted, where feasible, and transferred to the solid radwaste treatment system for packaging.

4.1.1.10 *Process Airborne Effluent.* - All processing cells, glove boxes, or other alpha enclosures, and process equipment units are connected with ducting for the collection of airborne effluents. The combined process airborne effluent contains small quantities of radioactive and nonradioactive materials, including gases that are produced in the various operations and are not removed by the scrubbers. Aerosols of solutions which dry to particulates represent a complete spectrum of the radioactive and nonradioactive materials in the process liquids. Additional particles are derived from drying and calcining operations, from powder handling procedures in the scrap recovery system and kernel and fuel rod fabrication operations, and from ventilation of alpha enclosures by resuspension of settled particles. This airborne effluent is combined with the plant ventilation air from personnel areas before release to the environment (Fig. 4.6). All airborne effluents generated by various sources in the fresh fuel fabrication plant are listed in Table 4.5.

HTGR fuel fabrication operations are dusty operations which generate considerable quantities of soot. Stack sample measurements of entrained radioactivity at HTGR fuel fabrication plants have indicated that approximately 0.03% of the activity fed to the plant is found in the process and cell off-gas after treatment with a scrubber and soot filter. Assuming an efficiency of 90% for scrubbers, 95% for soot filters, and 99.95% for HEPA filters (Sect. 4.3.1), the amount of activity in the process off-gas and process area ventilation air before treatment is estimated as approximately 3% of that fed to the plant. The source terms in this study of HTGR fuel fabrication are calculated based on the conservative estimate that approximately 4% of the total radioactive materials entering the plant will be suspended in the off-gas prior to any treatment of the off-gas (i.e., in the streams leaving the process equipment boxes shown in Fig. 4.6). Using these assumptions, the estimated amount of radioactive material in the airborne effluent from the plant in Case 1 (the source term, see Sect. 4.5) is 75% of the Radiation Concentration Guide (Code of Federal Regulations, Title 10, Part 20, Appendix B, Table I, Column I) for soluble materials.

4.1.1.11 *Ventilation Airborne Effluent.* - The ventilation air in the fabrication plant for personnel areas is normally free of radioactive materials, since all process operations are carried out within cells or alpha enclosures. The potential for contamination exists, however, and consequently the plant ventilation system is designed to provide air flow from areas having a low probability of contamination to those with greater potential for contamination. The ventilation air is combined with the process airborne effluent, and the combined off-gas is discharged through a single 10-meter stack. Current designs for HTGR fabrication facilities use high ventilation and process air flow rates, such that the total plant airborne flow rate amounts to 300 to 500 scfm per metric ton of annual capacity. Hence, a total flow of approximately 140,000 scfm is used in the final airborne radwaste treatment system for the model fresh fuel fabrication plant.

4.1.2 *Recycle Fuel Fabrication Plant (Refabrication)*

The recycle fuel elements are fabricated in a heavily-shielded remotely-operated facility located adjacent to the reprocessing plant. Two types of elements are fabricated: those containing residual ^{235}U recovered from the fissile particles in the fresh fuel elements, and those containing the ^{233}U bred from ^{232}Th in the fertile particles or recovered from irradiated ^{233}U containing fissile particles. These two isotopes of uranium are segregated at the reprocessing plant by elutriation of the fissile and fertile particles and, after dissolution in nitric acid and

purification by solvent extraction, are supplied as individual solutions to the plant. The individual manufacturing processing steps necessary to produce an HTGR fuel element are shown schematically in Fig. 3.1. These include: (a) production of fissile particles via the resin kernel method; (b) transportation of fertile particles, matrix material, and shim particles from the fresh fuel fabrication plant; and (c) fabrication of fuel rods and elements. Airborne effluents from these processes are treated before discharging them through a 100-meter stack.

4.1.2.1 Recycle Fissile Particle Production. - The recycle fissile particles are spherical particles of a multiphase material assumed to have the following molar proportions; (a) one to three moles of uranium dicarbide (UC_2), (b) one to three moles of uranium dioxide (UO_2), and (c) one to three moles of residual carbon. The particle is approximately 20% larger in diameter and of lower density than the fresh fuel fissile particle (Fig. 2.3). The process sequence, shown schematically in Fig. 4.7, consists of four general steps: (a) resin loading, (b) resin carbonization, (c) resin conversion, and (d) kernel coating.

Resin Loading. - An acid-deficient uranyl nitrate solution (ADUN) is loaded onto a weak-acid (carboxylate) ion exchange resin (Fig. 4.8).^{27,28} The resin, a commercial product, is screened to select particles in the 700 micrometer range, passed across a tilted, vibrating table to remove all nonspherical particles, and converted from its sodium (as-received) form to the hydrogen (or acid) form for use in the process. Before the primary feed solution [a 2 M uranyl nitrate (UN) solution] is loaded onto the resin, it is reduced in acidity by removing nitric acid in a series of contacts with an organic solvent containing a secondary amine (0.4 M Amberlite LA-2 in diethylbenzene) as an ion exchange medium. The two liquids are separated by gravity. The aqueous solution is concentrated in an evaporator before sending it to the resin loading system, and the organic solvent is sent to a regeneration system where entrained uranium is removed by a water wash and extracted nitric acid is removed by a NaOH and Na_2CO_3 wash. Several cycles of acid removal are required to fully load the resin with uranyl ions. The loaded resin is partially dried by heating the material (dried to about 10-15% residual water, where static effects and sticking are at a minimum).²⁹ The quantities of materials passing through the process are listed in Table 4.6.

Other alternative methods are being investigated for the loading of weak-acid ion exchange resin. One technique that is being studied involves modifications to the resin and to the uranium feed solution so as to replace the solvent extraction step by ammonia neutralization. The acid form of the resin is converted to the ammonium form by contact with ammonium hydroxide and then washed with water to remove excess base. The uranium nitrate feed solution is adjusted to the proper pH by addition of NH_4OH . The loading procedure is a two-step operation in which the feed solution is passed countercurrently through two batches of resin. The flowsheet is shown in Fig. 4.9; the material flows are presented in Table 4.7. This method requires additional development as the final product may contain excessive amounts of nitrogen (approximately 200 ppm)³⁰ which can be converted to carbon-14 via neutron reactions in an HTGR reactor.³¹

Recycle Fissile Kernel Coating. - The partially dried uranium-loaded resin kernels are subjected to a series of operations (Fig. 4.10) consisting of carbonization, conversion, and coating. In the carbonization process the kernels are heated to approximately 500°C to volatilize hydrocarbons and decomposition products and to convert the resin kernels to carbon and UO_2 . During carbonization, the kernels lose approximately one-third of their weight. In the

resin conversion process the fuel kernels are heated to approximately 1700°C in an argon atmosphere, where the UO_2 (interspersed in a carbon matrix) is converted to a multiphase material containing UC_2 , UO_2 , U(C,O) , and residual carbon. All further operations with carbonized resin kernels must be performed in a protective atmosphere because of their pyrophoric properties. The recycle fuel kernels are next encapsulated in three carbon coatings and one SiC coating to retain fission products and to allow for mechanical separation from the fertile particles during head-end reprocessing at the reprocessing plant after the fuel is irradiated. The fuel fabrication operations are identical to those for the fresh fuel fissile particles, which have been discussed in Sect. 4.1.1.1. A local off-gas treatment system is used for each separate process to remove HCl, SiC, and other particulates from the airborne effluents. Material flows through the various processes are given in Table 4.8.

4.1.2.2 *Fertile Particle Production.* - The fertile particles are produced in the fresh fuel fabrication building. The process sequence is shown in Fig. 4.2 and is discussed in Sect. 4.1.1.2.

4.1.2.3 *Fuel Rod and Element Production.* - The coated fissile particles, coated fertile particles, shim particles, and matrix material are formed into uncured fuel rods as in the fresh fuel facility where the latter three materials are produced (Sect. 4.1.1.4). The fuel rods are loaded into fuel holes in the graphite blocks, which are heated, first, to about 1000°C in an inert atmosphere to carbonize the fuel rods and then heated to 1800°C to anneal the fuel rods. After the annealing step, the elements are cleaned, inspected to ensure adequate carbonization and annealing, and checked for transferable contamination. The final element assembly consists of insertion and seating of plugs and dowels via cement and additional heat treatments, inspection of the fully-assembled element, and application of protective packaging for transfer to element storage. The process sequence is illustrated in Fig. 4.11, and the amounts of material flowing through the process are listed in Table 4.9.

4.1.2.4 *Scrap Recovery System.* - Only one scrap recovery facility (or "line") is provided for both uranium fuels (^{233}U or ^{235}U), each of which is processed intermittently in campaigns through the same equipment as justified by production needs. Minimal equipment cleanout is required between campaigns to minimize uranium "cross-over" of one mix into the other. Figure 4.12 shows both the dry-processing steps for the recovery of uranium in off-specification particles and fuel rod materials and the purification of the recovered uranium by wet processing operations. Many of the procedures are identical to those described for the fresh fuel scrap recovery system and need not be discussed further (Sect. 4.1.1.5).

The dissolver solution is processed in an anion exchange system which is designed to achieve a high degree of recovery of uranium and separation from thorium and other impurities.³² The feed solution, containing about 100 g of uranium per liter and less than 0.3 M in HNO_3 (HF is not required for uranium dissolution), is passed sequentially through two resin columns (each containing an analytical-grade polystyrene sulfonic acid resin), upflow through the first and downflow through the second. The uranium first saturates the resin, then breaks through as a purified product. The impurities are retained on the resin. The resin is regenerated by a water rinse to displace the residual uranyl nitrate solution followed by eluting with 6 M HNO_3 to remove thorium, radium, and other extractable material. The purified uranium is returned to the uranium feed storage tank for recycle into the fuel kernel preparation process (Fig. 4.8). The amounts of material flowing through the scrap recovery system are listed in Table 4.10.

4.1.2.5 *Scrubber Systems.* - Two types of scrubber systems are used to treat the airborne effluents before they are released to the environment. Scrubbers containing perchloroethylene (C_2Cl_4) are used to remove the carbonaceous material formed in the resin carbonization and conversion processes, coating operation, and element carbonization steps. The residues from the C_2Cl_4 scrubbers are dried and recycled to the scrap recovery system for uranium reclamation. Perchloroethylene is purified by distillation.

An aqueous scrubber containing a solution of sodium hydroxide is used to remove HCl from the SiC coating process. The solutions containing traces of uranium and other materials are concentrated by evaporation and incorporation in cement.

4.1.2.6 *Miscellaneous Liquid Wastes.* - All miscellaneous liquid wastes, such as are generated from laundering of clothing, personnel showers, floor drains, etc., are converted to solids. No liquid radioactive effluents are discharged from the plant. If any intermediate- or high-level wastes are generated as a result of process upset or other unusual circumstances, they are transferred to the reprocessing plant by special handling procedures and treated by its conventional facilities. All sanitary water, waste sewage streams, and cooling tower water are monitored and, if found free of radioactivity, are sent to a sanitary sewerage system and then transferred to an equalization pond before being discharged into a nearby stream. In the event radioactivity is found, the effluents are converted by evaporation to solids. The purified condensate is recycled or released.

4.1.2.7 *Miscellaneous Solid Wastes.* - Solidified liquid waste containing radioactivity is shipped from the plant as packaged solids. Contaminated solids such as paper, cans, clothing, and filters are compacted in drums at the refabrication plant and shipped off-site. These solids are not released to the environment but are disposed of in accordance with applicable regulations. In current practice these wastes are sent to commercial burial grounds. However, amendments³³ to 10 CFR 20 are being proposed by the USNRC which would prohibit the disposal-by-burial of wastes containing transuranic element concentrations in excess of 10 nanocuries/gram and require the transfer of such wastes to storage at a Federal repository.

4.1.2.8 *Process and Ventilation Airborne Effluents.* - There are three basic levels of confinement in the fuel refabrication plant. Confinement, in this context, means a complete enclosure around the radioactive material, where the pressure inside the contained volume is maintained at a lower level than the surrounding area so that any leakage in the enclosure will draw material inward rather than allowing escape. Confinement systems require complete enclosures with associated ventilation equipment. In a room that serves as the confinement barrier, this means that windows, doors, or other openings are normally closed and the room is kept at a lower pressure than its surroundings. The first level of confinement is the process vessel or equipment inside the glove box. The second level of confinement is the glove box or other equipment enclosure, or a totally enclosed transfer device. The final confinement is provided by the building structure.

In the recycle fuel fabrication plant, outside air is drawn into the manufacturing building via a filter, tempering coil, and fan set, and then distributed throughout the normal access area at slightly less than atmospheric pressure. The ventilation air is combined with the process gas,

and the combined off-gas (approximately 90,000 cfm) is discharged through a 100-m stack shared with the reprocessing plant

The source terms in this study are calculated based on the estimate that approximately 2% of the radioactive material entering the plant will be suspended in the off-gas prior to any treatment of the off-gas (i.e., in the streams leaving the process equipment in Fig. 4.13). Using these assumptions, the estimated amount of radioactive material in the airborne effluent from the plant in Case 1 is 55% of the Radiation Concentration Guide (Code of Federal Regulations, Title 10, Part 20, Appendix B, Table 1, Column 1) for soluble materials

4.2 Composition and Amount of Radioactive Material Entering the Model Plants

The fresh fuel fabrication plant processes approximately 490 thousand kg of thorium and 21 thousand kg of uranium per year. This amount of feed represents 2650 Ci of radioactivity, which is equally divided between the thorium and uranium streams. The refabrication plant processes 30 thousand kg of recycled uranium and receives approximately 225 thousand kg of thorium as coated fertile particles from the fresh fuel plant on a yearly basis. The total activity entering the refabrication plant is 690 thousand Ci per year, of which nearly 98% is contributed by the 23R stream. The isotopic composition of the feed to each of the fuel fabrication plants is given in Table 4.11, and the criteria for the selection of this list are as follows:

1. The feed to the two fuel fabrication plants is based on the requirements of a typical reference 1000-MW(e) reactor³⁴. Each reactor loading contains 8.1 metric tons of thorium and 0.81 metric ton of uranium. These quantities represent average annual reactor reload values over a 30-year lifetime for an HTGR (Table 3.1), assuming that the residency of the ²³⁵U will be eight years and will be burned twice. Therefore, the model fuel fabrication plants can service approximately 53 reference 1000-MW(e) HTGRs per year. The expected burnup in fissile particles is approximately 70% fissions per initial metal atom (FIMA) for fuel containing ²³⁵U after the first cycle. Dilution with thorium will reduce this value. Fuel containing only thorium will experience about 5% FIMA. The reference reactor assumed for the CITATION³⁴ computer code calculations operates with an average burnup of 95,000 MWd/MTM (40,000 MWd per metric ton of thorium and approximately 700,000 MWd per metric ton of uranium originally charged as enriched uranium).
2. The highly enriched uranium feed to the fresh fuel fabrication plant contains 0.94 wt % ²³⁴U, 93.09 wt % ²³⁵U, 0.21 wt % ²³⁶U, and 5.76 wt % ²³⁸U, and has aged for several months since passing through a gaseous diffusion plant. Thorium-234 and ²³⁴Pa are in secular equilibrium with ²³⁸U, ²³⁴Th requires 168 days to grow back to 99% of secular equilibrium with ²³⁸U. Protactinium-234 requires approximately 7 minutes to grow back to 99% of secular equilibrium with ²³⁴Th. Therefore, ²³⁴Pa will be in secular equilibrium with ²³⁴Th at all times. Thorium-231 is in secular equilibrium with ²³⁵U. Thorium-231 requires approximately 7.5 days to grow back to 99% of secular equilibrium with ²³⁵U.

3. Natural thorium is commonly considered to be ^{232}Th . However, thorium minerals or compounds over fifty years old contain approximately 1.3×10^{-10} grams of ^{228}Th per gram of ^{232}Th . In addition to ^{228}Th , the thorium decay chain (Fig. 4.14) includes ^{228}Ra , ^{228}Ac , ^{224}Ra , ^{220}Rn , ^{216}Po , ^{212}Pb , ^{212}Bi , ^{212}Po , ^{208}Tl , and ^{208}Pb , the latter being stable. All of these isotopes are in secular equilibrium if the thorium is "old." Extraction of thorium from minerals or thorium compounds separates the ^{232}Th and ^{228}Th isotopes from the radium, actinium, radon, polonium, lead, bismuth, and thallium daughters. In freshly purified thorium, the ratio of ^{232}Th and ^{228}Th activities is unity for a few moments. However, ^{228}Th , with a half-life of 1.9 years, will decay appreciably with a corresponding reduction in activity. The daughters of ^{228}Th , limited by the 3.64-day half-life of ^{224}Ra , reach secular equilibrium with ^{228}Th in a few weeks and then follow the ^{228}Th decay. The regrowth of the daughters of ^{232}Th is limited by the 5.75-year half-life of ^{228}Ra . This builds up the activity of ^{228}Th which otherwise would have been reduced by a factor of 1000 in approximately nineteen years. The decay of the ^{228}Th chain and the regrowth of the ^{232}Th chain result in a ^{228}Th activity level after a refining operation which goes through a broad minimum of 50% of the secular equilibrium activity at six years beyond refining (Fig. 4.15).^{35,36} The assumption has been made that the thorium feed material has "aged" for six months since refining. Therefore, the ^{228}Th activity plus the activities of its daughters comprise approximately 80% of the equilibrium activity.
4. The quantity of ^{230}Th in the fertile particle material has a significant influence on the amount of ^{232}U present in the 23R stream. Thorium-230 per se presents few problems but, during its residency in a nuclear reactor, is converted by neutron absorption into ^{232}U (Fig. 4.14) which has daughter products that emit high-energy gamma radiation. The most important daughters of ^{232}U are ^{212}Bi and ^{208}Tl . Bismuth-212 is produced from ^{232}U after a succession of five alpha emissions and a beta emission, and decays with highly penetrating gamma radiation (0.4 to 2.1 MeV). The decay of thallium-208 also produces a high-energy gamma ray (2.6 MeV). An alpha-produced neutron background is also present, since many of the alpha emissions have sufficient energy to strip neutrons from light metal impurities. The uranium will emit little gamma radiation for a limited time after being chemically processed because of the relatively long half-lives of ^{232}U (72-year) and ^{228}Th (1.9-year). All the daughter products after ^{228}Th have relatively short half-lives, and as a result, the radiation level increases gradually (Fig. 4.16). Thus, for a short period of time after reprocessing, uranium-233 can be handled in glove boxes with minimal shielding. After several weeks, the radiation level increases such that heavy shielding is required. The yield of ^{232}U from various nuclides after irradiation in an HTGR is listed in Table 4.12. Two values have been assumed for the ^{230}Th content in the initial thorium feed material to the fresh fuel fabrication plant: the maximum fuel specification value of 100 ppm, and a value of 10 ppm.³⁷ At a concentration of 100 ppm ^{230}Th , the steady-state concentration of ^{232}U is calculated to be about 940 ppm, Table 4.12, and its lifetime average is assumed to be about 80% of this value, namely 750 ppm. At a concentration of 10 ppm ^{230}Th , the steady-state concentration of ^{232}U is calculated to be about 370 ppm and its lifetime average is assumed to be about 80% of this value, or 300 ppm.

- 5 The feed material to the refabrication plant is received as two separate streams from the reprocessing plant. The aging time for the 23R stream (defined as the time since chemical purification and removal of ^{23}U daughter products) during refabrication is assumed to be 90 days. Aging time for the 25R stream is much less restrictive due to its low ^{23}U content, however, a time of one year is assumed.
- 6 Small amounts of fission products and transplutonium elements follow the uranium through the reprocessing plant and are associated with the uranium feed to the refabrication plant. The amounts present in the feed to the refabrication plant are based on (a) the calculated average amounts of fission products in the spent reactor fuel that enters the fuel reprocessing plant after a cooling time of 160 days (calculated using the ORIGEN computer code),³⁸ (b) decontamination factors (DFs) in the reprocessing plant of 1×10^6 for all fission products and transplutonium elements, and (c) the conservative assumption that the impurities remaining after fuel reprocessing emerge with the uranium product.
- 7 Cross-contamination (partial mixing) of the two streams (23R and 25R) will probably occur in the reprocessing plant. Crossover of uranium occurs in the leaching process by absorption through cracks or fissures in the particles and from fractured or broken particles during irradiation and crushing, and appears to be a function of the integrity of the particle coating. Uranium crossover is also a function of the leach time. The assumption has been made that there is a 5% crossover of the 25R stream into the 23R stream and a 1% crossover in the opposite direction.³⁹

The relative inhalation hazard for each nuclide is estimated by dividing the curies present in 1 ton of feed to the model plants by the Radiation Concentration Guide (Code of Federal Regulations, Title 10, Part 20, Appendix B, Table II, Column I) for that nuclide (Table 4.13). Nuclides whose contribution to the total relative inhalation hazard are $<0.02\%$ are excluded from consideration when calculating source terms. Radionuclides that are excluded on this basis are examined to ensure that they would not contribute more than 0.02% of the total body dose for individuals in the case studies as the result of bioaccumulation in the environment. Table 4.13 also lists the radionuclides selected as constituents of the source terms, along with their specific activities.

4.2.1 Source Terms for Radioactive Nuclides with Precursors Present

In the calculation of source terms for any facility processing radioactive material, one usually omits the quantities of nuclides being formed from precursors because the amounts are insignificant when compared with the secular equilibrium value. However, there are several isotopes in the HTGR fuel fabrication facilities where the rate of production is rapid enough to contribute materially to the source terms. The rate of formation and decay of such a nuclide, 2, with a precursor, 1, is given by

$$dN_2/dt = \lambda_1 N_1 - \lambda_2 N_2 \quad ,$$

where N_1 and N_2 are the numbers of atoms or gram-atoms of nuclide 1 and 2 present and λ_1 and λ_2 are their corresponding decay constants. At secular equilibrium the quantity of nuclide 2 will be constant, that is, it will be formed ($\lambda_1 N_1$) as fast as it decays ($\lambda_2 N_2$). Therefore, $\lambda_2 N_2$ can be used to calculate the production rate for an isotope that is in secular equilibrium with its parent. Table 4.14 is a listing of the formation rates of several nuclides present in the fuel fabrication plants. In most cases the formation of additional quantities of specific isotopes will have little effect on the source term because the material will decay nearly as fast as it is formed and will remain in the plant. However, several of the nuclides (lead, bismuth, and radium) are sufficiently volatile under the high-temperature conditions (approximately 1700°C)⁴⁰ of the fabrication operations so that their rate of production exhibits a marked increase in the source terms. Radon-220, a gas, presents the greatest hazard with respect to confinement for it enters the process off-gas system from all unencapsulated material. Retention tanks or charcoal traps have been included in process operations to permit the decay of ^{220}Rn to its solid daughter products (^{212}Pb and ^{212}Bi), which can be removed by filtration.

4.3 Description of Waste Treatment Methods

4.3.1 Airborne Radwaste Treatment Systems

During normal operation of the fuel fabrication facilities small amounts of uranium, thorium, and their daughter products are entrained in the process airborne effluent streams. These particles are generated by the drying of entrained droplets of process liquids and from the entrainment of fine particles in the fabrication operations. These effluents are treated using a variety of unit process operations to minimize the release of radioactive or other noxious materials. Volatile, semivolatile, and particulate radioactive materials are removed by dust collectors, filters, scrubbers, and radon retention or charcoal traps. Many of these treatment methods are in use or are in the development stage. Each of the case studies represents either increasingly efficient treatment systems or improvements in processes which are described in Sects. 4.5.1 and 4.5.2. The costs for each off-gas treatment system in the four case studies for each of the plants are estimated and are presented in Sect. 6.0. The design of the airborne treatment systems in the base case for the fresh fuel plant represents contemporary practice for design of fuel fabrication facilities (Sect. 3.2.1). Many of the off-gas treatment systems for the refabrication plant base case (Sect. 3.2.2) have been used in other industries but have not been applied to HTGR recycle fuel fabrication operations. However, these processes are being applied on an experimental engineering basis, and are expected to be available for inclusion in the first refabrication plant to be built in the middle 1980s. The treatment methods that have been considered for the airborne effluents are described in the following sections.

4.3.1.1 *Gas Scrubbing* - The term "gas scrubbing" describes the technique of bringing gas into intimate contact with a liquid. Under certain conditions the liquid is capable of removing polluting material, which may be either particulate or airborne, from the gas. The mechanisms involved in a particular process may be some or all of the following:

- (a) *Impaction* - The collision and absorption of aerosol particles by the liquid droplets.

- (b) *Diffusion* The diffusion of gases and very small aerosol particles through the boundary layers to the liquid droplets, if they are absorbed. This process is of great importance if particles are of diameters less than 0.05 micron.
- (c) *Condensation:* Vapors at temperatures below their dew points condense readily on nuclei, such as aerosol particles, which may thereby be agglomerated.
- (d) *Electrostatic charging.* The electrostatic charge required by liquid droplets during their formation could assist aerosol entrainment.

A major advantage of the wet scrubber is the great variety of designs, which allows selection of a collector suitable for almost any collection problem. Many of them are standard industrial equipment available "off the shelf." Another advantage of the scrubber is that the temperature and moisture content of the inlet gas are essentially unlimited. Some of the disadvantages of the wet scrubber include the disposal of a wet sludge, the high energy cost of the high-efficiency scrubber, the high material cost related to services where there is chemical corrosion, and the potential problems of plugged nozzles, unavailability of scrubbing liquid of sufficient clarity, and the treatment of corrosive scrubbing liquids. A unique disadvantage of the wet scrubber is the visible white plume which is characteristic of all aqueous scrubber stacks discharging to the atmosphere without downstream gas conditioning.

Most conventional scrubbers, when used in the normal manner, have a limited capability for retaining fine particulates⁴¹ because they depend on some form of inertial collection of particulates as their primary mechanism of capture. As a result, collection efficiency drops rapidly as particulate size is decreased to the point where inertial forces become negligibly small. Therefore, the energy input into a scrubber must be increased significantly to improve its ability to collect smaller particulates. The energy can be introduced in either the water cycle or the gas cycle. In most commercial collectors essentially all of the energy is introduced in the gas cycle and can be measured as draft loss in inches of water. Even with large energy inputs, their collection efficiencies in the submicron range are not good. For example, the orifice- or baffle-type collector is 93% efficient on 5-micron particles, 75% on 2-micron particles, and only 40% on 1-micron particles.⁴² However, scrubbers demanding high energies (e.g., the venturi) customarily exhibit efficiencies of 99% on 2-micron particles.

Spray Chamber Scrubber - This scrubber, one of the simplest, is a gravity settling scrubber in which fine water sprays wash the gas and settle the dust as sludge for removal.⁴³ The gas is slowed in the inlet nozzle, traverses its way through the turbulence caused by the force of the fine sprays, then passes through the demister section, and is speeded up in the outlet nozzle to its initial velocity. As in all settling chambers, some coarser dust will settle under the influence of gravity. Major collection is accomplished by collision between a dust particle and a water droplet. Efficiencies of spray tower scrubbers range from 94 (5-micron particles) to 55% (1-micron particles). A value of 90% was used for the efficiency of removal of entrained solids from airborne effluents, and a value of 99% for acidic mists (HCl, HNO₃, etc.) in the caustic scrubbers in this report.

Impingement Baffle-Plate Scrubber. - This device consists of a tower equipped with one or more wetted impingement baffles, each consisting of a perforated plate.⁴⁴ The gas and dust are first conditioned by a coarse spray, then passed up through the flooded impingement baffles. The small holes divide the total gas stream into many small ones. Because of the high velocity, perhaps 100 ft/sec, the edges of the holes atomize the liquid into 10-micron droplets. Fine droplets increase the collection of fine dust. Each hole is equipped with a small target plate

upon which the dust and droplets impinge at high velocity. Liquid flow control is effected by weirs and interstage overflow piping. The upper section of this scrubber is normally equipped with a vane axial demister. These scrubbers may be of single- or multiple-stage construction and may have a tangential inlet, thereby facilitating collection and wetting of dust by using centrifugal force as in a tangential inlet cyclone. An efficiency of 95% is assumed for particulate removal and 99.5% for acidic mists in this report.

Venturi Scrubber - In the venturi scrubber, the gas is passed through a rectangular or round venturi at high to very high velocities^{45,46}. The cleaning liquid is introduced into the throat of the venturi through coarse nozzles. Gas velocities in the range of 10,000 to 40,000 ft/min through the venturi throat impact the liquid, causing very small droplets to form. Extreme turbulence and mixing result. Because of high gas velocities, the venturi is the most compact of all scrubbers.

The collection efficiency of the venturi scrubber is directly related to the energy expended. At expenditures of energy of 3 to 10 in. of water, collection efficiency is comparable to that of a wet cyclone (approximately 90%). At pressure drops of 10 to 30 in., collection efficiency is comparable to that of a multiple impingement baffle scrubber, and at pressure drops of 30 to 100 in., efficiency exceeds all other wet scrubbers and can match that of the bag filter and the electric precipitator. The efficiency for particulate removal in this report is assumed to be 99% for particulates and 99.9% for acidic mists.

4.3.1.2 *Bag Filters*⁴⁷⁻⁴⁹ - In this report, the term "bag filter" embraces all versions of filters used for recovering or separating dust from air, and in which the filter medium is made from cloth fabricated in the form of a cylinder, tube, pocket, or bag. Bag filters are used to separate dust from large volumes of gases flowing under a small pressure differential, hence a large surface area is required. The medium is usually hung vertically to facilitate the removal of the deposited dust. The mechanisms acting in bag filters are considered to be:

- (a) *Direct interception* - If the center of a spherical particle follows faithfully the flowline around a fiber, and the flowline approaches closer to the fiber than the radius of the particle, then particle and fiber touch. This mechanism is obviously more important with larger particles.
- (b) *Diffusion* - The bombardment of particles by gas molecules causes them to deviate from the flowlines, thus increasing the chance of capture. Diffusion effects increase with smaller particles and lower velocities.
- (c) *Inertia* - Massive particles tend to follow a straight path instead of following the air streamlines around a fiber and, hence, may be captured. The inertial mechanism becomes more important with increasing particle mass and velocity.
- (d) *Electrical effects* - Charges on particles and fibers may play a considerable part in gas filtration. Neutral particles penetrate a filter more readily than charged particles of similar size.
- (e) *Sedimentation* - At low gas velocities the terminal velocity of large particles may be sufficient for capture by sedimentation. This mechanism is not, however, of concern in the usual type of bag filter. It is, perhaps, of more importance in granular filters of large volume, for example, sand beds.
- (f) *Sieving action* - Once an initial layer of the dust has been built up on the surface of the medium, this in turn provides the main means of filtering out further dust with

improved efficiency, analogous to cake filtration in the separation of solids from liquids

The media used are woven fabrics of natural or synthetic fibers. The type of yarn, weave, and final finish is chosen to suit the duty required. The formation of the surface layer is dependent on the fine hairs which protrude from the main fibers. Asbestos fibers have been used to increase the efficiency of filtration, but the practice is not recommended because a considerable health risk is attached with the use of asbestos. The inability to withstand extreme temperatures, corrosive atmospheres, and undue mechanical strain limits the use of bag filters. Other disadvantages include large size and high maintenance due to the cost of bag replacement, and plugging of fabric due to moisture resulting from operation below the dew point.

The efficiency of a bag filter increases dramatically as the initial layer of dust builds up on the surface medium. Efficiencies as low as 2% have been measured on new lightweight plain cloth. However, after deposition of the initial layer, the collection efficiency of an individual bag frequently approaches 100% for particles down to the submicron size range.⁵⁰ However, overall process efficiencies are somewhat lower, due to dust losses during initial layer formation. Two values were assumed for the efficiency of bag filters in this report: 95% for medium efficiency filters which are heavily challenged by carbonaceous material and exposed to high-temperature process off-gases (represented by soot filters in the flowsheets), and 99% for high efficiency filters used for final cleanup of gas streams or where less particulate material is involved (represented by bag filters in the flowsheets).

4.3.1.3 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. These filters, which are composed of expendable (single-use) pleated mats of fiberglass paper, are installed in banks to achieve the required system capacity. They are specified to exhibit a minimum efficiency of 99.97% for 0.3-micrometer particles and a maximum resistance (when clean) of 1.0 in. H₂O pressure when operated at rated airflow. Tests of filter efficiency are conducted in special facilities which ensure that no significant leakage occurs around the sides of the filter or through other bypasses. An equally tight filter enclosure in a field installation must be constructed to achieve the rated filtration efficiency. The construction of large, tight filter enclosures is a difficult engineering task. Testing of the individual filter banks in place in the enclosure, both before and periodically during the service period, by the dioctyl phthalate (DOP) smoke test is required to ensure that no significant leaks are present in either the filter or the enclosure.

Variables that have been considered in HEPA filter performance analyses include the particle size distribution of the various plutonium aerosols encountered. A recent literature survey, however, does not indicate a gross variation in the range of reported particle sizes in field operations.⁵¹

Several tests have been carried out with plutonium aerosols in small laboratory and large-scale field installations. In a detailed survey, Hetland and Russell found large-scale filter systems which produced overall mass removal efficiencies of 10^7 or greater.⁵² 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.^{53,54} Ettinger et al. have performed laboratory tests using plutonium aerosols in small installations that are tightly sealed and tested periodically for leaks with DOP.⁵⁵⁻⁵⁷ They have observed removal efficiencies of at least 99.97% for each of three single filter stages in series. AEC Regulatory Guide 3.12 for the design of plutonium ventilation systems indicates that removal efficiencies of $>99.95\%$ should be obtained for a single bank of HEPA filters if the installation containing the filters is constructed according to the recommended guidelines and is tested for leaks after the filters have been installed.⁵⁸ Consequently, a value of 99.95% has been used in this study to represent the *rated* efficiency of each HEPA filter that has been properly installed and DOP tested.

Several factors must be considered, however, in predicting the overall *installed* efficiency of multiple filters in series even though each bank is tested separately in place with DOP and shows an efficiency of 99.95 to 99.99%. First, several tests show that the second and third filters are exposed to much lower concentrations of particles with a size distribution that is strongly biased toward the smaller sizes.⁵⁶ Secondly, filter efficiencies are sensitive to gas flow rate, and possibly all filters in a bank may not experience the same flow rate. Finally, the concentration of particles is different for each stage of filtration, and filter efficiency varies with particle concentration. 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.⁵⁹ Consequently, the overall *installed* filter system DFs selected for use in this study for HEPA filters in series are based on a lower efficiency than the *rated* DF values. For each case study, this approach will result in costs and doses that are realistically conservative. An efficiency of 95% has been assigned to "low-efficiency" filters which are not tested periodically in place with DOP and are not monitored for efficiency by observing the pressure drop across the filters. Although the overall rated efficiency for two HEPA filters in series is equivalent to a DF of 4.0×10^6 , a conservative value of either 4×10^4 (a system comprising a "low efficiency" HEPA filter, 95% efficient, and a normal tested HEPA filter, 99.95% efficient) or 4.0×10^5 (a system consisting of two normal tested HEPA filters, the first filter exhibiting an efficiency of 99.95% and the second filter exhibiting an installed efficiency of 99.5%) is used in this study.

4.3.1.4 Charcoal Delay Traps⁶⁰⁻⁶² - Since radon-220 has a short half-life of 56 seconds, systems which delay the noble gases can be used effectively to reduce the total activity by radioactive decay. In the dynamic absorption process, an airborne species in a flowing carrier gas stream is physically adsorbed on the surface of a solid adsorbent. Although the adsorbate is not bound permanently to the adsorbent, its exit from the adsorption bed is delayed with respect to the carrier gas. Thus, the short-lived noble gas disappears by radioactive decay while it is detained on the charcoal bed. Currently, activated charcoal is used to remove krypton and xenon from the airborne effluents of nuclear power plants. Therefore, this method should be feasible for removing ^{220}Rn from off-gas streams. A recent review article summarizes the literature, theory, and data for the removal of ^{220}Rn from off-gas streams by adsorption on charcoal.⁶³ The following mathematical expression was derived:

$$DF = [(1 + NF/km \lambda)/(NF/km \lambda)]^N ,$$

which expresses the decontamination factor (DF) in terms of the number of theoretical plates (N), the volumetric flow rate of the carrier gas (F), the holdup coefficient (k), the mass of the sorbent in the adsorber (m), and the decay constant (λ).

The following items must be considered in the design and operation of charcoal adsorption beds:

- (a) A filter is placed upstream of the charcoal bed to prevent plugging of the bed, and a HEPA filter is placed downstream of the bed because ^{220}Rn daughters are not quantitatively retained in the bed. The daughters are formed as small dust particles.
- (b) Relative humidity of the air stream must be $<10\%$ if the above equation is to be used.
- (c) Shielding is required because of the increased level of radiation.
- (d) Buildup of mass and heat is negligible.
- (e) Large charcoal beds are a potential fire hazard.
- (f) There is a deficiency of both laboratory and operating data that can be extrapolated for design purposes.

4.3.1.5 *Subambient Process Cooling.*^{64,65} - HTGR fuel fabrication operations generate large amounts of heat which must be dissipated. Normally, major process heat dissipation is by means of a cooling tower system. Process cooling water is chilled by passage through a shell-and-tube heat exchanger to a cooling tower. The cooling tower water is pumped over open baffles where the water is cooled by evaporation. However, some process off-gas streams in the refabrication and fresh fuel plants require subambient cooling via condensation to remove perchloroethylene which would poison the charcoal delay traps.

Subambient cooling refers to operations where the temperatures are lower than that which can be obtained by the use of process water from the mains, from a cooling tower, or by the use of water to air heat exchangers. To achieve cooling in the subambient range, it is necessary to use a refrigerant system and to reject the waste heat into the standard sinks, such as cooling water or ambient air.

Initial capital costs and operating costs are important factors to be considered in the selection of a subambient cooling system. The effects of this choice are demonstrated by the following examples.

- (a) *Use of ice or of liquefied or solidified gas:* Although this type of operation reduces the initial capital cost, limitations may arise because of the temperatures of the media concerned and the methods of application.
- (b) *Use of a compression refrigerator coupled for direct expansion of refrigerant:* This type of equipment has limited flexibility, and careful manufacture and connection of the direct-cooling circuit are essential.
- (c) *Use of a chilled water refrigeration unit:* The use of this type of equipment provides flexibility. This system can be coupled to process equipment while eliminating the concern for the tightness of the true refrigerant circuit.

A variety of equipment is available for operations near the freezing point. Ice or ice-mixtures may be suitable on a small scale. Fractional horsepower hermetic compressor units are available for heat extractions at rates below 5,000 Btu/hr. Standard compressor units, with

installed ratings of 1/2 to 5 hp, will normally fill the requirements in the range between 5,000 and 50,000 Btu per hour

Several options are available where operations at near 0°F are required. Solid carbon dioxide may be used for small batch operations. Compressor refrigerators using a normal refrigerant can be used for the range between 5,000 and 500,000 Btu/hr, but their power requirements are nearly doubled when compared with their operation just above the freezing point. At -40°F the installed horsepower for this range becomes approximately 2 to 100 hp. At still lower temperatures, compressors in cascades or centrifugal compressors in cascades are required.

4.3.2 Liquid Radwaste Treatment Systems

Both fuel fabrication facilities generate liquid effluents which contain uranium and thorium compounds and their daughter products. These liquids containing radioactivity are produced in the scrap recovery operations, in several of the processing steps, and are found in the scrubbers that are used in the airborne radwaste treatment system. The major objectives of the liquid radwaste treatment system are (a) to return the valuable uranium and thorium components to the process lines along with a minimum amount of impurities, and (b) to prevent the release of small quantities of these materials which cannot be recovered economically. Various unit process operations are used to treat these effluents. The scrap recovery system utilizes solvent extraction (fresh fuel plant) or ion exchange (refabrication plant) to recover and separate the uranium and thorium from undesirable impurities and to prevent their release to the environment. Chemicals are added to process streams to remove radioactive materials via precipitation, occlusion, adsorption, etc. These solids are removed in holding and settling tanks and by filtration and centrifugation. In advanced case studies, liquid wastes are evaporated to retain both soluble and insoluble impurities and the purified condensate is recycled for reuse or released to the lagoon. Radioactive liquids are not released to the environs in any of the case studies at the refabrication plant or in Cases 2, 3, or 4 at the fresh fuel plant. Liquid effluents containing trace quantities of radioactivity are released in the base case of the fresh fuel plant. Miscellaneous liquid wastes are released after they have been filtered to remove solid matter, pumped to an equalization pond, sampled and analyzed for radioactive contamination, and discharged. The treatment methods that have been considered for the liquid effluents are described in the following sections.

4.3.2.1 *Holding and Settling*⁶⁶ - The uranium in the liquid wastes is present as sodium or potassium diuranate or some form of uranium oxide which is in solution or suspended as solids. Thorium is present as the hydroxide or hydrated oxide. The amounts of uranium and thorium in solution can be particularly high when the solution has not been retained long enough to achieve complete precipitation, i.e., long enough to approach the equilibrium solubility of these compounds. The use of holding tanks to allow time for additional precipitation, coagulation of colloidal particles, and settling of solid particles is an important treatment technique. A hold-up time of 16 to 20 hours significantly increases the amount of uranium and thorium 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.

4 3 2 2 *Filtration and Centrifugation*⁶⁷ - Filtration is used to remove the insoluble uranium and thorium 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 streams. Continuous rotating drum filters are used in this study but other types of filters could be used. The difference in cost would be minimal 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. 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, all but the finest particles are removed from the stream.

4 3 2 3 *Evaporation* - Evaporation is commonly used in the chemical industry to concentrate aqueous solutions by boiling off the water and leaving behind most of the dissolved solids and materials having vapor pressures lower than water.⁶⁸ Similarly, evaporation is very effective in separating dissolved radioactive solids from waste water, and essentially all sizes and types of evaporators have been used in the nuclear industry. However, materials which have vapor pressures higher than water or which combine with water to form high-vapor-pressure materials are difficult to separate from water by evaporation.

In evaporating radioactive waste, care must be taken to avoid too rapid boiling or foaming since each tends to cause the entrainment of minute particles of radioactive solids or liquid droplets in the vapor rising from the boiling liquid surface. Also, the velocity of the vapor must be kept low and the distance the vapor travels upward (disengaging space) must be as long as practicable to encourage particles and droplets to fall back into the liquid rather than be carried over into the condenser with the vapor. A variety of devices to de-entrain particles and droplets can be incorporated into evaporators to improve DFs to as high as 100,000 or even a million. Such devices work by changing the direction of the vapor path, causing particles and droplets to impinge on and adhere to metal surfaces from which they can later be flushed back into the liquid. Wire mesh filters, sieve trays, bubble-cap trays, and centrifugal separators are among such devices.

Evaporators for radioactive waste can vary from simple pots with steam heating pipes coiled inside to elaborate devices having pumps which circulate the feed through outside heaters and compressors which squeeze more heat efficiency from the hot vapor (vapor compression evaporators). In general, less expensive maintenance and more satisfactory operation are obtained from simple evaporators equipped with adequate auxiliaries to achieve the DF required. Depending on the amount of dissolved solids in the waste fed to an evaporator, a volume reduction of 10 to 50 can usually be achieved in the radioactive thick liquor (bottoms or concentrate) while maintaining the level of radioactive material in the condensate (overheads or distillate) 10,000 to a million times lower than that in the bottoms. To achieve such good separation, however, no foamover can be permitted and entrainment must be kept to a minimum. Therefore, laundry wastes containing detergents or other foam-producing materials

must be excluded from the evaporator. Liquid waste evaporators should be tested before use on actual waste streams. This is probably the only reliable method of demonstrating that the desired DF values can be achieved over the extremes of conditions expected. Stable isotopes and tracer levels of radioactivity can be used in these tests. An overall decontamination (separation) factor of more than 10,000 between condensate (distillate) and thick liquor (concentrate) is generally expected for nonvolatile radioactive contaminants treated in single-stage evaporators and was assumed in this study.

4.3.2.4 *Anaerobic Digestion*^(9, 71) - The denitration of thorium nitrate produces large quantities of nitric acid, considerably more than can be used by the plant. A biological denitrification disposal technique is used to convert the excess nitrate to nitrogen gas in advanced cases and to reduce the amount of nitrate released to the environment. The process requires anaerobic conditions and an organic carbon source as well as other life-sustaining compounds such as phosphates and sulfates. Acidic process effluents containing 15 to 50% nitrate ion are first neutralized with hydrated lime and diluted to obtain 10 to 13% nitrate ion in solution prior to feeding into a suspended growth-type biological reactor. No packing medium is required due to the presence of colloidal precipitates and significant growth of bacteria. During the growth of the bacteria, the calcium nitrate is converted to nitrogen gas and Ca(OH). The nitrogen content of the waste stream can be reduced by a factor of greater than 100. Detention times for batches can vary, depending on operating parameters and feed conditions. Anaerobic digestion is currently in use in municipal and industrial waste treatment systems and, with a competent development program, probably could be "reduced to practice" for use at fuel fabrication plants.

4.3.3 *Solid Radwaste Treatment Methods*

A principal operational function of the waste processing area is to reduce the volume of chemical solutions and waste solids so that they may be solidified and packaged for storage on-site or for shipment to a licensed commercial burial ground. The radwastes include aqueous residues, sludge from evaporative processes, incinerator ash, and nonburnable items that are slightly contaminated with radioactive materials. In the Case 1 study for the fresh fuel plant, the solid waste residues from the scrap recovery operations, along with other miscellaneous wastes, are packaged in drums for storage on-site or for shipment to a licensed, commercial burial ground. In the advanced case studies for the fresh fuel plant and for all case studies in the refabrication plant, the solid wastes and the concentrated bottoms from the evaporation of miscellaneous and scrap wastes are incorporated in cement. This technique is an established technology that is widely practiced at power reactor stations and is available for immediate use at fuel fabrication plants⁷⁷. Part of the waste from the refabrication plant may be shipped for storage in Federal repositories, if the proposed new Federal regulations³³ are adopted, since this material is slightly contaminated with uranium-232 and uranium-233. If so, these radwastes may be stored temporarily on-site in a licensed facility.

4.4 Selection of Case Studies

Four conceptual case studies, each chosen to reflect a decreasing release of radioactivity for an increasing sophistication of radwaste treatment, have been selected for each of the fuel fabrication plants. Inclusion of specific treatment techniques was not based on cost, but on the effectiveness in reducing the radioactivity of plant effluents. Most of the treatments included have been utilized in either pilot-plant or industrial-scale operations, although no existing fabrication plant has used some of the treatment methods selected for the advanced cases. The efficiency of a treatment system or process operation for retention of radioactive material is expressed as a decontamination factor (DF), i.e., the ratio of the amount of material entering the operation to that released in the waste effluent from the operation.

Case 1 reflects current practice in HTGR fresh fuel fabrication operations where small amounts of naturally-occurring radioactive materials are released to the environment in the plant effluent. No liquids containing radioactivity are released in the advanced cases of the fresh fuel plant or in any of the case studies for the refabrication plant. The cases studied, along with the treatment systems and the DFs for these systems, are summarized in Table 4.15 for the fresh fuel plant and in Table 4.16 for the refabrication plant.

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 summary figures for the case studies and in Table 4.17 for the fresh fuel plant and in Table 4.18 for the refabrication plant. The parameters used in the calculation of the source terms are presented in Sect. 4.5.3. The amounts of nonradioactive noxious materials (nitrate, fluoride, ammonia, etc.) are listed in the material balance tables for each case.

4.5.1 Fresh Fuel Fabrication Cases

4.5.1.1 *Case 1* - Case 1 is the "base case" for the model fresh fuel fabrication plant and is similar to and has features of an existing pilot plant⁷³ and a commercial plant⁷⁴ to be built in the late 1970s. The selection of assumptions used to calculate the source term in this case is particularly important since the improvements presented in succeeding cases are incremental with reference to the base case. The background information available to substantiate the estimates of the amounts of various types of radioactive materials released from the model plant is limited because of the limited experience established in private industry. Estimates of the amounts of radioactive materials released (Fig. 4.17) are based on experience at the General Atomics (GA) plant at LaJolla, California,⁷³ an environmental report of a plant to be built in Youngsville, North Carolina by GA,⁷⁴ on the experience of other fuel fabrication plants utilizing similar operations,⁷⁵⁻⁷⁷ and a current ERDA development program.⁷⁸

Fissile Particle Production. - A summary flowsheet for the production and waste effluent treatment systems for the fissile particles is shown in Fig. 4.1; the material flows are presented in Table 4.1. The following process decontamination (or containment) factors (ratio of amount of material processed to that released by a process) are used for particulate material for each of the operations listed: chemical conversion, 500; kernel preparation, 2×10^3 ; buffer and high-density isotropic coatings, 20; silicon carbide coating, 200; particle cleaning, 1×10^4 ; and drying, 1×10^6 . The complexity of the fissile particle production operations results in a recycle rate of approximately 8.2 thousand kg of uranium per year (about 40% of the process throughput). The uranium is reclaimed in the fissile scrap recovery process.

The off-gases from the chemical conversion operation contain UO_2F_2 , H_2 , HF, and water, as steam. These effluents are passed through a centrifugal collector, a metallic filter to remove particulate material, and then directed to a spray-chamber scrubber containing a KOH solution to remove 99% of the HF. The off-gas from the kernel preparation operation contains trace quantities of UO_2 and UC_2 which are removed by a soot filter. In the buffer and high-density PyC coating operation, carbon and hydrogen are produced as by-products and are carried out by the process off-gas. These elements are converted to water and CO_2 by controlled combustion. The gases are cooled by passage through a heat exchanger before entering a bag filter which removes approximately 98% of the remaining solids. The silicon carbide coating operation has HCl, SiC, H_2 , and soot as by-products. The off-gases, containing small amounts of UCl_4 , pass through a cooler and then through a caustic scrubbing tower to neutralize the HCl and to remove the entrained particulates. Prior to particle mixing and rod fabrication, the fissile particles are washed and dried to remove entrained carbon/soot and to remove any uranium adhering to the coated particle surfaces. The washing medium is water, which is recirculated through a filter for particle separation. A low-temperature oven with an air purge is used to dry the particles.

All process gases are combined, passed through controlled combustion equipment and a cooler, through a bag filter, monitored, and then vented to the atmosphere. All process liquids are treated by filtration and clarification, transported to an equalization pond where they are mixed with other process streams, and diluted with nonradioactive liquid effluents (cooling tower blowdown, sanitary wastes, etc.) before release.

Fertile Particle Production. - The steps in fertile particle production, together with the waste handling systems for each step, are shown schematically in Fig. 4.2; the material flows are presented in Table 4.2. The process decontamination (containment) factors for particulate material for each of the processes are: fluidized-bed denitration, 1×10^6 ; kernel preparation, 250; and kernel coating, 100. Approximately 61 thousand kg (about 13% of the process throughput) of thorium contained in off-specification particles are buried as unrecoverable waste on a yearly basis.

In the fluidized-bed denitrator, large quantities of nitric acid and water and smaller quantities of $\text{Th}(\text{NO}_3)_4$ and ThO_2 are discharged to the process off-gas. The nitric acid fumes are directed to a scrubber capable of removing 99% of the acid and 90% of the particulates. Included in the gases is radon-220, an airborne decay product of ^{228}Th , as well as trace quantities of other decay products (^{224}Ra , ^{212}Bi , and ^{212}Pb). The assumption is made that all of the ^{220}Rn that is present at secular equilibrium in the thorium nitrate raw material plus the ^{220}Rn that is produced during the processing steps are released over a 6-hour period. A baffled retention tank (300 gal) is used to allow sufficient time (13 minutes) for the ^{220}Rn to decay (DF of 2.2×10^4) to its solid decay products. The solid (particulates) decay products are removed from the airborne effluent by filtration through HEPA filters.

The solids discharged in the dryer and calciner operations are removed from the airborne effluents by passage through a soot filter. Radon-220 is delayed for approximately 5 minutes in a baffled hold-up tank (6×10^3 gal) to achieve a DF of approximately 50.

The effluents from the buffer and high-density isotropic coating operations, containing small amounts of ^{220}Rn , uranium, thorium, and decay products, and large quantities of hydrogen and soot/carbon, are mixed with air and ignited to burn the hydrogen gas, to oxidize any CO to CO_2 , and to convert the soot to CO_2 . The resulting gases are cooled in a heat exchanger and are subsequently passed through a bag filter to remove particulates. All process off-gases pass through a HEPA filtration system to reduce the concentration of particulate material to trace quantities before the airborne effluent is released to the environment. Liquid effluents are sent to a sump where radium, thorium, and other decay products are removed by coprecipitation with BaSO_4 . The clarified liquid stream is sent to the equalization pond where it is combined with other streams, monitored, and released.

Fuel Rod and Element Production. - The steps in fuel rod manufacture and element production, together with the waste handling system for each process, are shown in Fig. 4.4; the material flows are given in Table 4.3. The following process decontamination (containment) factors are used for particulates for each of the operations: injection press, 1×10^4 ; carbonization, 1×10^3 ; rod cleaning, 4×10^3 ; and baking, fuel element loading, and curing, 1×10^6 . Approximately 16 thousand kg of thorium and 16 hundred kg of uranium are found in the off-specification material per year. It is assumed that ^{220}Rn or decay products are not released from coated particles.⁷⁹

Matrix production (Fig. 4.3) is a process involving nonradioactive materials. The heated pitch emits sulfur, which combines with oxygen to form the dioxide. The other airborne effluents in this operation are carbon and pitch, which are removed via soot filtration equipment before release to the environment.

The coated fissile and fertile particles are mixed with shim particles and transferred to a hot mold. The matrix material is injected under high pressure to form a fuel rod, which is then carbonized. The rod carbonization process emits volatiles containing hydrogen and carbon from binders in the rod. The effluents are burned as they leave the furnace to oxidize the hydrocarbon of the binder to ash, CO_2 , and water, and the sulfur remaining after the matrix production steps to sulfur dioxide. The gases are cooled and passed through a soot filter to remove particulates. The radioactive effluents contain U_3O_8 , ThO_2 , and daughter products.

In the rod cleaning process, any residual uranium or thorium associated with the carbonized rods is converted by HCl gas to the chloride, which is volatilized at the process temperature. The effluents are scrubbed in a wet scrubbing tower using NaOH to convert the HCl to NaCl with an efficiency of 99%. The off-gases contain $\text{Th}(\text{OH})_4$, $\text{Na}_2\text{U}_2\text{O}_7$, carbon, NaOH, NaCl, and water vapor.

Process effluents are collected and directed to a bag filter system prior to being released to the atmosphere. Effluents released to the atmosphere after cleanup consist of small quantities of thoria, uranium oxide, water vapor, sulfur dioxide, carbon monoxide, and carbon dioxide. The small quantities of liquids generated by the scrubbing tower are filtered and then piped to the equalization pond before discharge.

Fissile Scrap Recovery. - The materials which are processed in the scrap recovery operation, together with the waste handling procedures, are shown schematically in Fig. 4.5; the material flow rates are given in Table 4.4. The scrap recovery system processes approximately 10 thousand kg of heavy metal per year. During the dry processing steps, crushing and grinding operations followed by

incineration are used to free the entrapped uranium from the waste material. These operations are performed on waste paper, rags, graphite furnace parts, off-specification fissile particles, reject fuel rods, etc. The airborne effluents containing uranium oxide, thoria, radon-220, carbon, carbon dioxide, and silicon carbide are cooled, directed to a soot filter, and then to a caustic scrubbing tower to remove entrained acidic mists.

Other effluents from the scrap recovery uranium purification process consist of exhaust fumes from dissolvers, filter presses, extraction columns, precipitators, dryers, calciners, and evaporators. These fumes are directed either to a scrubbing tower which is 99% efficient in removing acid and 90% efficient in absorbing uranium and thorium compounds and other particulates, or to a soot filter which is 95% efficient in removing particulates. All process effluents are given a final cleanup by passage through a soot filter before release. All liquids are treated by filtration and clarification before they are sent to the equalization pond for final release.

Miscellaneous Liquid Waste Treatment System. - The miscellaneous liquid effluents are treated as shown in Fig. 4.18 and subsequently released to the equalization pond. No material balance is presented for this system (12,000 gal/day), which contains a variable quantity of detergents. The uranium and thorium are present primarily as uranates and hydrated oxide, respectively.

Solid Waste Treatment. - The wet and solid waste processing operations are shown in Fig. 4.19. All waste solids and waste chemical solutions are sent to the waste processing area for reduction in volume so that they can be packaged in drums for storage or shipment to a licensed burial ground. Approximately 1500 tons of waste, containing 75 thousand kg of thorium (16% of plant throughput) and 270 kg of uranium (1.4% of plant throughput), are generated per year.

4.5.1.2 *Case 2.* - The airborne radioactive wastes are treated as in Case 1. The aqueous radioactive wastes are retained in a lined storage lagoon to prevent seepage of radioactive and nonradioactive materials into the ground water. No radioactive liquid wastes are released in this case study. Reject thorium is recycled through a scrap recovery system (Fig. 4.5). The quantity of unrecoverable thorium and uranium is reduced to 2% and 0.5%, respectively.

4.5.1.3 *Case 3.* - Several major process changes are made in this case. The fissile kernels are produced by the weak-acid resin loading method (flowsheet identical to Fig. 4.8). The "green" fuel rods are carbonized in the fuel block (flowsheet identical to Fig. 4.11). The more efficient (95% for entrained particles) impingement baffle-plate scrubbers containing perchloroethylene (C_2Cl_4) are used for the removal of carbonous material and soot from the process off-gases originating from the coating and carbonization furnaces. Radon releases are substantially reduced by additional radon retention tanks. The amounts of radioactive materials released by the plant are summarized in Fig. 4.20.

The fissile particle production operations are depicted in Fig. 4.21; the material flows are given in Table 4.19. The process decontamination (containment) factor for resin loading was assumed to be 1×10^5 ; the other factors are unchanged. The more efficient airborne waste treatment system reduces the uranium release by a factor of about 3.5 from the previous case studies. Subambient condensers ($-50^\circ C$) are used to recover C_2Cl_4 from the gas streams. Water is recycled in this case study.

The fertile particle waste treatment system is shown in Fig. 4.22; the material flows are given in Table 4.20. The major additions to the waste treatment system include: (a) a more efficient scrubber

in the denitration process, (b) substitution of a bag filter for the soot filter in the gel-sphere drying and calcining operation, and (c) the addition of a 60,000-gallon baffled radon retention tank in the kernel coating step. This tank, yielding a 7.5-minute delay of the process off-gases, results in a DF of about 300 for ^{220}Rn . Off-specification material from the operations in the fertile building is recycled to the appropriate processes. Small quantities of thorium are sent to the scrap recovery system for purification. Part of the nitric acid (approximately 10%) in the thorium denitration process is recycled to the scrap recovery system. The excess nitric 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 sent to solid waste treatment. An ammonia absorber is utilized to reclaim NH_4OH from the gel-sphere formation process.

The fuel rod and element waste treatment system (Fig. 4.23) has been modified to reflect the changes in processing (use of C_2Cl_4 scrubbers, whole block carbonization, and inclusion of more efficient scrubbers). Very little radioactivity is released in fuel rod and element production, but large quantities of soot and tars generated in the carbonization step are removed by a spray-chamber scrubber containing C_2Cl_4 . Material flows for these operations are given in Table 4.21. A subambient condenser operating at -50°C is used to remove and reclaim perchloroethylene from the process off-gas stream.

The fissile scrap recovery system has been altered (Fig. 4.24) to reflect the addition of more efficient scrubbers and the replacement of soot filters with bag filters. The material flow rates are given in Table 4.22.

The solid radwastes from the scrap recovery system and other miscellaneous solid radwastes are incorporated in cement and packaged in drums (Fig. 4.19). The drums are (a) stored or buried on-site, (b) buried in a local off-site landfill, or (c) shipped to a licensed commercial burial ground.

4.5.1.4 Case 4 - The liquid wastes are treated as in Case 3. Improvements are made to the airborne radwaste treatment systems in each of the process buildings to produce a significant reduction in the amount of radioactivity released (Fig. 4.25).

Modifications to the fissile production facility airborne radwaste treatment system (Fig. 4.26) include the use of high-efficiency venturi scrubbers, the addition of a caustic venturi scrubber to the waste effluent stream from the silicon carbide coating operation, and the use of two stages of HEPA filtration. It is assumed that these filters are properly installed and designed for in-place testing. Thus, an overall DF of 4×10^5 applies to this installation. The material flows are given in Table 4.23.

The major changes in the off-gas treatment system (Fig. 4.27) in the fertile particle production building are the substitution of a high-efficiency venturi scrubber for the impingement scrubber, the addition of a charcoal trap for ^{220}Rn delay, and the addition of another HEPA filter in the final airborne radwaste treatment system. The delay trap, containing one metric ton of charcoal in a 6-ft-diameter by 3-ft-deep tank, results in a DF of approximately 4×10^3 for radon-220. A DF of 200 for particulates has been assumed for the second HEPA filter. Material flows are presented in Table 4.24.

Gas recirculation is used in the rod fabrication and element loading operations in the production facility. Ninety-five percent of the process off-gases are passed through two stages of HEPA filtration. The remaining effluent is treated with one stage of HEPA filters before discharge. The element carbonization airborne effluents are passed through an impingement scrubber, subambient condenser (-50°C), and one stage of HEPA filtration before release (no recycle of this

stream) Material flows are presented in Table 4 25, the flowsheet is shown in Fig 4 28

The fissile scrap recovery system airborne radwaste treatment system (Fig 4 29) uses the high-efficiency venturi scrubbers, bag filters, and one stage of HEPA filtration Material flows are given in Table 4 26 Liquid and solid wastes are processed as in Case 3

4 5 2 *Recycle Fuel Fabrication Cases*

4 5 2 1 *Case 1* - A schematic representative of the "base case" for the refabrication plant is given in Fig 3 1 The fissile particle production operations are presented in more detail in Fig 4 7 The fertile particles are prepared at the fresh fuel fabrication facility and are shipped to the recycle plant The waste treatment methods used and the process DFs assigned to calculate the source terms in this case are important because the improvements introduced in succeeding cases are incremental with respect to the base case Definitive information that can be used to substantiate the estimates of the quantities of material released from the model plant is limited because of the limited experience established in private industry Estimates of the amounts of radioactive materials released are based on a current ERDA development program and on the experience of other fuel fabrication plants utilizing similar operations^{75 78}

Fuel Resin Loading - A summary flowsheet for the uranium loading of weak-acid resin is shown in Fig 4 8, the material flows are presented in Table 4 6 Although a process decontamination (containment) factor of 1×10^5 is assumed for the overall operations, a rather large amount of uranium (approximately 5 kg/year) is distributed to the off-gas treatment system because of the large quantities of uranium cycled through the process Four tanks (critically safe geometry) are required for storage of feed stock uranium solutions The size and operational characteristics of these tanks are important because the uranium they contain generates large quantities of ^{220}Rn These capacities and sparging methods are as follows a large storage tank containing a 30-day supply of uranium (about 8 5 thousand gallons) which is sparged with 5 cfm of air for 30 minutes every 12 hours, two metering tanks, each containing a 12-hour supply of feed (150 gallons) which are sparged with 5 cfm of air for 30 minutes every 24 hours, and a feed tank (one thousand gallons) which is not sparged The assumption is made that all of the ^{220}Rn that is produced and all that is present at equilibrium when the solution is received is released to the process off-gas treatment system A charcoal delay trap 1 5 ft in diameter by 2 ft deep (containing approximately 100 pounds of charcoal) in the process off-gas stream reduces the ^{220}Rn concentration by a factor of 1×10^{10} The final filtration system contains two banks of HEPA filters (one of "low efficiency," 95%, and the other of normal efficiency, 99 95%) which yield a DF of 4×10^4 for particulates About 270 kg of uranium are recycled to the scrap recovery process per year (1% of the plant throughput)

Recycle Fuel Particle Preparation - The steps in the preparation of fissile particles, together with the waste handling systems for each step, are shown in Fig 4 10, the material flows are presented in Table 4 8 The process decontamination (containment) factors for particulate material for each of the processes are resin carbonization, 100, resin conversion, 1×10^3 , and kernel coating, 200 Approximately 7 thousand kg of uranium are returned to the scrap recovery process as reject particles per year (25% of the plant throughput)

The off-gases from the carbonization and conversion steps contain uranium, ^{226}Ra , ^{210}Bi , ^{222}Rn , and large quantities of nonradioactive volatile products with a wide variety of boiling points, including some of a tar-like nature. The radium, bismuth, and lead components of the off-gas are present as the result of their volatilization at the high process temperature. The effluents are passed through an impingement baffle-plate scrubber containing C_2Cl_4 , which removes 95% of the solids. The process off-gases are then cooled to -50°C to reclaim perchloroethylene and to prevent it from poisoning the charcoal trap.

Hydrogen, silicon carbide, and hydrogen chloride are produced in the SiC coating operation. The off-gases are passed through a caustic scrubber (spray chamber) to neutralize the HCl and to remove entrained particulates. The water-saturated gases are passed through a subambient condenser to protect the final HEPA filtration system from excess moisture. The final filtering system includes controlled combustion equipment, cooler, HEPA filter, charcoal trap (4 ft diameter by 3 ft deep to provide a radon-220 DF of 4.1×10^5), and a final HEPA filter before release (DF for particulates of 4×10^4).

Fuel Rod and Element Production - These operations (shown schematically in Fig. 4.11, with material flows given in Table 4.9) release only very small quantities of radioactive materials to the process off-gas streams because both fissile and fertile particles are encapsulated in PyC and SiC coatings. However, large quantities of volatile carbonaceous materials are generated in the element carbonization process. The airborne effluents are directed to a spray-chamber scrubber containing C_2Cl_4 to remove the tars and other particulates and provide preliminary cooling. The gases are cooled (-50°C) to reclaim the perchloroethylene and are then passed through the final filtering system, which has a DF of 4×10^4 for solids. These solids, containing about 400 kg of thorium and uranium on a yearly basis (approximately 0.1% of the plant throughput), are returned to the reprocessing plant for reclamation.

Fissile Scrap Recovery - The reject material from all of the processes is transferred to the scrap recovery system. The flowsheet for the scrap recovery system is shown in Fig. 4.12, the material flows are given in Table 4.10. All process gases are passed through a radon retention tank (1.2×10^4 gal for a DF of 1.6×10^5) and two stages of HEPA filters in series which provide a DF of 4×10^4 for particulates. The airborne effluents from the combustion furnace are directed to a cooler and a bag filter before they are combined with other process gases. Approximately 140 kg of uranium per year (0.5% of plant throughput) is unrecovered in the process.

Liquid Waste Treatment - All process water containing radioactive materials is concentrated in an evaporator, and the concentrates are then incorporated in cement. Miscellaneous liquid wastes are released after they have been filtered to remove solid matter and then sampled and analyzed to ensure that the stream is free of radioactive contamination. If radioactive materials are detected in the miscellaneous liquid waste, i.e., the radioactive level is higher than background, the water is recycled to the process liquid evaporator.

Perchloroethylene is purified by distillation. The residues from this operation and from the C_2Cl_4 scrubbers are dried and recycled to the scrap recovery system for uranium reclamation.

Solid Waste Treatment - Solid radwastes consist mainly of solidified liquid radwastes. Solid waste from other sources is segregated according to radioactivity level, compacted where feasible, and packaged for disposal. The solid radwaste is shipped to the reprocessing plant for storage or disposal.

4 5 2 2 *Case 2* - Liquid wastes are treated as in Case 1. The final airborne radwaste treatment system consists of two banks of HEPA filters in series (same as in Case 1 but properly installed to allow for periodically testing in place). These filter banks provide a solid removal efficiency corresponding to a DF of 4×10^5 .

4 5 2 3 *Case 3* - Several process changes have been made in this case. Thorium and its decay products are removed from the uranium feed solution by ion exchange before they enter the resin kernel loading process. Air sparging is no longer used in the storage and feed tanks; mixing is accomplished by air-driven motors. The liquid wastes are treated as in Case 1.

The activity of the recycle uranium (^{238}U) increases sufficiently during the period following purification in the reprocessing plant that heavy shielding is required. The addition of an ion exchange cleanup system (similar to that used in the scrap recovery system, Fig. 4.12) removes nearly all of the daughter activity before it is introduced into the refabrication operations. For this case study, the assumption is made that, although resin loading is performed immediately following the cleanup operation, the concentration of the daughter products is equivalent to a five-day aging period averaged over all of the processing operations. The airborne radwaste treatment system is the same as in Case 2.

4 5 2 4 *Case 4* - The liquid wastes are treated as in Case 1. Several additions have been made to the airborne radwaste treatment system in each of the process operations to reduce significantly the amount of radioactive materials discharged to the environment. Flowsheets for the various processes are shown in Figs. 4.30-4.32 and the material flows are given in Tables 4.27-4.29.

The release of radon-220 and of particulates has been decreased by the use of somewhat larger charcoal delay traps and by the addition of a supplementary stage of HEPA filtration to each of the process streams. Ninety-five percent of the cell off-gases from the rod fabrication and element loading operations are recycled by passage of the gas through two stages of HEPA filters. The remaining effluent is treated with two stages of HEPA filters before discharge. High-efficiency venturi scrubbers are used in all operations producing large quantities of soot or acidic mists.

4 5 3 *Calculation of Source Terms*

The radionuclide concentrations in the effluent streams are multiplied by the average specific activity values from Table 4.13 to calculate the source terms for each of the two plants. The source terms for individual isotopes are obtained by multiplying the total radionuclide specific activity by the fraction of activity contributed by each given isotope. With a few exceptions, the activities of the uranium daughters and the thorium daughters, discussed in Sect. 4.2, are assumed to be in secular equilibrium with the parent elements. The exceptions occur in the processes where volatile (^{220}Rn) and semivolatile (^{224}Ra , ^{212}Pb , and ^{212}Bi) isotopes are released to the off-gas stream because of the particular operations involved (dissolution or high temperature). The amounts of these materials released to the in-plant off-gas streams and released from the plant annually must be calculated (Sect. 4.2.1). As noted in Sect. 4.2.1, the amounts released to in-plant off-gas streams annually are much higher than the amounts present at secular equilibrium. The source terms in all of the case studies for each of the plants reflect this effect for these isotopes. The source terms for the airborne and liquid effluents for the fresh fuel plant are listed in Table 4.17 and for the airborne effluents for

the refabrication plant in Table 4.18. Liquids containing radioactive materials are released only by the fresh fuel fabrication plant in the Case 1 study. The bases for calculation of the amounts of radioactive materials entering the plant are presented in Sect. 4.2.

The calculated concentrations of the radioactive materials in the liquid effluent at the outlet of the equalization lagoon are approximately 60% of the Radiation Concentration Guides (Code of Federal Regulations, Title 10, Part 20, Appendix B, Table II, Column 1 and 2) for releases to unrestricted areas for the fresh fuel plant in the Case 1 study; the concentrations in the airborne effluent at the point of release from the stack are approximately 75% of the Radiation Concentration Guides (Code of Federal Regulations, Title 10, Part 20, Appendix B, Table I, Column 1) for release to restricted areas for the fresh fuel plant. The calculated concentration in the airborne effluent at the point of release from the stack for the refabrication plant in Case 1 is approximately 75% of the Radiation Concentration Guides 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 airborne effluents to the Radiation Concentration Guides for that radionuclide for unrestricted and/or restricted areas and summing the ratios. Unrestricted areas are defined as areas that are not controlled by the licensee for purposes of protection of individuals from exposure to radiation and radioactive materials, and any area used for residential quarters. Radiation Concentration Guides for release to restricted areas are more than ten times higher than for the unrestricted areas. Also, releases from the model plants are diluted by a factor of at least 10^6 before reaching the boundary of the plant at 0.5 mile for the fresh fuel plant and 1.5 miles for the refabrication plant (Sect. 7.1). Thus, both model plants for the Case 1 study are within the federal guidelines listed for release of radioactive materials. The estimated amounts of uranium, thorium, and radon-220 in the airborne effluent from the fresh fuel fabrication plant are 1.55 g, 0.905 g, and 0.77 Ci per day, respectively. These values are comparable to the concentrations of 0.57 g, 1.18 g, and 0.17 Ci estimated to be present in the releases from a proposed fresh fuel fabrication plant.⁷⁴

4.6 References

1. R. C. Dahlberg, K. Asmussen, D. Lee, L. Brooks, and R. K. Lane, "HTGR Fuel and Fuel Cycle," Nucl. Eng. Des. 26, 58 (1974).
2. T. D. Gulden, C. L. Smith, D. P. Harmon, and W. W. Hundritsch, "The Mechanical Design of TRISO-Coated Particle Fuels for the Large HTGR," Nucl. Technol. 16, 100 (1972).
3. M. T. Simnad and R. Vanek, "Drop-Fusion Method for Producing Spherical Fuel Particles for HTGR and UHTREX Fuel Elements," Trans. Amer. Nucl. Soc. 14, 571 (1971).
4. O. M. Stansfield, T. D. Gulden, and D. P. Harmon, *Fuel Kernel Materials for the Thorium Cycle HTGR*, General Atomic Company, Gulf-GA-A-12632 (June 23, 1973).
5. P. E. Reagan, E. L. Long, Jr., J. G. Morgan, and J. H. Coobs, "Irradiation Performance of Pyrolytic Carbon- and Silicon-Carbide-Coated Fuel Particles," Nucl. Technol. 8, 417 (1970).

6. W. V. Goeddel, "Development and Utilization of Pyrolytic-Carbon-Coated Carbide Fuel for the High-Temperature Gas-Cooled Reactor," Nucl. Sci. Eng. 20, 201 (1964).
7. R. A. Reuter, "Duplex Carbon-Coated Fuel Particles," Nucl. Sci. Eng. 20, 119 (1964).
8. J. L. Scott and R. L. Beatty, "Pyrolytic-Carbon Coatings Formed at High Deposition Rates," Trans. Amer. Nucl. Soc. 10, 96 (1967).
9. H. Beutler, R. L. Beatty, and J. H. Coobs, "Low-Density Pyrolytic Carbon Coatings for Nuclear Fuel Particles," Electrochem. Technol. 5, 189 (1967).
10. T. G. Godfrey, R. L. Beatty, J. L. Scott, J. H. Coobs, J. W. Prados, L. G. Overholser, and L. M. Ferris, *Coated Particle Fuels*, ORNL-4324 (November 1968).
11. J. R. C. Gough and D. Kern, "Studies of the Coating of Fuel Particles for the Dragon Reactor Experiment," J. Nucl. Energy 21, 63 (1967).
12. A. W. Savolainen, *Gas-Cooled Reactor Program Semiannual Progress Report for Period Ending March 31, 1967*, ORNL-4133 (August 1967), p. 10.
13. E. Zimmer, P. Naefe, and H. Ringel, "Continuous Working Process for the Production of ThO_2 and $(\text{Th,U})\text{O}_2$ Fuel Kernels," Trans. Amer. Chem. Soc. 20, 591 (1975).
14. P. A. Haas, *Process Requirements for Preparing ThO_2 Spheres by the ORNL Sol-Gel Process*, ORNL-TM-3978 (December 1972).
15. E. N. Nelson, *Fluid-Bed Denitration of Thorium Nitrate*, MCW-1511 (Jan. 19, 1966).
16. P. A. Haas, *Sol-Gel Preparation of Spheres: Design and Operation of Fluidized Bed Columns*, ORNL-4398 (September 1969).
17. C. C. Haws, B. C. Finney, and W. D. Bond, *Engineering-Scale Demonstration of the Sol-Gel Process: Preparation of 100 kg of $\text{ThO}_2\text{-UO}_2$ Microspheres*, ORNL-4544 (May 1971).
18. P. A. Haas, F. G. Kitts, and H. Beutler, "Preparation of Reactor Fuels by Sol-Gel Processes," Chem. Eng. Progr., Symp. Ser. 63, 16 (1967).
19. R. W. Moore, "Molded Graphites for Prismatic HTR Fuel Blocks," Trans. Amer. Nucl. Soc. 20, 605 (1975).
20. M. Hrovat and H. Huschka, "Fabrication and Properties of Molded Block Fuel Elements for HTGRs," Trans. Amer. Nucl. Soc. 20, 603 (1975).

21. D. D. Cannon, F. C. Davis, R. A. Bradley, and J. D. Sease, "Development of a Laboratory Slug Injection Machine for Fabrication of HTGR Fuel Rods," *Trans. Amer. Nucl. Soc.* 17, 508 (1973).
22. F. C. Davis, D. D. Cannon, J. D. Sease, and R. A. Bradley, "Production Slug Injection Machine for Fabrication of HTGR Fuel Rods," *Trans. Amer. Nucl. Soc.* 17, 509 (1973).
23. E. Balthesen, K. Ehlers, H. Huschka, and H. Nichel, "State and Development of HTGR Fuel Elements in the FRG," *Trans. Amer. Nucl. Soc.* 20, 268 (1975).
24. L. H. Brooks, A. L. Lotts, and R. G. Wymer, "Progress in the Thorium-Uranium-233 Reprocessing-Refabrication Technology," in *Proceedings of the Conference on Gas-Cooled Reactors: HTGR and GCFBR, held in Gatlinburg, Tennessee, May 7-10, 1974*, ANS Topical Meeting, CONF-740501.
25. A. T. Gresky *et al.*, *Laboratory Development of the Thorex Process: Progress Report*, ORNL-1518 (July 1953).
26. R. H. Rainey and J. G. Moore, "Laboratory Development of the Acid Thorex Process for Recovery of Thorium Reactor Fuel," *Nucl. Sci. Eng.* 10, 367 (1961).
27. P. A. Haas, *HTGR Fuel Development: Use of UO_3 to Load Cation Exchange Resin for Microsphere Preparation*, ORNL-TM-3817 (September 1972).
28. P. A. Haas, *HTGR Fuel Development: Loading of Uranium on Carboxylic Acid Cation Resin Using Solvent Extraction of Nitrate*, ORNL-TM-495 (September 1975).
29. P. A. Haas, Oak Ridge National Laboratory, private communication, Feb. 25, 1975.
30. P. A. Haas, Oak Ridge National Laboratory, private communication, July 1, 1975.
31. L. H. Brooks, C. A. Heath, B. Kirstein, and D. G. Roberts, *Carbon-14 in the HTGR Fuel Cycle*, General Atomic Company, Gulf-GA-A-13174 (Nov. 29, 1974).
32. R. H. Rainey, *Laboratory Development of a Pressurized Cation Exchange Process for Removing the Daughters of ^{232}U from ^{233}U* , ORNL-4731 (December 1972).
33. U. S. Atomic Energy Commission, *Transuranium Waste Disposal*, 10 CFR Part 20 and Part 150, Federal Register, 39(178), 32921, 32922 (September 12, 1974).
34. T. B. Fowler and D. R. Vondy, *Nuclear Reactor Core Analysis Code: CITATION*, ORNL-TM-2496 (Supplement 3) (July 1972).
35. E. K. Hyde, I. Perlman, and G. T. Seaborg, *The Nuclear Properties of the Heavy Elements*, p. 490, Prentice-Hall, Inc., 1964.

36. E. K. Hyde, *The Radiochemistry of Thorium*, Office of Technical Services, Dept. of Commerce, 1960.
37. J. N. Rosholt, U.S. Dept. of Interior, Geological Survey, Denver, Colorado, letter to W. Davis, Jr., June 26, 1975.
38. M. J. Bell, *ORIGEN - The ORNL Isotope Generation and Depletion Code*, ORNL-4628 (May 1973).
39. J. W. Snider, Oak Ridge National Laboratory, private communication, March 11, 1975.
40. P. B. Jackson, H. H. Ficke, S. A. Reber, and C. I. Tech, *Determination of ^{232}U Daughter Product Release Rates from HTGR Fuel During Refabrication*, ORNL-MIT-206 (Dec. 17, 1974), report available from MIT Practice School, Oak Ridge National Laboratory.
41. S. Calvert, "Engineering Design of Fine Particle Scrubbers," *J. Air Pol. Control* 24, 929 (1974).
42. C. J. Stairmand, "Removal of Dust from Gases," p. 364 in *Process for Air Pollution Control*, G. Nonhebel, Ed., The Chemical Rubber Co., Cleveland, Ohio, 1972.
43. R. D. Ross, *Air Pollution and Industry*, p. 375, Van Nostrand Reinhold Company, New York, New York, 1972.
44. C. J. Stairmand, "Removal of Dust from Gases," p. 377 in *Process for Air Pollution Control*, G. Nonhebel, Ed., The Chemical Rubber Co., Cleveland, Ohio, 1972.
45. H. E. Gardenier, "Submicron Particulate Scrubbing with a Two-Phase Jet Scrubber," *J. Air Pol. Control* 24, 954 (1974).
46. J. S. Eckert and R. F. Strigle, Jr., "Performance of Wet Scrubbers on Liquid and Solid Particulate Material," *J. Air Pol. Control* 24, 961 (1974).
47. F. R. Cuthane, "Fabric Filters Abate Air Emissions," *Environ. Sci. Technol.* 8, 127 (1974).
48. R. G. Dorman *et al.*, "Solid-Gas Separation: Equipment," p. 20 in *Filtration* (Supplement to Chem. Eng.) (November 1973).
49. C. J. Stairmand, "Removal of Dust from Gases," p. 381 in *Process for Air Pollution Control*, G. Nonhebel, Ed., The Chemical Rubber Company, Cleveland, Ohio, 1972.
50. E. Rothwell, "Fabric Dust Filtration," *Chem. Eng.* 295, 138 (1975).

51. W. Davis, Jr., *High Efficiency Particulate Air Filters - State of the Art Summary Pertaining to Plutonia Aerosols*, ORNL-TM-4463 (April 1974).
52. M. Hetland and J. L. Russell, Jr., "Adequacy of Ventilation Exhaust Filtering Systems for New Plutonium Facilities," p. 619 in *Proceedings of the 12th AEC Air Cleaning Conference*, held in Oak Ridge, Tennessee, August 28-31, 1972, CONF-720823 (January 1973).
53. F. J. Linck and J. A. Geer, "In-Place Testing of Multiple Stage HEPA Filters," p. 526 in *Proceedings of the 13th AEC Air Cleaning Conference*, held in San Francisco, California, August 12-15, 1974, CONF-740807 (March 1975).
54. A. J. Oliver and C. L. Amos, "Ventilation Design for New Plutonium Recovery Facility," p. 320 in *Proceedings of the 13th AEC Air Cleaning Conference*, held in San Francisco, California, August 12-15, 1974, CONF-740807 (March 1975).
55. H. J. Ettinger, J. C. Elder, and M. Gonzales, *Performance of Multiple HEPA Filters Against Plutonium Aerosols, Progress Report for Period January 1 through June 30, 1973*, Report LA-5349-PR (July 1973).
56. H. J. Ettinger *et al.*, "Size Characteristics of Plutonium Aerosols," p. 740 in *Proceedings of the 12th AEC Air Cleaning Conference*, held in Oak Ridge, Tennessee, August 28-31, 1972, CONF-720823 (January 1973).
57. M. Gonzales, J. C. Elder, and H. J. Ettinger, "Performance of Multiple HEPA Filters Against Plutonium Aerosols," p. 501 in *Proceedings of the 13th AEC Air Cleaning Conference*, held in San Francisco, California, August 10-15, 1974, CONF-740807 (March 1975).
58. USAEC Regulatory Guide, August 1973, Regulatory Guide 3.12, "General Design for Ventilation Systems of Plutonium Processing and Fuel Fabrication Plants."
59. C. A. Burchsted, Oak Ridge National Laboratory, private communication, June 1974.
60. J. L. Kovach, "Recent Developments in Controlling the Release of Noble Gases by Absorption on Activated Carbon," *Trans. Amer. Nucl. Soc.* 15, 98 (1972).
61. D. P. Siegwarth *et al.*, "Measurement of Dynamic Adsorption Coefficients for Noble Gases on Activated Carbon," p. 28 in *Proceedings of the 12th AEC Air Cleaning Conference*, held in Oak Ridge, Tennessee, August 28-31, 1972, CONF-720823 (January 1973).
62. J. P. Nichols and F. T. Binford, *Status of Noble Gas Removal and Disposal*, ORNL-TM-3515 (August 1971).
63. R. D. Ackley, *Removal of Radon-220 from HTGR Fuel Reprocessing and Refabrication Off-Gas Streams by Adsorption (Based on a Literature Survey)*, ORNL-TM-4883 (April 1975).

64. S. A. Gregory, "Sub-Ambient Process Cooling," *Ind. Chem.* 38, 283 (1962).
65. R. D. Ross, *Air Pollution and Industry*, p. 440, Van Nostrand Reinhold Company, New York, New York, 1972.
66. R. Miller, "Sedimentation," *Water Wastes Eng.* 11, 40 (1974).
67. R. G. Dorman *et al.*, "Solid-Liquid Filtration: Equipment," p. 1 in *Filtration*, (Supplement to Chem. Eng.) (November 1973).
68. H. W. Godbee, *Use of Evaporation for the Treatment of Liquids in the Nuclear Industry*, ORNL-4790 (September 1973).
69. T. E. Wilson and M. D. R. Riddel, "Nitrogen Removal: Where do we stand?," *Water Wastes Eng.* 11, 56 (1974).
70. H. C. Francke, F. E. Clark, and J. W. Strohecker, "Biological Denitrification Disposal Techniques," p. 339 in *Proceedings of the Second AEC Environmental Protection Conference*, held in Albuquerque, New Mexico, April 16-19, 1974, WASH-1332 (1974).
71. C. E. Adams, Jr., "Removing Nitrogen from Waste Water," *Environ. Sci. Technol.* 7, 696 (August 1973).
72. A. H. Kibbey and H. W. Godbee, *A Critical Review of Solid Radioactive Waste Practices at Nuclear Power Plants*, ORNL-4924 (March 1974).
73. E. Bordens, General Atomics Company, private communication, September 10, 1974.
74. USAEC, Fuels and Materials Directorate of Licensing, *Draft Environmental Statement Concerning the Issuance of a Special Nuclear Material License to General Atomic Company in Connection with the Planned General Atomic Fuel Fabrication Facility*, Docket No. 70-1372 (January 1974).
75. *Description of Waste Management Program*, Westinghouse Nuclear Fuel Division, Columbia Plant, USAEC Docket No. 70-1291 (December 1971).
76. Kerr-McGee Corporation, letter dated Oct. 11, 1971, Docket No. 70-1151, SNM-1107.
77. B. Shelley, Kerr-McGee Corporation, private communication, June 1, 1973.
78. R. C. Dahlberg, R. F. Turner, and W. V. Gueddel, *HTGR Fuel and Fuel Cycle Summary Description*, General Atomic Company, Gulf-GA-A-12801(Rev.), (Jan. 21, 1974), p. 24.
79. A. R. Olsen, Oak Ridge National Laboratory, private communication, June 27, 1975.

5.0 NONRADIOACTIVE RELEASES

Various nonradioactive chemical compounds and materials are released to the environment from both fuel fabrication plants, but the ones which present the greatest health hazard are generated by the operations in the fresh fuel facility. This group includes sulfur oxides, fluorides, nitrogen oxides, hydrocarbons, chlorides, ammonia, and nitrates. Other off-gas constituents such as steam, nitrogen, carbon dioxide, helium, argon, and hydrogen are innocuous.

5.1 Airborne Effluents

The most significant airborne chemical effluents from the fresh fuel fabrication plant are fluorine as fluoride, sulfur as sulfur oxides, and nitrogen as nitrogen oxides. The fluorine becomes a waste product during the production of UO_2 powder from UF_6 . The treatment of airborne effluents by scrubbing and demisting reduces the average fluoride concentration to approximately 0.1 ppm in the air released from the stack. The sulfur oxides are formed in the preparation of the matrix material and in the final carbonization of the fuel elements. The concentration of SO_x in the air released to the environment is approximately 0.4 ppm. The nitrogen oxides are produced in the various combustion operations and amount to about 0.5 ppm of the discharged air.

5.2 Liquid Effluents

A water usage diagram for the model fresh fuel plant, Case 1, is shown in Fig. 5.1; the material flows are given in Table 5.1. The refabrication plant discharges contain insignificant quantities of chemical wastes. The chemical species of most consequence in the liquid effluents from the model fresh fuel plant are nitrogen compounds that are generated from the use of ammonium hydroxide and nitric acid in the scrap recovery operation and in the generation of HNO_3 and the use of NH_4OH in the production of the fertile particles. The aqueous effluent stream from the equalization pond carries about 55 pounds per day of nitrogen in the form of ammonia, and about 910 pounds per day of nitrogen in the form of nitrates. This results in the discharge of about 8 MT of nitrogen as ammonia, and 124 MT of nitrogen as nitrate per year. The concentrations released from the pond are about 64 mg/liter of nitrogen in the form of ammonia and 1040 mg/liter of nitrogen in the form of nitrates. Smaller quantities of fluorides and chlorides are released from the pond at concentrations of about 90 and 720 mg/liter, respectively.

As a point of reference for the chemical contaminants, the March 1972 report on Water Quality Criteria by the National Technical Advisory Committee to the Secretary of the Interior recommends the following surface water criteria for public water suppliers: for nitrogen as NH_3 , 0.5 mg/liter; for nitrogen as nitrate, 10 mg/liter; for chlorides, 250 mg/liter; and for fluorides, 0.8 to 1.7 mg/liter, depending on the ambient air temperature.¹ Thus, the effluents

may have chemical concentrations above these recommended upper levels for drinking water supplies. However, it is expected that the lagoon effluent would be discharged into a river to provide dilution. The limiting releases are for ammonia, nitrate, and fluoride and would require reduction in their concentrations by two orders of magnitude to reach recommended levels for surface water; a reduction of $>10^3$ was illustrated in the advanced cases.

5.3 Thermal Releases

Heat is released from both facilities by: (a) building ventilation exhausts, (b) process exhausts, (c) evaporated water from cooling towers, (d) water effluents, and (e) boiler effluents. The two plants, when operating at design capacity, generate about 1×10^8 Btu per hour. Of the total energy released, approximately 68 million Btu/hr are discharged to the atmosphere via cooling towers, 19 million Btu/hr from process emissions are discharged to the atmosphere, 1.5 million Btu/hr are discharged through water directed to the sewage treatment facility, and 6 million and 4 million Btu/hr are discharged directly to the atmosphere from the building ventilation exhaust and boiler flue gases, respectively. Approximately 94% of the thermal load on the cooling towers is generated by exothermic chemical reactions and requirements to cool process equipment.

5.4 Recovery and Reuse of Chemicals

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

5.5 References

1. Environmental Services Board, National Academy of Sciences – National Academy of Engineering, "Water Quality Criteria 1972," The Environmental Protection Agency, 1972 (EPA-R3-73-033-March 1973).

6.0 COSTS

Costs for the various waste treatment cases for the 450-metric ton/yr model fresh fuel fabrication plant (FFP) and the 245-metric ton/yr model fuel refabrication plant (FRP) are estimated as additions to the base plants, which are considered Cases 1. Treatment of the airborne wastes is essentially the same for both plants. For liquid waste from the model fresh fuel fabrication plant, the cases vary from the use of a small equalization pond prior to release of the treated waste to the environment (Case 1) to evaporation with no release (Case 3). In all cases of the model fuel refabrication plant, liquid wastes are evaporated and the purified water is recycled. No liquid wastes are released to the environment. 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 6.2-6.9.

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. 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. The 450-metric ton/yr fresh fuel fabrication plant and the 245-metric ton/yr fuel refabrication plant will service a nuclear economy of approximately fifty-three 1000-MW(e) HTGRs (based on a burnup of 95,000 MWd/metric ton, an 80% load factor, and 32.5% thermal efficiency).

All costs are estimated in terms of early 1973 dollars. A factor of 30% may be used to increase this cost to the 1975 level. The cost estimates are expected to have an accuracy of about $\pm 30\%$. 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 the direct and indirect costs. 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. The 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

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 for the fresh fuel plant and for the recycle fuel plant. The annual cost of cement and drums for the fuel refabrication plant is accumulated as an additional operating expense.

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

6.3 References

- 1 *Siting of Fuel Reprocessing Plants and Waste Management Facilities*, ORNL-4451 (July 1971)
- 2 M S Peters and K D Timmerhaus, *Plant Design and Economics for Chemical Engineers*, 2nd edition, McGraw-Hill, New York, 1968
- 3 K M Guthrie, "Capital Cost Estimating," *Chem Eng*, pp 114-42 (March 24, 1969)
- 4 *Reactor Fuel Cycle Costs for Nuclear Power Evaluation*, WASH-1099 (December 1971)

7.0 ENVIRONMENTAL IMPACT

The radiological impact of the model HTGR fresh fuel fabrication and fuel refabrication plant is assessed by calculating radiation doses to individuals, populations, and, where appropriate, to 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 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. Maximum annual radiation dose commitments to individuals (in millirems) and average annual dose commitments to the population (in person-rems) are estimated from the release of radioactive airborne and liquid effluents from the model plants. 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 one 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 one year of exposure (i.e., a 50-year 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 for the dose from the uranium radionuclides, since uranium is eliminated from the body fairly rapidly. However, the thorium is eliminated only slowly from the body and the half-lives of the isotopes are long, i.e., ^{228}Th - 1.9 yr, ^{230}Th - 8.0×10^4 yr, and ^{232}Th - 1.4×10^{10} yr.

Organ doses may vary considerably for internal exposure from ingested or inhaled materials because some radionuclides concentrate in certain organs of the body. 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 for the total body are the sums of the total body doses to individuals within 55 miles of the plant. Since radiation doses to the total body are relatively independent of age,¹ the person-rem estimates are based on total body doses calculated for adults. Similarly, the population dose estimates for the various organs are the sums of the specific organ doses of the individuals within 55 miles of the plant.

Assumptions, models, and codes used to estimate radiation doses are given in ORNL-4992.²

7.1 Meteorology

The release of airborne 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 using the Gaussian plume equation of Pasquill³ as modified by Gifford.⁴ The AIRDOS computer code⁵ was used 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 wind velocity and direction summarized by stability class. Meteorologic data from representative midwestern and southeastern coastal regions⁶ are used to calculate average values of χ/Q (sec.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 χ/Q values are calculated for sectors in the 16 principal compass directions bounded by radial distances out to 55 miles from the point of release.

7.1.1 Fresh Fuel Fabrication Airborne Releases

A total gas flow rate of 1.4×10^5 cfm is assumed to be released through a roof vent at a height of 10 meters above ground level. Plume rise resulting from the momentum of the released gas is calculated on the assumption that the vent diameter was 1.524 meters. The maximum χ/Q value for ^{234}U is approximately $2.1 \times 10^{-6} \text{ sec.m}^{-3}$ at 0.25 mile (400 meters) from the plant at the midwestern site. The maximum χ/Q for ^{234}U at 0.5 mile is $8.9 \times 10^{-7} \text{ sec.m}^{-3}$ at the coastal site and $1.3 \times 10^{-6} \text{ sec.m}^{-3}$ at the midwestern site.

7.1.2 Fuel Refabrication Airborne Releases

χ/Q values are based on release from a 100-meter stack and a plume rise resulting from momentum of stack gases estimated by assuming a 9.25×10^4 cfm flow rate through a stack 2.1336 meters in diameter. Magnitudes of χ/Q values are somewhat similar at the two sites, but directions at which maximum-minimum values are attained are different.

For both locations, the maximum concentration of radioactive substances in air (largest χ/Q , least dilution) occurs at approximately 0.56 mile from the point of release. Maximum χ/Q values are predicted over the range of 0.5 to 2 miles, beyond which the χ/Q values decrease greater than tenfold out to a distance of 55 miles. The appropriate χ/Q value for each of the 16 quadrants and for the distance from the stack is multiplied by the release rate at the stack to obtain the concentration at the desired point. χ/Q values of $6.4 \times 10^{-8} \text{ sec.m}^{-3}$ and $5.2 \times 10^{-8} \text{ sec.m}^{-3}$ are used at the midwestern and coastal locations, respectively, to calculate the maximum doses at a distance of 1.5 miles. Details of the use of χ/Q values to calculate doses are given in a recent publication, ORNL-4992.² Concentrations in air for each sector are used to calculate dose via inhalation and submersion in air.

7.1.3 Deposition of Particles and Reactive Gases

Accumulation of radioactive materials on the ground surface is represented by an infinite plane source model for external radiation exposure. The ground deposits are also assimilated into food which, when ingested, result 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 adsorption, particle interception, diffusion, and chemical-electrostatic effects.⁷ The rate of dry deposition on ground surfaces is calculated by multiplying the concentration of the radionuclide in air at ground level by the deposition velocity, V_d . Deposition velocity values for particles and reactive gases commonly range from 0.1 to 1.0 $\text{cm}\cdot\text{sec}^{-1}$.^{7,8} A value of 1.0 $\text{cm}\cdot\text{sec}^{-1}$ is used for calculation of ground concentrations of radioactive particles.

Many variables influence the washout of radioactivity from the atmosphere.⁹ The process through which rain or snow washes out radioactive particles or dissolves gases and deposits them on ground or water surfaces is referred to as scavenging. The fraction of particles or soluble gases removed by scavenging from a vertical column of air per unit time during rain or snow is the scavenging coefficient. A discussion of methods used to estimate scavenging coefficients during the rainfall (or snowfall) at the plant site can be found in *Meteorology and Atomic Energy - 1968*.¹⁰ A value of $2.0 \times 10^{-5} \text{ sec}^{-1}$ is used for particulates.

Values for deposition velocities and for scavenging coefficients are used in the AIRDOS code⁵ to estimate the rate of ground deposition through both processes as a function of distance and direction from the plant. The code takes into account the depletion of the plume by deposition processes as well as by radioactive decay as it is blown downwind from the plant.

7.2 Population

Population distributions are 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, N. C., are 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 PANS¹¹ provides sector summaries for annuli bounded by distances of 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 χ/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 result in cumulative totals which are somewhat similar to those reported for actual fuel fabrication facilities^{12,13}.

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 is 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 55-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 Environmental Impact of the Fresh Fuel Fabrication Plant

7.3.1 *Radiation Dose from Airborne 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. Dose conversion factors used in the AIRDOS computer code⁵ to estimate doses resulting from submersion in the airborne effluent, exposure to contaminated ground surface, and intake of radionuclides through inhalation and ingestion are calculated with computer codes¹⁴ 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 are made with a model and computer code,¹⁵ incorporated within AIRDOS,⁵ 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 a recent report².

7.3.2 Individual and Population Doses

The maximum annual total body dose and organ doses to individuals from airborne effluents at 0.5 mile (800 m) from the model plant are summarized in Table 7.4 for all radwaste treatment cases for the coastal and midwestern sites. Total population doses out to 55 miles are presented in Table 7.5. The maximum dose to individuals at 100 m from the plant is approximately 0.029 of the dose at 0.5 mile. At 200 m it is 0.916; at 300, 1.548; at 400, 1.606; at 500, 1.477; at 600, 1.310; and at 700, 1.148. 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 airborne effluents are given in Table 7.6. Internal exposure from inhalation and ingestion accounts for 60% of the total body dose while exposure to the contaminated ground is responsible for the remainder (40%). The major radionuclides contributing to the total body and organ doses are shown in Table 7.7. The ^{234}U and ^{235}U contribute 47% and 28%, respectively, of total body dose and ^{230}Th contributes 17%.

Maximum total body doses and population doses for the midwestern site are slightly higher than at the coastal site. Although the population around the midwestern site is over six times greater than that around the coastal site, the dose to this population (person-rem) is only 1.7 times greater for the midwestern site. This is because the airborne releases are essentially at ground level and the radioactive materials tend to be deposited closer to the plants than would be the case with airborne releases from a tall stack.

The relative contributions of radionuclides in the airborne effluent of a fuel fabrication plant to total body dose by terrestrial pathways are given in Table 7.8. Most of the internal dose (inhalation, 31%, and ingestion, 92%) and dose from contaminated ground (18%) is due to ^{234}U , which is the radionuclide which contributes the major alpha radioactivity in uranium particulates. The dose from submersion in air, which is very small (see Table 7.6), comes mainly from ^{220}Rn and its daughters. Since about 60% of the total body dose is due to inhalation and ingestion of radioactivity (Table 7.6), ^{234}U and ^{230}Th , which account for 93% of the dose due to ingestion (Table 7.8) and 94% of the inhalation dose, are among the most important radionuclides in the airborne effluent of a fuel fabrication plant. Uranium-235 (67%) and ^{234}U (18%) are the major contributors to the dose from contaminated ground.

7.3.3 Doses to Organs of Individuals

Maximum annual doses to organs of individuals from airborne effluents at 0.5 mile from the model plant located at each site are given in Table 7.4 for all radwaste treatment cases.

Table 7.9 gives the relative contributions of radionuclides in the airborne effluent to individual organ doses. Most of the organ doses (over 85%) are due to ^{234}U and ^{230}Th , and to a lesser extent ^{235}U and ^{220}Rn with its daughter ^{212}Pb . 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 fresh fuel fabrication plant, radwaste treatment Case 3 is

effective in reducing doses to body organs by a factor of 4 less than those for radwaste Cases 1 and 2 (Table 7.4).

7.3.4 Radiation Doses from Liquid Effluents

Since the model fresh 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 empties into a freshwater river having 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 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.

7.3.5 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. 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 ^{212}Pb and ^{212}Bi contribute greatly, ^{234}U , ^{230}Th , and ^{212}Pb are the main contributors to the dose from aquatic exposures.

Annual doses to total body and bone from drinking water are given in Table 7.10. 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 the 15-cfs small stream. It is possible that an individual may occasionally drink from such a source. It is more probable that the 1300-cfs 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 7.10. While the bioaccumulation factors for radionuclides in fish are higher for freshwater than for saline water,^{16,17} the doses from freshwater sources of fish are less than those in the estuary since, under the assumptions used in the calculations, the river furnishes more dilution (approximately 73 times more) than the estuary. Although estimates are made for eating fish from the 15-cfs streams into which liquid effluents are 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 (submersion) in waters around a fresh fuel fabrication plant are given in Table 7.10. Dose from this mode of exposure is higher in the estuary than the river because of the lower dilution pattern. 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 approximately 50 times less than the maximum total body dose from airborne effluents.

7.3.6 *Total Radiation Dose from All Pathways*

The annual individual total-body dose commitment of approximately 0.10 to 0.16 millirem from liquid (1300-cfs stream) and airborne effluents (Case 1) from the model fuel fabrication plant obtained through both the terrestrial and the aquatic pathways is several orders of magnitude less than the normal background dose of 100 to 170 millirems in the United States.

7.3.7 *Radiation Doses to Organisms Other than Man*

Radiation doses to aquatic plants, invertebrates, fish, and waterfowl are estimated for 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 7.12. 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 to the fact that these effluents would not be found in a physical habitat conducive to higher aquatic life.

For the radwaste treatment Case 1 study, doses to organisms living in the 15-cfs streams (freshwater and saline) are only slightly higher than those in the estuary but are orders of magnitude higher than those estimated for organisms living in the river where appreciable dilution takes place. Doses to organisms inhabiting the freshwater river are much less than those for organisms in the estuary since, despite the fact that bioaccumulation factors for freshwater biota¹⁶ are higher than those for saline water biota,¹⁷ the estuary, under the assumptions used, furnishes less dilution for the radionuclides.

Table 7.13 gives the relative contribution of radionuclides in the aquatic habitats to dose to the biota. For both plants and invertebrate organisms, ²¹²Bi is, by far, the most important contributor to dose. Due to relatively high bioaccumulation factors, ²¹²Pb is an important contributor to dose to fish in freshwater and saline water and ²³⁰Th to fish in saline water.

7.3.8 *Postoperational Exposure from Long-Lived Radionuclides Released into the Environment from an HTGR Fresh Fuel Fabrication Plant*

Potential releases of radionuclides during plant operation and estimations of resulting radiation doses to individuals and populations are discussed in Sects. 7.3.2-7.3.7. In this section, estimates are presented of future potential radiation doses to individuals and populations exposed to the long-lived radionuclides that are deposited on the land surface as a result of plant operation.

These estimates involve many complex considerations. All of the information necessary to make accurate predictions is not available. In the absence of complete information, estimates are made using the best current knowledge. Conservative assumptions are used in areas where deficiencies of knowledge exist. These assumptions make it likely that the estimates of health consequence are well above the probable effects. A more detailed assessment of the radiation exposure to future generations from long-lived radionuclides has been included in a recent environmental analysis of the LMFBR program.¹⁸

7 3 9 *Postoperational Source Term*

The model fresh fuel fabrication plant (Case 1) releases a total of 230 25 Ci of radionuclides per year of operation in the airborne effluent. During this time, individuals and populations are exposed to an airborne radioactive cloud from which they receive radiation doses due to immersion in the cloud and inhalation. At the same time, radionuclides deposited on the ground surface from the cloud lead to exposures from contaminated ground and ingestion of contaminated food.

During the lifetime of the plant, radionuclides are deposited and accumulate in the environment around the plant. The radionuclides with long half-lives continue to expose people long after the plant has ceased operation. Table 7 14 lists these radionuclides and the total quantities released from the model fuel fabrication facility. The longest-lived radionuclides, such as ^{230}Th , ^{231}Th , ^{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 radioactive elements are deposited in a 55-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 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 (10-meter release height). Other estimates of the deposition of these materials indicate that most of the materials are deposited within 50 miles, even though the release point is the top of a 100-m-high stack.⁸

The average exposure to individuals and populations is estimated using the assumption that the radionuclides deposited during the operational lifetime of the model plant are uniformly distributed in the 55-mile radius area ($2.46 \times 10^{10} \text{ m}^2$). The use of this assumption causes an underestimation of the dose to individuals living near the facility or in areas of the prevailing wind direction and an overestimation of the dose to individuals living in the outer annulus of the 55-mile radius of the plant.

7 3 10 *Postoperational 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.¹⁸ 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} .¹⁸ 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} .¹⁸ 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 long-lived radionuclides 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 radionuclides 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 radionuclides, 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 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 uranium, radium, and thorium are strongly excluded from plant uptake and poorly translocated by plant systems.

The fraction of 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 (C_f value) of uranium equal to 2.5×10^{-3} , thorium equal to 4×10^{-3} , and radium equal to 3×10^{-4} of the concentration in the soil in which the plants grow, that there is no downward movement of the radionuclide in the soil beyond the root zone (15 cm), and that the radionuclide is not lost by drainage of water. With a soil density of 1.5 g cm^{-3} , the radionuclides deposited on a square meter of earth are contained in $2.25 \times 10^5 \text{ g}$ of soil. The following expression is used to estimate the intake of radionuclides via ingestion of plants:

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

Additional intake from the ingestion of plants contaminated via resuspended radionuclides is calculated using the TERMOD code.¹⁵

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

Aquatic Pathways. - Doses from long-lived radionuclides deposited in aquatic ecosystems during the 20-yr life of the facility are largely dependent on the extent to which radionuclides become bound in sediments. Since the long-term rates of such binding are not known, a very conservative estimate of doses from buildup of radionuclides can be made by simply multiplying annual doses for one year of plant operation (Table 7.10) by 20. Thus, an individual drinking water, eating fish, and swimming in the freshwater river would receive a total-body dose of 0.3 millirem/yr. From the estuary, the individual total-body dose would be 0.04 millirem/yr.

7.3.11 Estimates of Postoperational Doses

The radiation dose to an individual residing within the uniformly contaminated area of 9.5×10^3 square miles is estimated for total body and for the organs that are known to accumulate the long-lived radionuclides. The actual population living within a 55-mile radius of the midwestern plant site is used, and population doses are expressed as person-rem per 3.6 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 the purpose of 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 Doses. - As a result of the deposition of long-lived radionuclides such as the actinides, persons living within a 55-mile radius of the model fresh fuel fabrication plant will continue to receive some radiation 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 55 miles for the various radionuclides and exposure modes are shown in Table 7.15. Almost all of the total body dose of 1.1×10^{-4} millirem results from exposure to contaminated ground. The average annual total body dose due to ^{234}U , which accounts for about 54% of the total dose, is 5.9×10^{-5} millirem. Uranium-235 accounts for 4.8×10^{-5} millirem and 45% of the total body dose. These are the average doses out to 55 miles, and the dose range, as a function of distance, will vary considerably over the 55-mile span.

The average annual doses to the organs resulting from the various radionuclides and for the major internal pathways are shown in Table 7.16. The bone receives the highest organ dose, due primarily to the inhalation dose resulting from ^{230}Th . The lung dose is lower by a factor of three.

Population Doses. - The annual dose to the population, given as person-rem per 3.6 million persons, is shown in Table 7.17. The annual total-body dose to the population is again primarily due to ^{234}U and ^{235}U , which account for 98% of the dose. The bone, as a result of its concentration of ^{230}Th , ^{226}Ra , and ^{234}U , receives the highest organ dose. The total body population dose, 0.39 person-rem/ 3.6×10^6 people, is based on the actual population out to 55 miles of the midwestern plant site.

7.4 Environmental Impact of the Fuel Refabrication Plant

The release of radioactive materials to the atmosphere is the principal mode of environmental contamination from the fuel refabrication plant. In this study, no radioactive materials are released in liquid effluents.

7.4.1 Radiation Dose from Airborne 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. Dose conversion factors used in the AIRDOS computer code⁵ to estimate doses resulting from submersion in the airborne effluent, exposure to contaminated ground surface, and intake of radionuclides through inhalation and ingestion are calculated with computer codes¹⁴ 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 are made with a model and computer code,¹⁵ incorporated within AIRDOS,⁵ 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 a recent report.²

7.4.2 Individual and Population Doses

The maximum annual total body dose and organ doses to individuals from airborne effluents at 0.5 mile from the model plant are summarized in Table 7.18 for all radwaste treatment cases for the coastal and midwestern sites. The maximum doses to individuals at 1.0

mile and at 1.5 miles are shown in Tables 7.18a and 7.18b. The total population dose out to 55 miles is presented in Table 7.19. Estimated maximum total-body doses are well below 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 airborne effluents are given in Table 7.20. External exposure to the contaminated ground results in 83% of the total body dose while internal exposure from ingestion accounts for 16%, or most of the remaining 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 due to meteorological differences, the dose to this population (person-rem) is only 2.8 times greater for the midwestern site.

The relative contributions of radionuclides in the airborne effluent of a fuel refabrication plant to total-body dose and organ doses are given in Tables 7.21 and 7.22. Almost 90% of the total-body dose is due to the ^{232}U radionuclide (Table 7.21), and most of the remaining dose is due to ^{224}Ra (8.1%). Most of the dose from contaminated ground (99%) is due to ^{232}U . Similarly, most of the inhalation dose is due to ^{232}U (60%) while 31% comes from ^{228}Th . Approximately 45% of the ingestion dose is due to ^{232}U and 50% to the ^{224}Ra radionuclide. The dose from submersion in air, which is quite small, comes mainly from ^{208}Tl and ^{212}Pb . Since about 83% of the total-body dose is due to contaminated ground (Table 7.20), ^{232}U , which accounts for 99% of the dose due to this pathway (Table 7.22), is the most important radionuclide in the airborne effluent of a fuel refabrication plant.

7.4.3 Doses to Organs of Individuals

Maximum annual doses to organs of individuals from airborne effluents at 1.5 miles from the model plant located on both sites are given in Table 7.18b for all radwaste treatment cases.

Table 7.23 gives the relative contributions of radionuclides in the airborne effluent to individual organ doses. Most of the organ doses from ingestion (over 85%) are due to ^{232}U and ^{224}Ra , while the dose resulting from inhalation is due primarily to ^{232}U and ^{228}Th . 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 refabrication 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 7.18b).

7.4.4 Postoperational Exposures from Long-Lived Radionuclides Released into the Environment from an HTGR Fuel Refabrication Plant

Potential releases of radionuclides during plant operation and estimations of resulting radiation doses to individuals and populations are discussed in Sect. 7.4.2. In this section, estimates are presented of future potential radiation doses to individuals and populations exposed to the long-lived radionuclides that are deposited on the land surface as a result of plant operation.

These estimates involve many complex considerations. All of the information necessary to make accurate predictions is not available. In the absence of complete information, estimates are made using the best current knowledge. Conservative assumptions are used in areas where deficiencies of knowledge exist. These assumptions make it likely that the estimates of health consequence are well above the probable effects. A more detailed assessment of the radiation exposure to future generations from long-lived radionuclides has been included in a recent environmental analysis of the LMFBR program.¹⁸

7.4.5 *Postoperational Source Term*

The model fuel refabrication plant (Case 1) releases approximately 53.1 Ci of radionuclides per year of operation. During this time, individuals and populations are exposed to an airborne 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 7.24 lists these radionuclides and the total quantities released from the model fuel refabrication facility. The longest-lived radionuclides, ²²⁶Ra, ²³⁰Th, ²³²Th, ²³³U, ²³⁴U, ²³⁵U, ²³⁶U, and ²³⁸U, 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 radioactive elements are deposited in a 55-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.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 most of the materials are deposited within 55 miles, even though the release point is the top of a 100-m-high stack.⁸

The average exposure to individuals and populations is estimated using the assumptions that the radionuclides deposited during the operational lifetime of the model plant are uniformly distributed in the 55-mile radius area (2.46×10^{10} m²). 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 55-mile radius of the plant.

7.4.6 *Postoperational Pathways of Exposure*

The pathways of exposure have been discussed in Sect. 7.3.10.

7.4.7 Estimates of Postoperational Doses

The radiation dose to an individual residing within the uniformly contaminated area of 9.5×10^3 square miles is estimated for total body and for the organs that are known to accumulate the long-lived radionuclides. No additional population assumptions are made, and population doses are expressed as person-rem per 3.6 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 the purposes of 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 Doses. - As a result of the deposition of long-lived radionuclides such as the actinides, persons living within a 55-mile radius of the model fuel refabrication plant will continue to receive some radiation 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 55 miles for the various radionuclides and exposure modes are shown in Table 7.25. Almost 100% of the total body dose of 4.9×10^{-3} millirem results from exposure to contaminated ground. The average annual total body dose due to ^{232}U , which accounts for about 100% of the total dose, is 4.9×10^{-3} millirem. These doses are the average doses out to 55 miles, and the dose range, as a function of distance, will vary considerably over the 55-mile span.

The average annual doses to the organs resulting from the various radionuclides and for the major internal pathways are shown in Table 7.26. The bone receives the highest organ dose, which is about 7 times the dose to the kidney and 3 times that to the lungs.

Population Doses. - The annual dose to the population, given in person-rem per 3.6 million persons, is shown in Table 7.27. The annual dose to the population (total body and organs) is again almost wholly due to ^{232}U , which accounts for approximately 100% of the dose. The bone receives the highest organ dose. The total body population dose, 17 person-rem per 3.6×10^6 people, is based on the actual population of the midwestern plant site.

7.5 References

1. Federal Radiation Council, *Estimates and Evaluation of Fallout in the United States from Nuclear Weapons Testing Conducted through 1961*, Report No. 4 (May 1963).
2. G. G. Killough and L. R. McKay, (eds.), *A Methodology for Calculating Radiation Doses from Radioactivity Released to the Environment*, ORNL-4992 (March 1976).
3. F. Pasquill, *Meteorol. Mag.* 90, 1063 (1961).

4. F. A. Gifford, Jr., "Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion," *Nuclear Safety* 2(4), 47 (1961).
5. R. E. Moore, *AIRDOS - A Computer Code for Estimating Population and Individual Doses Resulting from Atmospheric Releases of Radionuclides from Nuclear Facilities*, ORNL-TM-4687 (January 1975).
6. Since only limited joint frequency data are available for existing fuel fabrication and reprocessing sites, the model evaluation was based on the arbitrary selection of data from St. Louis, Mo., and Wilmington, N. C., first-order records for midwestern and coastal environments, respectively. Joint frequency velocity and direction data by stability class were provided in the STAR tabulation format by the National Climatic Center, Asheville, N. C., for a 5-year period of record (St. Louis 1/65 to 12/69; Wilmington 1/66 to 12/70).
7. F. A. Gifford, Jr., and D. H. Pack, "Surface Deposition of Airborne Material," *Nuclear Safety* 4(4), 76-80 (1962).
8. K. E. Cowser, M. Reeves, P. G. Fowler, and W. M. Culkowski, "Evaluation of the Potential Radiological Impact of Airborne Effluents on Local Environments," *Proceedings of the International Symposium on Radioecology Applied to the Protection of Man and His Environment*, EUR-4800 (September 1971).
9. R. J. Engelmann, "The Calculation of Precipitation Scavenging," in D. H. Slade, *Meteorology and Atomic Energy*, TID-24190 (1968), pp. 208-221.
10. D. H. Slade, *Meteorology and Atomic Energy*, TID-24190 (1968).
11. P. R. Coleman and A. A. Brooks, *PANS: A Program to Tally Population by Annuli and Sectors*, ORNL-TM-3923 (October 1972).
12. *USAEC Final Environmental Statement Related to the Operation of the Midwest Fuel Recovery Plant*, DOCKET 50-268 (December 1972), p. 9.
13. *USAEC Draft Environmental Statement Related to the Barnwell Nuclear Fuel Plant*, DOCKET 50-332 (January 1973), pp. II-5, II-6, II-7. Additional population data appear in the *Allied-Gulf Nuclear Services Environmental Report Barnwell Nuclear Fuel Plant*, (November 1971).
14. W. D. Turner, S. V. Kaye, and P. S. Rohwer, *EXREM and INREM Computer Codes for Estimating Radiation Doses to Populations from Construction of a Sea-Level Canal with Nuclear Explosives*, K-1753 (Sept. 16, 1968).

- 15 R S Booth and S V Kaye, *A Preliminary Systems Analysis Model of Radioactivity Transfer to Man from Deposition in a Terrestrial Environment*, ORNL-TM-3135 (October 1971)
- 16 S E Thompson *et al* , *Concentration Factors of Chemical Elements in Edible Aquatic Organisms*, UCRL-50564, Rev 1 (1972)
- 17 A M Freke, "A Model for the Approximate Calculation of Safe Rates of Discharge of Radioactive Wastes into Marine Environments," *Health Physics* 13(7), 743 (1967)
- 18 *Proposed Final Environmental Statement, Liquid Metal Fast Breeder Reactor Program, Vol II, Environmental Impact of the LMFBR Fuel Cycle*, USAEC, WASH-1535 (December 1974)

8.0 CORRELATION OF ENVIRONMENTAL IMPACT WITH COST OF WASTE TREATMENT

The relationship between the annual costs of the radwaste treatment systems described in Sects. 4.5 and 6.0 and the impact of radioactive releases (dose) from these systems as described in Sect. 7.0 is presented in this section. The accuracy of the cost estimates is about $\pm 30\%$, and the dose commitments represent maximum values. The base case studies illustrate the important features of currently proposed plants. The advanced cases use technology ranging 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. Similarly, many of the models for the movement and concentration of radionuclides in the environment are receiving additional study to increase their accuracy. In all cases, the various assumptions made in estimating the makeup of the feed to the fabrication plants, selecting treatment efficiency ratings for equipment, assessing process decontamination (containment) factors, estimating costs, defining the movement of radionuclides in the environment, and selecting food and liquid consumption patterns were realistically conservative, and this is reflected in the costs and doses.

8.1 Fresh Fuel Fabrication Plant

The annual costs and dose commitments for the base case (Case 1) and succeeding case studies (Cases 2 to 4) at the midwestern and coastal sites from airborne effluents are summarized in Table 8.1 and Figs. 8.1 and 8.2. The estimated annual costs required for additional airborne radwaste treatment in each case beyond that required for the previous case, i.e., the added incremental costs, are presented in Table 8.2. The dose commitments from the airborne effluents are reported on several bases, including (a) the maximum annual individual total body, bone, liver, kidney, and lung doses (other body organs which were discussed in Sect. 7.0 but which will not be considered here include GI tract, thyroid, muscle, spleen, testes, and ovaries) at 0.5 mile from the plant, which represent the doses from all radioactive materials released from the fresh fuel fabrication plant in each case study; (b) incremental maximum annual individual doses at 0.5 mile, which represent the differences in dose between a given case and the preceding case; and (c) the annual dose to the population out to a distance of 55 miles. Factors for calculating maximum doses at distances other than 0.5 mile are given in Sect. 7.0. Actually, the maximum doses occur at 0.25 mile from the point of release, and they are approximately 60% greater than the doses at one-half mile. However, major comparisons of dose are made at 0.5 mile so that this report will be comparable with other reports in this series. The maximum doses for a given annulus are considered rather than the average individual doses to total body, bone, liver, kidney, lung, and the average population dose, to illustrate the cost/benefit relationships in this section and thus maintain the principle of the selection of maximum effect in this study. Total body dose was selected

because of its obvious importance, and bone, liver, kidney, and lung doses because the principal radionuclides that contribute to the total body dose also contribute to these organ doses. The major radionuclides contributing to the radiological doses are ^{234}U , ^{235}U , and ^{230}Th . For example, their contributions to the total body dose are 47%, 28%, and 17%, respectively. The dose from submersion in air, which is very small ($<0.01\%$ of the total body dose), comes mainly from ^{220}Rn and its daughters.

The fresh fuel fabrication plant releases liquid radwastes in Case 1, and dose commitments from these effluents are compared with treatment costs on two bases, i.e., annual total body dose and bone dose (millirem) from aquatic pathways after dilution in a 15-cfs stream and after the 15-cfs stream flows into a 1300-cfs river 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 major radionuclides contributing to the radiological doses from liquid effluents are ^{212}Pb , ^{212}Bi , ^{234}U , and ^{230}Th .

8.1.1 Comparison of Airborne Radwaste Treatment Costs and Radiological Dose

Cases 1 and 2 are identical with respect to airborne radwaste treatment and radiological dose. The two cases are designed in this manner so that the effect of eliminating the release of liquid radwastes (the difference between Cases 1 and 2) can be easily ascertained (Sect. 8.1.2).

Individual Total Body Dose. - The maximum annual individual total body dose is derived mostly from ^{230}Th , ^{234}U , and ^{235}U (about 92% of the total dose). The annual costs for reducing this dose from airborne effluents at 0.5 mile are presented in Tables 8.1 and 8.2 and Fig. 8.1. The total body dose is reduced by a factor of about four, i.e., from 0.14 to 3.3×10^{-2} millirem at the midwestern site and 9.5×10^{-2} to 2.3×10^{-2} millirem at the coastal site, from Case 1 (or 2) to Case 3 by modifications to the processing operations and improvements in the filtration system at a total annual cost increase of \$616 thousand. The cost/benefit ratio for this increment is \$5.76 million per millirem (\$8.56 million per millirem at the coastal site), corresponding to an annual expenditure of about 1.2% of the \$50 million capital cost of the plant. A further reduction in dose by a factor of nearly 400 occurs in Case 4. This reduction in dose is achieved at an added cost of \$1.65 million per year, which corresponds to a cost/benefit ratio of \$50.2 million per millirem at the midwestern site (\$72.1 million per millirem at the coastal site). The high cost/benefit ratio results from the small amounts of radioactive materials that are available for removal after the treatments applied in Case 3, rather than from the magnitude of the treatment cost. The incremental expenditure between Case 3 and Case 4 (\$1.65 million) amounts to about 3.3% of the plant capital cost. As a comparison, the treatment of the airborne effluents in the basic model plant (Case 1) achieves a dose reduction by a factor of 8.1×10^3 at an annual cost of \$1.39 million to provide a cost/benefit ratio of \$1.23 thousand per millirem at the midwestern site (\$1.81 thousand per millirem at the coastal site). Thus, the lowest cost/benefit ratio is attained in Case 1. The value rises quickly for succeeding case increments as a result of the low residual amounts of radioactive materials present. The coastal site shows slightly lower doses (20 to 30%) and slightly higher cost/benefit ratios (Table 8.2).

Bone Dose. - The maximum annual individual bone dose is derived mostly from ^{230}Th and ^{234}U . Annual costs to reduce the bone dose are presented in Tables 8.1 and 8.2 and Fig. 8.1. The initial dose reduction by a factor of 8.1×10^3 achieved by the final off-gas treatment system in the model plant (Case 1) provides a cost/benefit ratio of \$90.3 per millirem at the midwestern site. An additional dose reduction by a factor of about four in Case 3 is obtained at a cost/benefit ratio of \$419 thousand per millirem (midwestern site). Further reduction in bone dose (by a factor of 360) in Case 4 is obtained at a cost/benefit ratio of \$3.85 million per millirem. The most efficient system as measured by the cost/benefit ratio is the basic model plant (Case 1).

Liver and Kidney Doses. - The maximum annual individual liver and kidney doses are also derived from ^{230}Th and ^{234}U with significant contributions produced from ^{220}Rn and from its ^{212}Pb daughter. Cost/benefit ratios for the model plant (Case 1) off-gas treatment system are \$1.23 thousand and \$350 per millirem for liver and kidney doses, respectively. The ratios that represent the effects of equipment changes in Case 3 are \$5.70 million and \$1.58 million per millirem, while the Case 4 values are \$51.7 million and \$16.6 million per millirem. All of these values are for the midwestern site. The cost/benefit ratios at the coastal site are about 44% higher for each of the case studies.

Lung Dose. - The maximum annual individual lung dose is derived mostly from ^{234}U , with minor contributions from ^{230}Th and ^{220}Rn (including its daughter ^{212}Pb). The model plant (Case 1) provides an initial reduction in dose of 8.1×10^3 for a cost/benefit ratio of \$249 per millirem at the midwestern site. The Case 3 equipment and operation modifications provide a cost/benefit ratio of \$1.18 million per millirem. The Case 4 cost/benefit ratio is \$9.73 million per millirem. Again, the most efficient system is the basic model plant (Case 1).

Population Dose. - The annual cost of reducing the annual population total-body dose (person-rem) out to a distance of 55 miles is presented in Table 8.1 and Fig. 8.2. A cost/benefit ratio of \$327 per person-rem results from the factor of 8.1×10^3 reduction in the initial dose achieved by the model plant (Case 1) final off-gas treatment system at the midwestern site (\$564 per person-rem at the coastal site). The population dose values for Case 1 are low, i.e., 0.524 and 0.304 person-rem for the midwestern and coastal sites, respectively. These values are low when compared with the natural background radiation dose of 5.5×10^4 to 6.1×10^5 person-rem for the same population.¹ The cost/benefit ratios are much higher in Cases 3 and 4, where additional airborne radwaste treatment equipment is used to decrease the release of radioactive materials. The population dose is reduced by a factor of four in Case 3 at an increased annual cost of \$616 thousand. This corresponds to cost/benefit ratios of \$1.56 million and \$2.68 million per person-rem for the midwestern and coastal sites, respectively. Additional dose reductions from Case 3 values to Case 4 are estimated at an increased annual expense of \$1.65 million. Cost/benefit ratios for this increment are \$12.8 million and \$22.3 million per person-rem for the midwestern and coastal sites, respectively.

8.1.2 Comparison of Liquid Radwaste Treatment Costs and Radiological Dose

Liquid radwastes are released only in the Case 1 study, therefore, the incremental costs between Case 1 and other cases reflect the effect of eliminating the discharge of this stream. The Case 2 study demonstrates a temporary solution to liquid radwaste treatment where the effluents are discharged to a lined lagoon for concentration via solar evaporation. In the Case 3 and Case 4 studies, the liquid effluents are concentrated via evaporators, and water, nitric acid, and ammonia are recycled where feasible. The excess water is evaporated and released to the atmosphere, and the excess nitrate and ammonia are converted to nitrogen by anaerobic digestion. The radioactive materials in the residues are incorporated in cement and packaged in drums for disposal. No economic credit is taken for the recycle streams. The annual costs for liquid radwaste treatment are given in Table 8.3, and the added incremental costs are presented in Table 8.4.

Two points are selected for analysis of the impact of the liquid waste effluent, i.e., (a) after dilution in a 15-cfs stream and (b) 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. However, it is included to illustrate the maximum impact at the point of discharge from the model plant. The doses for drinking water, fish consumption, and swimming are combined in the cost/benefit analyses. However, the doses 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 dose and bone dose from liquid effluents after dilution in the 15-cfs stream, 1300-cfs river, and the coastal estuary are compared with the annual liquid radwaste treatment costs in Table 8.3, and the incremental costs are presented in Table 8.4. Doses are nearly 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. The maximum annual individual dose from aquatic pathways associated with the 15-cfs stream is 1.4 millirem, which is ten times higher than the maximum individual dose of 0.14 millirem from the airborne effluent from the fresh fuel fabrication plant. However, the more realistic annual dose associated with the 1300-cfs river is 0.016 millirem at the midwestern site, about nine times lower than the airborne and about 90 times lower than the 15-cfs stream cases. The bone dose associated with the 15-cfs stream is about nine times higher than that from the airborne effluent case. However, the bone dose from the 1300-cfs river is about nine times lower than the airborne and about 86 times lower than the 15-cfs stream cases.

Individual Total Body Dose - The major radionuclide contributors in the liquid effluents to total body dose are ^{210}Bi , ^{210}Pb , ^{230}Th , and ^{234}U . The treatment of the liquid effluents in the basic model plant (Case 1) achieves a dose reduction for the 15-cfs stream of 60 at an annual cost of \$22 thousand to provide a cost/benefit ratio of \$262 per millirem at the midwestern site. In Case 2, where the liquid radwastes are discharged to a lined lagoon for concentration by solar evaporation, the total body dose is reduced to zero for an additional annual expenditure of \$209 thousand and a cost/benefit ratio of \$149 thousand for the 15-cfs stream at the midwestern site. In Cases 3 and 4 several chemical components of the liquid effluents

are either recycled, where feasible, or converted into innocuous compounds before release to the environment. These processing modifications, while adding an additional \$461 thousand to the annual costs, do not reduce the total body dose but do reduce the environmental effects of chemical releases. The cost/benefit ratio for the increment Case 1/Case 3 (or Case 4) is \$329 thousand per millirem for the 15-cfs stream at the midwestern site. When the dose calculated for the 1300-cfs river (which occurs only at the midwestern site) is considered, the cost/benefit ratio is much higher than for the 15-cfs stream because the dose is lower by a factor of about 90 in the river as a result of the greater dilution. In this case, the cost/benefit ratios are \$13.1 million per millirem for the increment Case 1/Case 2, and \$28.8 million per millirem for the increment Case 1/Case 3 (or Case 4), while the treatment in the base plant (Case 1) provides a cost/benefit ratio of \$22.9 thousand per millirem.

Bone Dose - Bismuth-212, ^{212}Pb , ^{230}Th , and ^{234}U are the major contributors to the maximum annual individual bone dose. The initial liquid radwaste treatment system for the basic plant (Case 1) provides a cost/benefit ratio for the 15-cfs stream of \$20.4 per millirem. The elimination of the release of liquid radwaste effluents in the Case 2 study provides a cost/benefit ratio of \$11.6 thousand per millirem for the 15-cfs stream at the midwestern site. The cost/benefit ratio for the Case 3 (or 4) study is \$25.6 thousand per millirem. The cost/benefit ratios for the 1300-cfs river and the estuary are much higher because of the small doses calculated for these two sites.

8.2 Refabrication Plant

The annual costs and dose commitments for the base case (Case 1) and succeeding case studies (Cases 2, 3, and 4) at the midwestern and coastal sites are summarized in Tables 8.5 and 8.6 and Figs. 8.3 and 8.4. The costs are the estimated total annual costs required for the additional radwaste treatment system for a given case beyond that required for the base case (Case 1), i.e. in effect, the added incremental cost. The dose commitments from the airborne effluents are reported as was done for the fresh fuel fabrication plant (Sect. 8.1).

Since liquid radwastes are contained and isolated from the environment, the dose calculations are based solely upon the radioactive particulates released in the airborne effluent from the plant. The calculated population doses for the midwestern site are about 280% greater than those for the coastal site because of variations in atmospheric dispersion patterns and population densities.

The estimated maximum individual annual doses are <1 millirem for bone and total body in Case 1, the case which represents the greatest release of radionuclides. These values are low compared with the natural background radiation dose of 100 to 170 millirem per year in the United States.¹

8.2.1 Comparison of Airborne Radwaste Treatment Costs and Radiological Dose

The most important radionuclide in the airborne effluent from the refabrication plant is ^{232}U with minor contributions from ^{230}Th and ^{224}Ra . The airborne effluent treatment system for the basic plant (Case 1) achieves a dose reduction of 5.1×10^5 at an annual cost of \$3.79 million (Table 8.5). The doses in Case 4 are about 7000 times lower than in Case 1. The largest dose is for bone, followed by lung and total body. The individual doses at the midwestern site are approximately 25% higher than those at the coastal site.

Individual Total Body Dose. - Almost 90% of the total-body dose is due to the ^{232}U radionuclide, and most of the remaining dose is due to ^{224}Ra (8.1%). For the midwestern site, the total body dose decreases by a factor of 10 between Cases 1 and 2 for an additional annual cost of \$24 thousand to provide a cost/benefit ratio of \$178 thousand per millirem. Only a slight reduction in total body dose occurs for the increment Case 2 to Case 3 because the major objective in Case 3 is to reduce the bone dose by decreasing the concentration of thorium and its daughters in the product streams. The cost/benefit ratio for the Case 2/Case 3 increment is \$112 million per millirem at the midwestern site. The Case 4 treatment is designed to achieve a significant reduction in the amount of radioactive material released from the plant and provides a reduction of about 670 in the total body dose at an additional annual cost of \$830 thousand and a cost/benefit ratio of \$59.3 million per millirem at the midwestern site. For comparison, the basic model plant achieves a dose reduction of 5.1×10^5 at an annual cost of \$3.79 million to provide a cost/benefit ratio of \$49.5 per millirem at the midwestern site. The cost/benefit ratios are slightly higher at the coastal site for all cases.

Bone Dose. - The major radioactive contributors to the bone dose are ^{228}Th and ^{232}U , with a minor contribution from ^{233}U . The bone dose is reduced from 0.44 to 4.4×10^{-2} millirem at the midwestern site from Case 1 to Case 2 at a total annual cost increase of \$24 thousand. A cost/benefit ratio for this increment is \$60.6 thousand (\$68.4 thousand at the coastal site). The bone dose is reduced by about 35%, i.e., from 4.4×10^{-2} to 3.2×10^{-2} millirem, from Case 2 to Case 3 by reducing the concentration of thorium and its daughters in the fabrication operation at a total annual cost increase of \$112 thousand. The cost benefit ratio for this increment is \$9.33 million per millirem. A further reduction in dose by a factor of 640 occurs in Case 4. The added cost for this reduction is \$830 thousand per year, which corresponds to a cost/benefit ratio of \$25.9 million per millirem at the midwestern site (\$28.6 million at the coastal site).

Population Dose. - The annual cost of reducing the annual population total body dose (person-rem) out to a distance of 55 miles is presented in Table 8.5 and Fig. 8.4. The population doses are approximately 14 times higher than those calculated for the fresh fuel plant (7.54 vs 0.524 person-rem), but they are several orders of magnitude lower than that found for natural background radiation (doses of 5.5×10^4 to 6.1×10^5 person-rem). The dose is reduced by a factor of about ten in the Case 2 study for a cost increase of \$24.0 thousand per year and a cost/benefit ratio of \$3.54 thousand for the midwestern site (\$9.95 thousand for the coastal site). There is a very slight dose reduction in Case 3 which is obtained at a cost/benefit ratio of \$3.39 million for the midwestern site. Further reduction in the population dose by a factor of 660 in Case 4 is obtained at a cost/benefit ratio of \$1.15 million.

Combined Reprocessing-Refabrication Plant Doses. - Davis *et al.*² have correlated waste treatment costs and the environmental impact of an HTGR fuel reprocessing plant which is expected to be located adjacent to the refabrication plant. The population annual average doses in the base case of the reprocessing plant at the midwestern site are as follows: total body, 2360 person-rem; GI tract, 1330 person-rem; bone, 3600 person-rem; and thyroid, 10,400 person-rem. By comparison, with corresponding base-case values for the refabrication plant, namely 7.54, 6.08, 18.3, and 7.21 person-rem, respectively, it is apparent that the dose commitment due to the refabrication plant is, in all cases, less than 1% of that due to reprocessing.

8.3 Comparison of Airborne Radwaste Treatment Costs and Power Costs

Although the two fuel fabrication plants operate as separate entities and their airborne radwaste treatment costs and power costs have been so calculated in Sect. 6.0 (Table 6.1), the plants are considered as a fabrication complex in this section because the refabrication plant relies on the fresh fuel plant to supply all of its fertile material. The capital cost of the two plants, when they are considered as a complex for the base case (Case 1), is \$450 million. The estimated capital cost of an airborne radwaste treatment system in these plants is \$14.0 million (Table 6.1). The corresponding annual off-gas treatment and contribution to power costs are \$5.21 million and 0.014 mill/kWhr. Capital costs for airborne radwaste treatment in advanced cases range from \$14.7 to \$24.1 million, or up to about 5.4% of the capital cost of the base complex. The annual costs for the advanced cases of airborne radwaste treatment range from \$5.46 to \$8.90 million and are equivalent to contribution to power costs of 0.014 and 0.024 mill/kWhr, respectively. All of these values are less than 0.4% of an estimated total power generation cost of 7 to 10 mill/kWhr. Thus, the cost of airborne radwaste treatment is a small fraction of total capital and power generation costs.

8.4 References

1. P. C. Tompkins, "The Use and Misuse of Population Exposures in Radiation Protection," p. 9 in *Population Exposures*, held in Knoxville, Tennessee, Oct. 21-24, 1974, CONF-741018 (October 1974).
2. W. Davis, Jr., R. E. Blanco, B. C. Finney, G. S. Hill, R. E. Moore, and J. P. Witherspoon, *Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle - Reprocessing of High-Temperature Gas-Cooled Reactor Fuel Containing U-233 and Thorium*, ORNL/NUREG/TM-4 (in press).

Table 2.1. Purposes of the layers in the fissile and fertile coatings

Coating layer		Purpose
BISO ^a	Buffer	Attenuate fission recoils Provide void volume for gaseous fission products and fuel swelling
	Isotropic PyC ^b	Act as a pressure vessel to contain gaseous fission products
TRISO ^c	Buffer	Attenuate fission recoils Provide void volume for gaseous fission products and fuel swelling
	Inner isotropic PyC ^b	Protect the SiC layer from detrimental reactions with fuel and fission products
	SiC ^d	Provide fissile-fertile separation capability Provide mechanical support for the particle Provide structural rigidity and dimensional stability Provide containment of gaseous and solid fission products
	Outer isotropic PyC ^b	Provide mechanical support for the SiC layer Protect the SiC layer from damage during handling

^aAcronym for the two coating layers on the fertile particle.

^bPyrolytic carbon.

^cAcronym for the three types of coating layers on the fissile particle.

^dSilicon carbide.

Table 3.1. The 30-year lifetime average loading and the equilibrium reloading for the reference 1000-MW(e) HTGR^a

Nuclide	Thorium	23R	IM	25R	Average
<u>30-year lifetime average loading</u>					
²³⁰ Th	0.81	0.0	0.0	0.0	0.81
²³² Th	8099.91	0.0	0.0	0.0	8099.91
²³² U	0.0	0.22	0.0	0.0	0.22
²³³ U	0.0	194.58	0.0	0.0	194.58
²³⁴ U	0.0	63.86	3.83	1.49	69.18
²³⁵ U	0.0	22.45	377.07	45.77	445.29
²³⁶ U	0.0	12.96	0.85	45.54	59.35
²³⁸ U	0.0	0.0	23.33	15.03	38.36
<u>Equilibrium reloading</u>					
²³⁰ Th	0.73	0.0	0.0	0.0	0.73
²³² Th	7264.58	0.0	0.0	0.0	7264.58
²³² U	0.0	0.33	0.0	0.0	0.33
²³³ U	0.0	216.26	0.0	0.0	216.26
²³⁴ U	0.0	82.71	3.31	1.45	87.47
²³⁵ U	0.0	31.31	326.37	41.58	399.26
²³⁶ U	0.0	19.33	0.74	46.81	66.88
²³⁸ U	0.0	0.0	28.19	14.92	43.11

^aUnits are kilograms. Values are based on recycle of uranium in 23R and 25R streams one year after discharge. From CITATION calculations (ref. 9).

Table 4.1. Material flow in the production of fissile particles - Cases 1 and 2
(FRESH FUEL FABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Liquid flow rate (gpd)	Flow rate (lb/day)																			
	Process	Cell		UF ₆	UO ₂ F ₂	NH ₃	H ₂ O	H ₂	HF	KOH	K ₂ U ₂ O ₇	KF	UO ₂	CO _x	Soot (C)	NaOH	HCl	UC ₂	Na ₂ U ₂ O ₇	UCl ₄	U ₃ O ₈	NaCl	SiC
1	-	-	-	2.30E+2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	4.5E+1	-	-	-	3.8E+2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	5.4E+2	-	-	-	-	2.6E+1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	3.2E+2	-	-	-	2.6E+3	-	-	2.9E+2	-	-	-	-	-	-	-	-	-	-	-	-	-
5	4.32E+3	8.64E+6	-	-	4.00E-1	-	3.5E+2	3.2E+0	7.9E+1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	4.32E+3	8.64E+6	-	-	-	-	8.0E+0	3.2E+0	7.9E-1	2.9E-1	4.30E-2	2.3E-1	-	-	-	-	-	-	-	-	-	-	-
7	-	-	3.6E+2	-	-	-	3.0E+3	-	-	7.1E+1	3.70E-4	2.3E+2	-	-	-	-	-	-	-	-	-	-	-
8	-	-	-	-	-	-	-	-	-	-	-	-	1.75E+2	-	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-	-	-	-	-	8.07E+1	-	-	-	-	-	-	-	-	-	-
10	2.16E+4	4.32E+6	-	-	-	-	-	-	-	-	-	-	1.00E-1	6.3E+1	1.0E+0	-	-	3.00E-2	-	-	-	-	-
11	2.16E+4	4.32E+6	-	-	-	-	-	-	-	-	-	-	5.00E-3	6.3E+1	5.0E-2	-	-	1.50E-3	-	-	-	-	-
12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.27E+2	-	-	-	-	-
13	1.08E+5	1.01E+7	-	-	-	-	-	3.8E+2	-	-	-	-	-	-	7.5E+2	-	-	9.60E+0	-	-	-	-	-
14	1.08E+5	1.01E+7	-	-	-	-	3.4E+3	-	-	-	-	-	-	2.8E+3	-	-	-	-	-	-	2.06E-1	-	-
15	-	-	1.2E+3	-	-	-	1.0E+4	-	-	-	-	-	-	-	-	9.4E+2	-	-	-	-	-	-	-
16	8.64E+4	8.64E+6	-	-	-	-	-	1.0E+3	-	-	-	-	-	-	3.0E+2	-	7.2E+2	-	-	1.30E+0	-	-	5.0E+1
17	8.64E+4	8.64E+6	-	-	-	-	5.4E+1	1.0E+3	-	-	-	-	-	-	3.0E+1	-	7.2E+0	-	1.10E-1	-	-	1.1E-1	5.0E+0
18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.81E+2	-	-	-	-	-
19	-	-	2.8E+2	-	-	-	2.4E+3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	-	-	1.2E+3	-	-	-	1.0E+4	-	-	-	-	-	-	-	-	1.5E+2	-	-	9.70E-3	-	-	1.1E+3	-
21	-	-	2.8E+2	-	-	-	2.3E+3	-	-	-	-	-	-	-	-	-	-	-	-	-	1.90E-2	-	-
22	-	-	2.8E+2	-	-	-	2.3E+3	-	-	-	-	-	-	-	-	-	-	-	-	-	1.90E-4	-	-
23	-	4.32E+6	-	-	-	-	5.0E+1	-	-	-	-	-	-	-	-	-	-	1.80E-4	-	-	-	-	-
24	-	4.32E+6	-	-	-	-	5.0E+1	-	-	-	-	-	-	-	-	-	-	9.00E-6	-	-	-	-	-
25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.81E+2	-	-	-	-	-
26	2.20E+6	3.68E+7	-	-	-	-	1.3E+4	-	8.0E-1	-	4.30E-4	2.3E-3	-	2.9E+3	-	-	7.2E+0	-	1.10E-3	-	2.13E-3	1.4E+0	5.0E-2
27	-	-	1.2E+3	-	-	-	9.8E+3	-	-	7.1E+1	3.70E-4	2.3E+2	-	-	-	2.2E+2	-	-	9.70E-3	-	1.90E-4	1.1E+3	-

^aProcess streams are identified in Fig. 4.1.

Table 4.2 Material flow in the production of fertile particles - Cases 1 and 2
(FRESH FUEL FABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Liquid Flow rate (gpd)	Flow rate (lb/day)																
	Process	Cell		Th(NO ₃) ₄	CH ₂ O	H ₂ O	NaOH	HNO ₃	ThO ₂	Th(NO ₃) ₄	Th(OH) ₄	NaNO ₃	NH ₃	BaCO ₃	(NH ₄) ₂ SO ₄	NH ₄ NO ₃	NH ₄ OH	CO _x	Soot (C)	H ₂
1	-	-	-	9.13E+3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	1.3E+3	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	4.32E+3	1.44E+6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	9.7E+2	-	-	8.2E+3	2.5E+3	-	-	-	-	-	-	-	-	-	-	-	-	-
5	4.32E+3	1.44E+6	-	-	-	2.4E+3	-	3.9E+3	2.10E+0	3.63E+0	-	-	-	-	-	-	-	-	-	-
6	4.32E+3	1.44E+6	-	-	-	6.0E+0	2.5E+0	-	2.10E-1	-	2.30E-1	5.2E+0	-	-	-	-	-	-	-	-
7	-	-	-	-	-	2.4E+1	-	3.9E+1	4.05E+3	-	-	-	-	-	-	-	-	-	-	-
8	-	-	1.4E+3	-	-	1.1E+4	9.5E+0	-	-	-	1.52E+0	5.2E+3	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-	-	-	-	-	8.3E+1	3.5E+1	-	-	-	-	-	-
10	-	-	2.6E+2	-	-	2.0E+3	-	-	-	-	2.90E-1	-	-	-	-	8.0E+1	1.0E+2	-	-	-
11	-	-	2.6E+2	-	-	2.0E+3	-	-	-	-	2.90E-1	-	-	-	-	8.0E+1	1.0E+2	-	-	-
12	2.16E+5	4.32E+6	-	-	-	2.1E+3	-	-	1.51E+1	-	-	3.5E+1	-	-	-	-	-	2.4E+2	-	-
13	2.16E+5	4.32E+6	-	-	-	2.1E+3	-	-	7.55E-1	-	-	3.5E+1	-	-	-	-	-	2.4E+2	-	-
14	-	-	-	-	-	-	-	-	3.76E+3	-	-	-	-	-	-	-	-	-	-	-
15	1.08E+6	1.44E+7	-	-	-	-	-	-	3.63E+1	-	-	-	-	-	-	-	-	-	3.5E+3	1.8E+3
16	1.61E+6	1.44E+7	-	-	-	1.6E+4	-	-	3.63E-1	-	-	-	-	-	-	-	-	1.3E+4	-	-
17	-	-	-	-	-	-	-	-	3.59E+3	-	-	-	-	-	-	-	-	-	-	-
18	1.83E+6	2.02E+7	-	-	-	1.8E+4	-	-	6.65E-4	-	1.15E-4	-	3.5E+1	-	-	-	-	1.3E+4	-	-
19	-	-	1.8E+3	-	-	1.3E+4	9.5E+0	-	-	-	2.04E-2	5.2E+3	-	-	-	8.0E+1	1.0E+2	-	-	-

^aProcess streams are identified in Fig. 4.2

Table 4.3. Material flow in the production of fuel rods and elements - Cases 1 and 2
(FRESH FUEL FABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Liquid flow rate (gpd)	Flow rate (lb/day)														
	Process	Cell		ThO ₂	UC ₂	HCl	NaOH	H ₂ O	NaCl	Th(OH) ₄	Na ₂ U ₂ O ₇	ThCl ₄	Soot (C)	U ₂ O ₈	NO _x	SO _x	UCl ₄	Al ₂ O ₃
1	-	-	-	1.87E+3	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	1.81E+2	-	-	-	-	-	-	-	-	-	-	-	-	-
3	6.48E+6	-	-	1.87E-1	1.81E-2	-	-	-	-	-	-	5.0E-1	-	-	-	-	-	-
4	6.48E+6	-	-	9.35E-3	9.05E-4	-	-	-	-	-	-	2.5E-2	-	-	-	-	-	-
5	7.33E+6	2.66E+7	-	9.74E-4	-	-	6.0E-4	2.0E+2	9.0E-4	5.00E-4	5.12E-5	-	1.6E+0	1.01E-4	1.3E+1	5.0E+0	-	3.6E-3
6	-	-	-	1.76E+3	1.70E+2	-	-	-	-	-	-	-	-	-	-	-	-	-
7	7.20E+5	1.73E+7	-	1.76E+0	1.70E-1	-	-	6.4E+1	-	-	-	-	3.2E+3	-	1.3E+1	5.0E+0	-	7.1E+0
8	7.20E+5	1.73E+7	-	8.80E-2	-	-	-	6.4E+1	-	-	-	-	-	9.11E-3	1.3E+1	5.0E+0	-	3.6E-1
9	-	-	-	1.75E+3	1.69E+2	-	-	-	-	-	-	-	-	-	-	-	-	-
10	-	-	2.4E+3	-	-	-	6.5E+1	2.0E+4	-	-	-	-	-	-	-	-	-	-
11	5.7E+2	-	-	-	-	5.8E+1	-	-	-	-	-	-	-	-	-	-	-	-
12	8.64E+4	8.64E+6	-	-	-	5.5E+1	-	-	-	-	-	6.20E-1	1.8E+1	-	-	-	6.15E-2	-
13	8.64E+4	8.64E+6	-	-	-	-	6.0E-2	1.4E+2	9.0E-2	5.00E-2	5.12E-3	-	1.8E+0	-	-	-	-	-
14	-	-	-	1.74E+3	1.68E+2	-	-	-	-	-	-	-	-	-	-	-	-	-
15	-	-	2.4E+3	-	-	-	4.0E+0	2.0E+4	8.9E+1	4.50E-1	4.60E-2	-	-	-	-	-	-	-
16	4.32E+4	7.20E+5	-	1.74E-3	1.68E-4	-	-	-	-	-	-	-	-	-	-	-	-	-
17	4.32E+4	7.20E+5	-	8.70E-5	8.40E-6	-	-	-	-	-	-	-	-	-	-	-	-	-
18	-	-	-	1.74E+3	1.68E+2	-	-	-	-	-	-	-	-	-	-	-	-	-

^aProcess streams are identified in Fig. 4.4.

Table 4.4. Material flow in the fissile scrap recovery system - Cases 1 and 2
(FRESH FUEL FABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Liquid flow rate (gpd)	Flow rate (lb/day)																
	Process	Cell		Li ₂ O ₂	ThO ₂	H ₂ O	HNO ₃	NH ₄ OH	NH ₄ NO ₃	HF	NaOH	UO ₂	UO ₂ (NO ₃) ₂	SiC	Th(OH) ₄	NaNO ₃	(NH ₄) ₂ U ₂ O ₇	Soot (C)	Na ₂ U ₂ O ₇	NaF
1	-	-	-	8.65E+1	4.00E+1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	-	-	1.49E+2	-	-	1.1E+3	2.5E+2	-	-	6.0E+0	-	-	-	-	-	-	-	-	-	-
3	-	-	1.42E+2	-	-	1.2E+3	1.2E+0	-	-	-	-	-	-	-	-	-	-	-	-	-
4	-	-	1.42E+2	-	-	1.2E+3	1.1E+0	-	-	-	-	-	1.18E+2	-	-	-	-	-	-	-
5	-	-	1.54E+2	-	-	1.2E+3	-	3.8E+1	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	1.44E+3	-	-	8.0E+3	-	-	-	1.0E+2	-	-	-	-	-	-	-	-	-	-
7	7.20E+4	1.27E+7	-	-	-	7.2E+3	-	-	-	6.0E-1	-	-	-	3.0E-1	1.00E-3	-	-	1.6E+0	2.20E-2	-
8	-	-	1.90E+1	-	-	1.6E+2	-	4.3E-1	3.2E+0	-	-	-	-	-	-	-	9.00E-1	-	-	-
9	-	-	3.08E+2	-	-	2.5E+3	-	5.9E+0	4.5E+1	-	-	-	-	-	-	-	1.00E+0	-	-	-
10	-	-	-	-	-	3.0E+1	-	7.0E-2	5.6E-1	-	-	-	-	-	-	-	9.34E+1	-	-	-
11	-	-	1.02E+2	-	-	8.0E+2	-	-	-	9.5E+1	-	-	-	-	3.70E-4	-	-	-	6.50E-4	-
12	-	-	4.20E+1	-	-	3.4E+2	3.1E+1	-	-	-	-	-	-	-	-	-	-	-	-	-
13	-	-	3.12E+2	-	-	2.6E+3	-	-	-	1.5E+2	-	-	-	-	-	-	-	-	-	-
14	-	-	-	-	4.00E-4	1.4E+3	1.7E+2	-	-	5.4E+0	-	-	-	-	-	-	-	-	-	-
15	-	-	2.84E+2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	-	-	2.75E+2	-	-	2.4E+3	-	5.5E+0	4.1E+1	-	-	-	-	-	-	-	9.00E-2	-	-	-
17	-	-	-	-	-	-	-	-	-	-	-	8.07E+1	-	-	-	-	-	-	-	-
18	-	2.16E+6	-	-	-	3.3E+1	-	7.0E-2	-	-	-	1.70E-1	-	-	-	-	1.00E-1	-	-	-
19	-	4.32E+6	-	-	-	2.7E+3	-	2.4E+1	4.0E-2	-	1.5E-1	-	-	-	4.60E-5	2.7E-1	-	1.0E-1	9.10E-3	-
20	-	-	4.74E+2	-	-	3.8E+3	-	-	4.1E+1	-	9.8E+0	-	-	-	4.11E-4	2.7E+2	-	-	9.00E-4	1.1E+1
21	7.20E+4	1.80E+7	-	-	-	9.9E+3	-	2.4E+1	-	-	-	8.50E-5	-	3.0E-3	1.05E-5	-	5.00E-5	1.6E-2	3.11E-4	-
22	-	-	5.76E+2	-	-	4.6E+3	-	-	4.1E+1	-	1.0E+2	-	-	-	7.81E-4	2.7E+2	-	-	1.55E-3	1.1E+1

^aProcess streams are identified in Fig. 4.5.

Table 4.5. Airborne radwaste generated daily by the model fresh fuel fabrication plant before effluent treatment - Case 1

Source	Volume (ft ³ /day)	Percent of total volume	Concentration (lb/day)		Primary chemical constituents	
			U	Th	Type	Quantity (lb/day)
Fissile particle production	5.43E+7	27	9.96E+0	-	HCl	7.2E+2
					H ₂ O	4.0E+2
					HF	7.9E+1
					CO _x	6.3E+1
					H ₂	1.4E+3
					Soot	1.0E+3
Fertile particle production	3.28E+7	16	-	4.90E+1	H ₂ O	4.5E+3
					HNO ₃	3.9E+3
					CO _x	2.4E+2
					C	3.5E+3
					H ₂	1.8E+3
Fuel rod and element production	5.10E+7	25	2.09E-1	2.10E+0	H ₂ O	6.4E+1
					HCl	5.5E+1
					NO _x	1.3E+1
Scrap recovery	2.70E+7	13	3.74E+0	1.62E-1	Soot	3.2E+2
					H ₂ O	2.7E+3
Miscellaneous liquid waste	2.16E+7	11	1.54E-4	2.87E-3	Detergent	Variable
Solid waste	1.51E+7	8	2.50E-2	1.00E-1	-	-

Table 4.6 Material flow in the resin loading operation - Case 1
(REFABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Liquid flow rate (gpd)	Flow rate (lb/day)											
	Process	Cell		Resin	HNO ₃	H ₂ O	NaNO ₃	UO ₂ (NO ₃) ₂	NaOH	Na ₂ CO ₃	Na ₂ U ₂ O ₇	NaHCO ₃	Organic	UO ₂ ²⁺	NO ₃ ⁻
1	-	-	-	3.9E+7	-	3.9E+2	-	-	-	-	-	-	-	-	-
2	-	-	-	1.7E+2	-	1.7E+2	-	-	-	-	-	-	-	-	-
3	-	-	1.6E+1	-	7.0E+1	9.9E+1	-	-	-	-	-	-	-	-	-
4	-	-	1.4E+2	-	1.2E+1	1.1E+3	7.9E+1	-	-	-	-	-	-	-	-
5	-	-	2.8E+2	-	5.9E+0	2.2E+3	-	6.0E+2	-	-	-	-	-	-	-
6	-	-	6.9E+3	-	5.9E+0	5.4E+4	-	6.18E+3	-	-	-	-	-	-	-
7	-	-	9.4E+2	-	1.3E+1	-	-	-	-	-	-	-	-	-	-
8	-	-	9.4E+2	-	-	-	-	-	-	-	-	-	6.0E+3	-	-
9	-	-	4.8E+1	-	-	4.0E+2	-	-	-	-	-	-	-	-	-
10	-	-	1.8E+2	-	-	1.5E+3	-	-	6.0E+0	1.6E+2	-	-	-	-	-
11	-	-	4.8E+1	-	-	4.0E+2	-	-	-	-	-	-	-	-	-
12	-	-	4.5E+2	8.8E-2	-	3.7E+3	1.7E+2	-	-	1.0E+2	1.16E-1	4.5E+1	1.0E-1	-	-
13	-	-	6.8E+3	-	-	5.4E+4	-	-	-	-	-	-	-	4.34E+3	1.7E+3
14	-	-	4.8E+1	-	-	4.0E+2	-	1.38E-2	-	-	-	-	-	-	-
15	-	-	6.1E+3	-	-	5.2E+4	-	-	-	-	-	-	-	4.10E+3	1.7E+3
16	-	-	-	2.2E+2	-	7.7E+1	-	-	-	-	-	-	-	2.47E+2	-
17	-	-	6.6E+3	-	-	5.2E+4	-	-	-	-	-	-	-	4.34E+3	1.7E+3
18	-	-	3.1E+2	-	-	6E+3	-	-	-	-	-	-	-	-	-
19	-	-	-	2.2E+1	-	7.7E+1	-	-	-	-	-	-	-	2.47E+2	-
20	-	-	-	2.2E+2	-	6.4E+1	-	-	-	-	-	-	-	2.44E+2	-
21	2.88E+4	-	-	-	-	1.8E+1	-	6.36E-2	-	-	-	-	5.0E+0	-	-
22	2.88E+4	6.48E+6	-	-	-	1.8E+1	-	1.59E-6	-	-	-	-	5.0E+0	-	-

^aStreams are identified in Fig. 4.8

Table 4.7. Material flow in the resin loading operation - Alternative Case 1 (under development)
(REFABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Liquid flow rate (gpd)	Flow rate (lb/day)						
	Process	Cell		H ₂ O	NH ₄ OH	HNO ₃	UO ₂ (NO ₃) ₂	Resin	UO ₂ ²⁺	NH ₄ NO ₃
1	-	-	4.6E+1	3.3E+2	3.9E+1	-	-	-	-	-
2	-	-	1.2E+2	9.8E+2	6.5E+0	-	-	-	-	-
3	-	-	2.8E+2	2.2E+3	-	5.9E+0	3.62E+2	-	-	-
4	-	-	7.4E+1	5.4E+2	-	5.0E-1	3.62E+2	-	-	3.0E+0
5	-	-	-	6.4E+1	-	-	-	2.2E+2	2.44E+2	-
6	2.88E+4	6.48E+6	-	1.8E+1	-	-	1.27E-7	-	-	-

^aStreams are identified in Fig. 4.9.

Table 4.8. Material flow in the production of recycle fuel particles - Case 1
(REFABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Flow rate (lb/day)												
	Process	Cell	UO ₂ ²⁺	Resin	H ₂ O	UO ₂	Soot (C)	UC ₂	CO _x	C ₂ Cl ₄	SiC	HCl	H ₂	NaCl	U ₃ O ₈
1	-	-	2.44E+2	2.2E+2	6.4E+1	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	2.25E+2	6.1E+1	-	-	-	-	-	-	-	-
3	1.15E+5	2.30E+6	-	2.0E+0	6.4E+1	2.25E+0	1.4E+2	-	-	-	-	-	-	-	-
4	5.04E+4	2.83E+6	-	-	-	5.60E-2	1.5E+1	1.64E-1	4.6E+1	-	-	-	-	-	-
5	2.74E+5	1.53E+7	-	2.0E+0	6.4E+1	2.31E+0	1.1E+3	1.24E+0	4.6E+1	-	-	-	-	-	-
6	2.74E+5	1.53E+7	-	1.0E-1	6.4E+1	1.20E-1	5.7E+1	6.20E-2	4.6E+1	1.0E+3	-	-	-	-	-
7	-	-	-	-	-	5.56E+1	1.5E+1	1.62E+2	-	-	-	-	-	-	-
8	1.08E+5	1.01E+7	-	-	-	-	9.9E+2	1.08E+0	-	-	-	-	-	-	-
9	2.02E+5	3.64E+6	-	-	-	-	2.9E+2	1.07E+0	-	-	4.3E+1	7.2E+2	8.8E+2	-	-
10	2.02E+5	8.64E+6	-	-	1.3E+2	-	2.9E+1	1.07E-1	-	-	4.3E+0	7.2E-1	8.8E+2	1.3E+0	-
11	4.75E+5	2.39E+7	-	-	3.0E+2	-	-	-	3.6E+2	2.0E+1	-	-	-	-	7.64E-6
12	-	-	-	-	-	-	-	1.81E+2	-	-	-	-	-	-	-

^aStreams are identified in Fig. 4.10.

Table 4.9. Material flow in the production of recycle fuel rods and elements -
Case 1

(REFABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Flow rate (lb/day)				
	Process	Cell	ThO ₂	UC ₂	Soot (C)	C ₂ Cl ₄	U ₃ O ₈
1	-	-	1.88E+3	-	-	-	-
2	-	-	-	1.81E+2	-	-	-
3	-	2.88E+6	1.88E-2	1.81E-3	2.0E-1	-	-
4	-	-	1.88E+3	1.80E+2	-	-	-
5	-	2.88E+6	1.87E-3	1.80E-4	-	-	-
6	4.32E+4	3.24E+7	2.07E-2	1.99E-3	5.6E+1	3.1E+0	-
7	-	-	1.87E+3	1.80E+2	-	-	-
8	2.16E+4	2.66E+7	-	-	5.6E+2	-	-
9	4.32E+4	2.66E+7	-	-	5.6E+1	2.7E+2	-
10	-	-	1.85E+3	1.78E+2	-	-	-
11	4.32E+4	3.24E+7	5.18E-7	-	-	3.1E+0	5.34E-8

^aStreams are identified in Fig. 4.11.

Table 4.10. Material flow in the scrap recovery system - Case 1
(REFABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Inquid flow rate (gpd)	Flow rate (lb/day)								
	Process	Cell		ThO ₂	UC ₂	U (as scrap)	HNO ₃	H ₂ O	UO ₂ (NO ₃) ₂	U ₃ O ₈	Soot (C)	SiC
1	-	-	-	3.10E+1	2.99E+0	-	-	-	-	-	-	-
2	-	-	-	-	-	5.26E+1	-	-	-	-	-	-
3	-	-	6.4E+1	-	-	-	3.8E+1	5.1E+2	-	-	-	-
4	-	-	6.4E+1	-	-	-	9.8E+0	5.1E+2	8.62E+1	-	-	-
5	-	-	1.8E+1	-	-	-	5.8E+1	1.2E+2	-	-	-	-
6	-	-	7.3E+0	-	-	-	-	6.4E+1	-	-	-	-
7	-	-	2.4E+1	-	-	-	5.8E+1	1.7E+2	6.50E+0	-	-	-
8	-	-	6.5E+1	-	-	-	9.5E+0	5.3E+2	7.97E+1	-	-	-
9	1.44E+5	2.52E+7	-	1.55E-2	-	-	-	-	-	3.27E-2	4.0E-1	1.0E-1
10	1.44E+5	2.52E+7	-	2.88E-7	-	-	-	1.4E+1	-	8.18E-7	-	-

^aStreams are identified in Fig. 4.12.

Table 4.11. Characteristics of the isotopes in the feed to the model HTGR fuel fabrication plants

Nuclide	Half-life	Principal type of decay	Feed composition (wt %)
<u>Fresh fuel plant^a</u>			
²⁰⁸ Tl	3.0 minutes	β	1.0E-14
²¹² Pb	10.6 hours	β	6.3E-12
²¹² Bi	60.6 minutes	β	6.0E-13
²²⁰ Rn	56 seconds	α	9.5E-15
²²² Rn	3.82 days	α	2.5E-13
²²⁴ Ra	3.64 days	α	5.5E-11
²²⁶ Ra	1.6E+03 years	α	4.0E-08
²²⁸ Ra	5.75 years	β	2.2E-09
²²⁸ Th	1.91 years	α	1.1E-08
²³⁰ Th	7.7E+04 years	α	9.5E-03
²³¹ Th	25.52 hours	β	1.7E-11
²³² Th	1.41E+10 years	α	9.5E+01
²³⁴ Th	24.1 days	β	3.8E-12
²³⁴ Pa	1.2 minutes	β	1.3E-16
²³⁴ U	2.47E+05 years	α	4.4E-02
²³⁸ U	7.1E+08 years	α	4.3E-00
²³⁶ U	2.42E+07 years	α	9.7E-03
²³⁸ U	4.51E+09 years	α	2.7E-01
<u>Refabrication fuel plant^b</u>			
²⁰⁸ Tl	3.0 minutes	β	1.1E-11
²¹² Pb	10.6 hours	β	6.2E-09
²¹² Bi	60.6 minutes	β	5.9E-10
²¹² Po	45 seconds	α	3.0E-20
²²⁰ Rn	56 seconds	α	9.4E-12
²²² Rn	3.82 days	α	2.4E-13
²²⁴ Ra	3.64 days	α	5.4E-08
²²⁶ Ra	1.6E+03 years	α	3.8E-08
²²⁸ Ra	5.75 years	β	2.1E-09
²²⁸ Th	1.91 years	α	1.1E-05
²²⁸ Th	7.3E+03 years	α	4.5E-06
²³⁰ Th	7.7E+04 years	α	9.1E-03
²³¹ Th	25.52 hours	β	6.2E-12
²³² Th	1.41E+10 years	α	9.1E+01
²³⁴ Th	24.1 days	β	4.5E-12
²³⁴ Pa	1.2 minutes	β	1.5E-16
²³³ U	72 years	α	5.0E-03
²³³ U	1.6E+05 years	α	4.4E+00
²³⁴ U	2.47E+05 years	α	1.5E+00
²³⁵ U	7.1E+08 years	α	1.5E+00
²³⁶ U	2.4E+07 years	α	1.3E+00
²³⁸ U	4.5E+09 years	α	3.4E-01
Rare earths ^c	-	γ	3.4E-11
Other actinides ^d	-	α	2.3E-14

^a Fission products cannot be detected in the feed material. The ²³⁴Th and ²³⁴Pa are in secular equilibrium with ²³⁸U. The ²³¹Th is in secular equilibrium with ²³⁵U. The thorium feed is received approximately six months after refining and is assumed to contain 100 ppm ²³⁰Th. Therefore, the ²²⁸Th activity as well as the activities of its daughters are 80% of the equilibrium activity. All radioactivity due to other daughters in other decay chains is negligible.

^b The feed to the refabrication plant is received approximately 90 days after reprocessing.

^c Includes all fission products.

^d Includes all transuranium elements.

Table 4.12. Calculated steady-state ^{232}U content of the 23R stream charge for various quantities of ^{230}Th in the thorium^a

	Source of ^{232}U			
	^{230}Th	^{232}Th	^{232}U	^{233}U
Yield of ^{232}U from source, after irradiation in HTGR				
After 1-year decay, g/g source	2.38E-1	1.15E-5	2.20E-1	2.77E-6
After 2-years decay, g/g source	2.36E-1	1.14E-5	2.18E-1	2.74E-6
Symbol for yield	x_{00}	x_{02}	x_{22}	x_{23}
Mass of source nuclide used in 20th charge for CITATION calculation, g				
	0	7,264,580	0	216,260
Symbol for mass	W_{00}	W_{02}	W_{22}	W_{23}
Calculated ^{232}U content in 23R stream				
1) For 1-year recycle time	0 ppm		309 ppm	
	10 ppm		370 ppm	
	50 ppm		625 ppm	
	100 ppm		940 ppm	
2) For 2-year recycle time	0 ppm		306 ppm	
	10 ppm		370 ppm	
	50 ppm		620 ppm	
	100 ppm		930 ppm	

^aCalculated as $W_{22} = (W_{00}x_{00} + W_{02}x_{02} + W_{23}x_{23}) / (1 - x_{22})$, where W_{00} is obtained by multiplying assumed ppm ^{230}Th by 1.E-6 and then by W_{02} .

Table 4.13. Specific activity and relative inhalation hazards
in the feed to the model HTGR fuel fabrication plants^a

Nuclide	Specific activity of pure isotope (Ci/g)	Contribution to the total relative inhalation hazard ^b (%)
²⁰⁸ Tl	3.0E+8	<0.02
²¹² Pb ^c	1.4E+6	<0.02
²¹² Bi ^c	1.5E+7	<0.02
²¹² Po	1.2E+9	<0.02
²²⁰ Rn ^c	9.2E+8	<0.02
²²² Rn	1.5E+5	<0.02
²²⁴ Ra ^c	1.6E+5	0.06
²²⁶ Ra ^c	9.9E-1	<0.02
²²⁸ Ra	2.7E+2	<0.02
²²⁸ Th ^c	8.2E+2	35.95
²²⁹ Th	2.1E-1	<0.02
²³⁰ Th ^c	2.0E-2	17.03
²³¹ Th	5.3E+5	<0.02
²³² Th ^c	1.1E-7	0.06
²³⁴ Th	2.3E+4	<0.02
²³⁴ Pa	6.7E+8	<0.02
²³² U ^c	2.1E+1	37.84
²³³ U ^c	9.6E-3	7.57
²³⁴ U ^c	6.2E-3	1.46
²³⁵ U ^c	2.1E-6	<0.02
²³⁶ U ^c	6.4E-5	<0.02
²³⁸ U ^c	3.3E-7	<0.02
Rare earth elements ^d	-	<0.02
Transuranium elements ^e	-	<0.02

^aList includes all nuclides considered.

^bRelative inhalation hazard = curies present in one metric ton of fuel
divided by Radiation Concentration Guide value.

^cNuclides used in calculating source terms.

^dIncludes all fission products.

^eIncludes all transuranium elements.

Table 4.14. Formation rates for several isotopes from one curie
at secular equilibrium present in HTGR fuels

Nuclide formed	Nuclide half-life	Precursor	Precursor half-life	Formation rate at secular equilibrium (Ci per year)
^{212}Pb	1.06E+1 hr	^{216}Po	1.50E-1 sec	5.7E+1
^{220}Rn	5.56E+1 sec	^{224}Ra	3.64E+0 day	3.9E+3
^{224}Ra	3.64E+0 day	^{228}Th	1.91E+0 yr	7.0E+1
^{228}Th	1.91E+0 yr	^{232}U	7.20E+1 yr	3.6E-1
^{230}Th	7.70E+4 yr	^{234}U	2.44E+5 yr	9.0E-6
^{232}Th	1.40E+10 yr	-	-	5.0E-11

Table 4 15 Summary of variables for model HTGR fresh fuel fabrication plant - airborne and liquid radioactive waste treatment systems

	Case 1	Case 2	Case 3	Case 4
Treatment objective	Base case	Reduce uranium and thorium release by a factor of 14 and 180, respectively, reduce or eliminate release of ammonia nitrate and fluoride by eliminating release of liquids	Reduce uranium, thorium, and radon release by a factor of 50, 900, and 45 respectively, from the base case by process changes and additional radon retention tanks	Reduce uranium, thorium, and radon release by a factor of 2.5×10^4 , 2.9×10^6 , and 370, respectively, from the base case, clean and recycle process and cell gases where feasible
Plant decontamination factor (wt metal entering plant/wt metal released)				
For uranium	3.3E+03	4.5E+04	1.7E+05	8.3E+07
For thorium	9.9E+03	1.8E+06	8.9E+06	2.9E+09
Process changes	--	--	Resin kernel loading for uranium, whole block carbonization, perchloroethylene scrubbers for soot removal	Same as Case 3
Liquid radioactive waste treatment	Filter, radium removal by coprecipitation with BaSO ₄ , equalization pond, release	No liquid released, discharged to lined lagoon for evaporation	Recycle of nitric acid, NH ₃ , and water, nitrate removal by anaerobic digestion	Same as Case 3
Airborne radioactive waste treatment	Scrubber, soot, bag, and HEPA filters, controlled combustion, radon retention tank	Same as Case 1	Perchloroethylene scrubbers, additional radon retention tanks, replacement of soot filters with more efficient bag filters	Same as Case 3, use of charcoal trap for radon delay, recycle 9% of the process and cell gas through two HEPA filters where practical, combine remaining gases with ventilation effluents and pass through two HEPA filters in series before release

Table 4.16. Summary of variables for model HTGR refabrication plant - airborne radioactive waste treatment system

	Case 1	Case 2	Case 3	Case 4
Treatment objective	Base case	Reduce uranium, thorium, and daughter release by a factor of at least 10	Reduce thorium and thorium daughter release	Clean and recycle process and cell gases where applicable; extensively treat and discharge small fraction of process and cell gases
Plant decontamination factor (wt metal entering plant/wt metal released)				
For uranium	2.7E+07	2.7E+08	~2.0E+08 (varies with isotope)	1.9E+11
For thorium	2.0E+08	2.0E+09	~1.0E+09 (varies with isotope)	9.1E+13
<u>Process Airborne Radioactive Waste</u>				
	Scrubber; cooler; charcoal traps or radon delay tanks; controlled combustion equipment; cooler; blend with cell and plant ventilation air; roughing filter; HEPA filter	Replace roughing filter in Case 1 with HEPA filter	Same as in Case 2	Same as in Case 2; recycle 95% of process air through HEPA filter for some of the process operations; discharge 5% through two HEPA filters in series after combining with plant ventilation air
<u>Cell Ventilation Air</u>				
	Roughing filter; HEPA filter; blend with process and plant ventilation air; HEPA filter	Replace roughing filter in Case 1 with HEPA filter	Same as in Case 2	Same as Case 2; recycle 95% of cell air through HEPA filter for some of the process operations; blend with plant ventilation; two HEPA filters in series
<u>Plant Ventilation Air</u>				
	Roughing filter; HEPA filter; blend with process and cell ventilation air; HEPA filter	Replace roughing filter in Case 1 with HEPA filter	Same as in Case 2	Roughing filter; HEPA filter; blend with process and cell ventilation air; two HEPA filters in series

Table 4.17. Source terms for model HTGR fresh fuel fabrication plant -- calculated release of radioactive material in airborne and liquid effluents^a

Nuclide	Case 1				Case 2 ^c		Case 3 ^c		Case 4 ^c	
	Airborne release		Liquid release		Airborne release		Airborne release		Airborne release	
	Concentration ($\mu\text{Ci/ml}$)	Amount (Ci/yr)	Concentration ($\mu\text{Ci/ml}$)	Amount (Ci/yr)	Concentration ($\mu\text{Ci/ml}$)	Amount (Ci/yr)	Concentration ($\mu\text{Ci/ml}$)	Amount (Ci/yr)	Concentration ($\mu\text{Ci/ml}$)	Amount (Ci/yr)
²¹⁴ Bi	3.3E-12	5.7E-03	8.0E-06	9.6E-01	3.3E-12	5.7E-03	1.6E-12	2.7E-03	1.6E-14	2.7E-05
²²⁰ Rn	1.3E-07	2.3E+2	-	-	1.3E-07	2.3E+2	2.9E-09	5.0E+0	3.6E-10	6.2E-01
²²⁶ Ra	1.5E-15	1.0E-8	9.6E-11	1.2E-05	1.5E-15	1.0E-8	2.7E-18	4.7E-9	1.1E-20	1.8E-11
²²⁸ Ra	7.7E-17	1.3E-7	1.3E-09	1.5E-04	7.7E-17	1.3E-7	3.6E-17	6.2E-8	1.4E-19	2.4E-10
²²⁸ Th	1.4E-14	2.5E-5	3.7E-08	4.5E-03	1.4E-14	2.5E-5	2.9E-15	5.0E-6	9.1E-18	1.6E-08
²³⁰ Th ^b	3.1E-13	5.3E-4	8.0E-07	9.6E-02	3.1E-13	5.3E-4	6.2E-14	1.1E-4	1.9E-16	3.3E-07
²³² Th	1.7E-14	3.0E-5	4.5E-08	5.4E-03	1.7E-14	3.0E-5	3.5E-15	6.0E-6	1.1E-17	1.9E-08
²³⁴ U	1.6E-11	2.7E-2	2.8E-06	3.4E-01	1.6E-11	2.7E-2	4.2E-12	7.1E-3	8.7E-15	1.5E-05
²³⁵ U	5.4E-13	9.3E-4	1.0E-07	1.2E-02	5.4E-13	9.3E-4	1.4E-13	2.4E-4	3.0E-16	5.1E-07
²³⁶ U	3.6E-14	6.2E-5	6.5E-09	7.8E-04	3.6E-14	6.2E-5	9.5E-15	1.6E-5	2.0E-17	3.4E-08
²³⁸ U	5.2E-15	8.9E-6	9.1E-10	1.1E-04	5.2E-15	8.9E-6	1.4E-15	2.3E-6	2.8E-18	4.9E-09

^aAssuming 100 ppm ²³⁰Th in fertile material.

^bIf fertile material contains 10 ppm ²³⁰Th, the source terms for this isotope are changed to: gaseous release, 5.3E-5 Ci/yr; liquid release, 9.6E-3 Ci/yr.

^cNo radioactive liquid effluents released.

Table 4.18. Source terms for model HTGR refabrication plant - calculated release of radioactive material in the airborne effluents^a

Nuclide	Case 1 ^b		Case 2		Case 3		Case 4	
	Concentration ($\mu\text{Ci/ml}$)	Amount (Ci/yr)	Concentration ($\mu\text{Ci/yr}$)	Amount (Ci/yr)	Concentration ($\mu\text{Ci/yr}$)	Amount (Ci/yr)	Concentration ($\mu\text{Ci/yr}$)	Amount (Ci/yr)
²¹² Pb	4.8E-11	5.4E-02	4.8E-12	5.4E-03	8.6E-14	9.7E-05	8.4E-16	9.5E-07
²²⁴ Ra	9.1E-12	1.0E-02	9.1E-13	1.0E-03	2.0E-14	2.3E-05	1.9E-16	2.1E-07
²²⁸ Th	9.5E-13	1.1E-03	9.5E-14	1.1E-04	5.7E-15	6.5E-06	7.8E-18	8.8E-09
²³⁰ Th	1.9E-16	2.1E-07	1.9E-17	2.1E-08	1.9E-17	2.1E-08	4.2E-21	4.8E-12
²³² Th	1.0E-17	1.2E-08	1.0E-18	1.2E-09	1.0E-18	1.2E-09	2.4E-22	2.7E-13
²³² U	1.1E-11	1.2E-02	1.1E-12	1.2E-03	1.1E-12	1.2E-03	1.6E-15	1.8E-06
²³³ U	4.3E-12	4.9E-03	4.3E-13	4.9E-04	4.3E-13	4.9E-04	6.2E-16	7.0E-07
²³⁴ U	9.4E-13	1.1E-03	9.4E-14	1.1E-04	9.4E-14	1.1E-04	1.3E-16	1.5E-07
²³⁵ U	3.6E-16	4.1E-07	3.6E-17	4.1E-08	3.6E-17	4.1E-08	4.9E-20	5.6E-11
²³⁶ U	1.0E-14	1.1E-05	1.0E-15	1.1E-06	1.0E-15	1.1E-06	1.2E-18	1.4E-09
²³⁸ U	1.2E-17	1.4E-08	1.2E-18	1.4E-09	1.2E-18	1.4E-09	1.7E-21	1.9E-12
²²⁰ Rn	4.7E-08	5.3E+01	4.7E-08	5.3E+01	6.9E-10	7.8E-01	1.9E-12	2.1E-03

^aAssuming fertile material contains 100 ppm ²³⁰Th which results in 750 ppm ²³²U as an average value in the 23R stream.

^bIf fertile material contains 10 ppm ²³⁰Th producing approximately 300 ppm ²³²U in the 23R stream, the source terms for the following isotopes are changed to: ²¹²Pb, 2.2E-2; ²²⁴Ra, 4.1E-3; ²²⁸Th, 4.3E-4; ²³⁰Th, 2.1E-8; and ²³²U, 5.0E-3 Ci/yr.

Table 4 19 Material flow in the production of fissile particles - Case 3
(FRESH FUEL FABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Flow rate (lb/day)																	
	Process	Cell	UF ₆ F ₂	H ₂	NaCl	H ₂ O	Na ₂ U ₂ O ₇	HF	HNO ₃	UO ₂ (NO ₃) ₂	UC ₂	Soot (C)	C ₂ Cl ₄	HCl	UCl ₄	SiC	K ₂ U ₂ O ₇	KF	UO ₂	U ₂ O ₈
1	4 32E+3	8 64E+6	4 00E-1	3 2E+0	-	3 5E+2	-	7 9E+1	-	-	-	-	-	-	-	-	-	-	-	-
2	4 32E+3	8 64E+6	-	3 2E+0	-	8 0E+0	-	7 9E-2	-	-	-	-	-	-	-	-	2 16E-2	2 3E-2	-	-
3	2 88E+4	6 46E+6	-	-	-	1 8E+1	-	-	1 0E+0	6 12E-2	-	-	-	-	-	-	-	-	-	-
4	2 88E+4	6 46E+6	-	-	-	1 8E+1	-	-	1 0E+0	3 06E-3	-	-	-	-	-	-	-	-	-	-
5	1 66E+5	5 18E+6	-	-	-	6 4E+1	-	-	-	-	1 93E+0	1 1E+3	-	-	-	-	-	-	1 83E-1	-
6	1 08E+5	1 01E+7	-	3 8E+2	-	-	-	-	-	-	7 48E+0	7 5E+2	-	-	-	-	-	-	-	-
7	2 74E+5	1 53E+7	-	3 8E+2	-	-	-	-	-	-	2 35E-2	4 6E+0	7 8E+0	-	-	-	-	-	4 58E-4	-
8	8 64E+4	8 64E+6	-	1 0E+3	-	-	-	-	-	-	-	3 0E+2	-	7 2E+2	1 30E+0	5 0E+1	-	-	-	-
9	8 64E+4	8 64E+6	-	1 0E+3	2 0E-1	5 4E+1	5 41E-2	-	-	-	-	1 5E+1	-	7 2E-1	-	2 5E+0	-	-	-	-
10	3 94E+5	3 90E+7	-	1 4E+3	2 0E-1	8 0E+1	5 41E-2	7 9E-2	1 0E+0	3 06E-3	2 35E-2	2 0E+1	7 8E+0	7 2E-1	-	2 5E+0	2 16E-2	2 3E-2	4 58E-4	-
11	3 94E+5	3 90E+7	-	-	-	1 4E+2	5 41E-4	7 9E-2	1 0E+0	-	-	2 0E-1	7 8E+0	7 2E-1	-	2 5E-2	2 16E-4	-	-	2 78E-4

^aProcess streams are identified in Fig 4 21.

Table 4.20. Material flow in the production of fertile particles - Case 3
(FRESH FUEL FABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Flow rate (lb/day)										
	Process	Cell	H ₂ O	HNO ₃	ThO ₂	Th(NO ₃) ₄	NaOH	NaNO ₃	CO _x	NH ₃	Soot (C)	H ₂	Th(OH) ₄
1	4.32E+3	1.44E+6	2.4E+3	3.9E+3	2.10E+0	3.64E+0	-	-	-	-	-	-	-
2	4.32E+3	1.44E+6	6.0E+0	-	1.05E-1	-	6.0E-1	5.2E-1	-	-	-	-	1.14E-1
3	2.16E+6	4.32E+6	2.1E+3	-	1.51E+1	-	-	-	2.4E+2	3.5E+1	-	-	-
4	2.16E+6	4.32E+6	2.1E+3	-	1.51E-1	-	-	-	2.4E+2	3.5E+1	-	-	-
5	1.08E+6	1.44E+7	-	-	3.63E+1	-	-	-	-	-	3.5E+3	1.8E+3	-
6	1.61E+6	1.44E+7	1.6E+4	-	3.63E-1	-	-	-	1.3E+4	-	-	-	-
7	1.83E+6	2.02E+7	1.8E+4	-	6.19E-1	-	6.0E-1	5.2E-1	1.3E+4	3.5E+1	-	-	1.14E-1
8	1.83E+6	2.02E+7	1.8E+4	-	3.10E-4	-	-	-	1.3E+4	3.5E+1	-	-	5.70E-5

^a Process streams are identified in Fig. 4.22.

Table 4.21. Material flow in the production of fuel rods and elements - Case 3
(FRESH FUEL FABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Flow rate (lb/day)			
	Process	Cell	ThO ₂	UC ₂	Soot (C)	C ₂ Cl ₄
1	6.48E+6	-	1.87E-1	1.81E-2	5.0E-1	-
2	2.88E+6	-	1.86E-3	1.80E-4	-	-
3	9.36E+6	-	1.89E-3	1.83E-4	-	-
4	2.16E+4	2.66E+7	-	-	7.0E+2	-
5	2.16E+4	2.66E+7	-	-	7.0E+1	1.3E+2
6	9.38E+6	2.66E+7	1.89E-5	1.83E-6	7.0E-1	1.6E+0

^aProcess streams are identified in Fig. 4.23.

Table 4.22. Material flow in the scrap recovery system - Case 3
(FRESH FUEL FABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Flow rate (lb/day)					
	Process	Cell	H ₂ O	Th(OH) ₄	Na ₂ U ₂ O ₇	NH ₄ OH	UO ₂	(NH ₄) ₂ U ₂ O ₇
1	7.20E+4	1.37E+7	7.2E+3	1.00E-4	6.20E-3	-	-	-
2	-	2.16E+6	3.3E+1	-	-	7.0E-2	2.03E-1	1.58E-1
3	-	4.32E+6	2.7E+3	2.27E-5	4.57E-3	2.4E+1	-	-
4	7.20E+4	1.80E+7	9.9E+3	1.23E-4	6.77E-3	2.4E+1	2.04E-3	1.58E-3
5	7.20E+4	1.80E+7	9.9E+3	1.23E-6	6.77E-5	2.4E+1	2.04E-5	1.58E-5

^aStreams are identified in Fig. 4.24.

Table 4.23. Material flow in the production of fissile particles - Case 4
(FRESH FUEL FABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Flow rate (lb/day)															
	Process	Cell	UO ₂ F ₂	H ₂	H ₂ O	Na ₂ U ₂ O ₇	HF	HNO ₃	UO ₂ (NO ₃) ₂	UC ₂	Soot (C)	C ₂ Cl ₄	HCl	UCl ₄	SiC	K ₂ U ₂ O ₇	UO ₂	U ₃ O ₈
1	4.32E+3	8.64E+6	4.00E-1	3.2E+0	3.5E+2	-	7.9E+1	-	-	-	-	-	-	-	-	-	-	-
2	4.32E+3	8.64E+6	-	3.2E+0	8.0E+0	-	-	-	-	-	-	-	-	-	-	4.33E-3	-	-
3	2.88E+4	6.46E+6	-	-	1.8E+1	-	-	1.0E+0	6.12E-2	-	-	-	-	-	-	-	-	-
4	2.88E+4	6.46E+6	-	-	1.8E+1	-	-	1.0E+0	6.12E-4	-	-	-	-	-	-	-	-	-
5	1.66E+5	5.18E+6	-	-	6.4E+1	-	-	-	-	1.93E+0	1.1E+3	-	-	-	-	-	1.83E-1	-
6	1.08E+5	1.01E+7	-	3.8E+2	-	-	-	-	-	7.48E+0	7.5E+2	-	-	-	-	-	-	-
7	2.74E+5	1.53E+7	-	3.8E+2	-	-	-	-	-	9.41E-4	1.8E-1	7.8E+0	-	-	-	-	1.83E-5	-
8	8.64E+4	8.64E+6	-	1.0E+3	-	-	-	-	-	-	3.0E+2	6.2E+0	7.2E+2	1.30E+0	5.0E+1	-	-	-
9	8.64E+4	8.64E+6	-	1.0E+3	5.4E+1	1.08E-4	-	-	-	-	3.0E-2	6.2E+0	1.0E-1	-	-	-	-	-
10	3.94E+5	3.90E+7	-	1.4E+3	8.0E+1	1.08E-4	-	1.0E+0	6.12E-4	9.41E-4	2.1E-1	1.4E+1	1.0E-1	-	-	4.33E-3	1.83E-5	-
11	3.94E+5	3.90E+7	-	-	1.4E+2	2.70E-10	-	1.0E+0	-	-	-	1.4E+1	1.0E-1	-	-	1.08E-8	-	3.66E-9

^aProcess streams are identified in Fig. 4.26.

Table 4.24. Material flow in the production of fertile particles - Case 4
(FRESH FUEL FABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Flow rate (lb/day)								
	Process	Cell	H ₂ O	HNO ₃	ThO ₂	Th(NO ₃) ₄	CO ₂	NH ₃	Soot (C)	H ₂	Th(OH) ₄
1	4.32E+3	1.44E+6	2.4E+3	3.9E+3	2.10E+0	3.64E+0	-	-	-	-	-
2	4.32E+3	1.44E+6	6.0E+0	-	2.10E-2	-	-	-	-	-	2.28E-2
3	2.16E+6	4.32E+6	2.1E+3	-	1.51E+1	-	2.4E+2	3.5E+1	-	-	-
4	2.16E+6	4.32E+6	2.1E+3	-	1.51E-1	-	2.4E+2	3.5E+1	-	-	-
5	1.08E+6	1.44E+7	-	-	3.63E+1	-	-	-	3.5E+3	1.8E+3	-
6	1.61E+6	1.44E+7	1.6E+4	-	3.63E-1	-	1.3E+4	-	-	-	-
7	1.83E+6	2.02E+7	1.8E+4	-	5.35E-1	-	1.3E+4	3.5E+1	-	-	2.28E-2
8	1.83E+6	2.02E+7	1.8E+4	-	1.34E-6	-	1.3E+4	3.5E+1	-	-	5.70E-8

^aProcess streams are identified in Fig. 4.27.

Table 4.25. Material flow in the production of fuel rods and elements - Case 4
(FRESH FUEL FABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Flow rate (lb/day)			
	Process	Cell	ThO ₂	UC ₂	Soot (C)	C ₂ Cl ₄
1	6.48E+6	-	1.87E-1	1.81E-2	5.0E-1	-
2	2.88E+6	-	1.86E-3	1.80E-4	-	-
3	9.36E+6	-	1.89E-3	1.83E-4	-	-
4	4.68E+5	-	4.73E-8	4.58E-9	-	-
5	2.16E+4	2.66E+7	-	-	7.0E+2	-
6	2.16E+6	2.66E+7	-	-	3.5E+1	1.3E+2
7	4.69E+5	1.33E+6	4.73E-8	4.58E-9	3.5E+1	1.6E+0
8	4.69E+5	1.33E+6	2.36E-11	2.29E-12	1.8E-2	1.6E+0

^aProcess streams are identified in Fig. 4.28.

Table 4.26. Material flow in the scrap recovery system -- Case 4
(FRESH FUEL FABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Flow rate (lb/day)					
	Process	Cell	H ₂ O	Th(OH) ₄	Na ₂ U ₂ O ₇	NH ₄ OH	UO ₂	(NH ₄) ₂ U ₂ O ₇
1	7.20E+4	1.37E+7	7.2E+3	1.00E-4	6.20E-3	-	-	-
2	-	2.16E+6	3.3E+1	-	-	7.0E-2	2.04E-1	1.58E-1
3	-	4.32E+6	2.7E+3	4.56E-6	9.14E-4	2.4E+1	-	-
4	7.20E+4	1.80E+7	9.9E+3	5.54E-6	9.36E-4	2.4E+1	2.04E-3	1.58E-3
5	7.20E+4	1.80E+7	9.9E+3	2.77E-9	4.68E-7	2.4E+1	1.02E-6	7.90E-7

^aProcess streams are identified in Fig. 4.29.

Table 4.27. Material flow in the production of recycle fuel particles - Case 4
(REFABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Flow rate (lb/day)											
	Process	Cell	Resin	H ₂ O	UO ₂	Scot (C)	UC ₂	CO _x	C ₂ Cl ₄	SiC	HCl	H ₂	NaCl	U ₃ O ₈
1	2.74E+5	1.53E+7	2.0E+0	6.4E+1	2.31E+0	1.1E+3	1.24E+0	4.6E+1	-	-	-	-	-	-
2	2.74E+5	1.53E+7	2.0E-2	6.4E+1	2.31E-2	1.1E+1	1.24E-2	4.6E+1	1.0E+3	-	-	-	-	-
3	2.02E+5	8.64E+6	-	-	-	2.9E+2	1.07E+0	-	-	4.3E+1	7.2E+2	8.8E+2	-	-
4	2.02E+5	8.64E+6	-	1.3E+2	-	2.9E+0	1.07E-2	-	-	4.3E-1	-	8.8E+2	1.0E-1	-
5	4.76E+5	2.39E+7	2.0E-2	3.0E+0	2.31E-2	1.4E+1	2.31E-2	4.6E+1	2.0E+1	4.3E-1	-	8.8E+2	1.0E-1	-
6	4.76E+5	2.39E+7	-	3.0E+0	-	-	-	9.8E+2	2.0E+1	-	-	-	-	1.22E-9

^aStreams are identified in Fig. 4.30.

Table 4.28. Material flow in the production of recycle fuel rods and elements - Case 4
(REFABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Flow rate (lb/day)				
	Process	Cell	ThO ₂	UC ₂	Soot (C)	C ₂ Cl ₄	U ₃ O ₈
1	-	5.76E+6	2.07E-2	1.99E-3	2.0E-1	-	-
2	-	2.88E+5	5.18E-7	4.98E-8	-	-	-
3	2.16E+4	2.66E+7	-	-	5.6E+2	-	-
4	2.16E+3	2.66E+7	-	-	5.6E+0	3.1E+0	-
5	2.16E+4	2.69E+7	5.18E-7	4.98E-8	5.6E+0	3.1E+0	-
6	8.64E+4	2.69E+7	1.30E-12	-	-	3.1E+0	1.33E-13

^aStreams are identified in Fig. 4.31.

Table 4.29. Material flow in the scrap recovery system - Case 4
(REFABRICATION PLANT)

Stream ^a	Gas flow rate (ft ³ /day)		Flow rate (lb/day)	
	Process	Cell	ThO ₂	U ₃ O ₈
1	3.64E+4	6.30E+6	1.55E+0	1.60E-1
2	1.08E+5	1.89E+7	-	3.11E+0
3	1.44E+5	2.52E+7	7.75E-4	1.64E-3
4	1.44E+5	2.52E+7	1.94E-11	4.09E-11

^aStreams are identified in Fig. 4.32.

Table 5.1 Water usage and overall liquid material balance
(FRESH FUEL FABRICATION PLANT^a)

Stream ^a	Flow rate (gpd)	Flow rate (lb/day)														
		H ₂ O	KOH	NaOH	K ₂ U ₂ O ₇	KF	Na ₂ U ₂ O ₇	U ₃ O ₈	NaCl	HNO ₃	NH ₄ OH	HF	Th(OH) ₄	NaNO ₃	NaF	NH ₄ NO ₃
1	2.5E+5	2.1E+6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	1.9E+5	1.6E+6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3	1.4E+5	1.1E+6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4	7.0E+3	5.8E+4	-	-	-	-	-	-	-	-	-	-	-	-	-	-
5	4.8E+4	4.0E+5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	4.0E+4	3.3E+5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	2.0E+4	1.6E+5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	1.8E+3	1.5E+4	-	2.5E+3	-	-	-	-	-	-	-	-	-	-	-	-
9	1.9E+3	1.5E+4	2.9E+2	9.4E+2	-	-	-	-	-	-	-	-	-	-	-	-
10	2.2E+3	1.4E+4	-	2.5E+2	-	-	-	-	-	2.8E+2	3.8E+1	6.0E+0	-	-	-	-
11	2.4E+3	2.0E+4	-	6.5E+1	-	-	-	-	-	-	-	-	-	-	-	-
12	1.2E+4	1.0E+5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	1.8E+3	1.3E+4	-	9.5E+0	-	-	-	-	-	-	1.0E+2	-	2.04E-2	5.2E+3	-	8.0E+1
14	1.2E+3	9.8E+3	7.1E+1	2.2E+2	3.70E-4	2.3E+2	9.70E-3	1.90E-4	1.1E+3	-	-	-	-	-	-	-
15	5.8E+2	4.6E+3	-	1.0E+2	-	-	1.55E-3	-	-	-	-	-	7.81E-4	2.7E+2	1.1E+1	4.1E+1
16	2.4E+3	2.0E+4	-	4.0E+0	-	-	4.60E-2	-	8.9E+1	-	-	-	4.50E-1	-	-	-
17	1.2E+4	1.0E+5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18	8.8E+4	7.3E+5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19	1.8E+4	1.5E+5	7.1E+1	2.7E+2	3.70E-4	2.3E+2	5.72E-2	1.90E-4	1.1E+3	-	1.0E+2	-	4.71E-1	5.5E+3	1.1E+1	8.0E+1
20	1.1E+5	8.8E+5	7.1E+1	2.7E+2	3.70E-4	2.3E+2	5.72E-2	1.90E-4	1.1E+3	-	1.0E+2	-	4.71E-1	5.5E+3	1.1E+1	8.0E+1

^aProcess streams are identified in Fig. 5.1

Table 6.1. Estimated annual costs and contribution to power costs for the 450-metric ton/yr model fresh fuel fabrication plant and the 245-metric ton/yr model fuel refabrication plant

Radwaste case	Capital ^a cost (\$1000)	Annual fixed charges (\$1000)	Annual operating cost (\$1000)	Total annual cost (\$1000)	Contribution to power cost (mills/kWhr) ^b
FFP-1	3,886	1010	404	1414	3.8E-3
FFP-2	4,520	1175	470	1645	4.4E-3
FFP-3	6,841	1779	712	2491	6.7E-3
FFP-4	11,369	2956	1182	4138	1.1E-2
FRP-1	10,090	2623	1169	3792	1.0E-2
FRP-2	10,155	2640	1176	3816	1.0E-2
FRP-3	10,462	2720	1208	3928	1.0E-2
FRP-4	12,741	3313	1445	4758	1.2E-2

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

^bThe contribution to power is computed from the total annual cost on the basis of a 450-metric ton/yr fresh fuel fabrication plant and a 245-metric ton/yr fuel refabrication plant supplying fuel to be consumed at 95,000 MWd/ton with a thermal efficiency of 32.5%.

Table 6.2. Installed cost of equipment for waste treatment system - FFP-1

Item	Cost (\$1000)	
	Direct	Capital ^a
HF scrubber, 1 ft diam x 12 ft, Monel	15	36
Rotary drum filter, 1/2 ft ²	2	5
Centrifugal pump, 5 gpm	6	14
KOH tanks, 750 gal (2)	16	38
Liquid waste line, 1 in., SS	24	58
Process piping	2	5
Soot filter, 15 cfm	2	5
Burner	5	12
Bag filter, 100 cfm	6	14
Cooler, 75 ton	22	53
Spray scrubber	17	41
Rotary drum filter, 1/2 ft ²	2	5
Centrifugal pump, 5 gpm	6	14
NaOH tanks, 750 gal (2)	16	38
Process piping	2	5
Rotary drum filter, 1/2 ft ²	2	5
Soot filter, 3000 cfm	46	110
Burner	20	48
Cooler, 100-ton units (2)	40	96
Bag filter	37	89
Equalization pond	1	2
Structure, 1494 ft ²	82	197
Spray chamber, 4 cfm	1	2
Radon retention tank, 250 gal, SS	8	19
Rotary drum filter, 1 ft ²	3	7
Rotary drum filter, 1/2 ft ²	2	5
Sump tank, 250 gal, SS	8	19
HEPA filter, 20,000 cfm	280	672
Bag filter, 200 cfm	9	22
Radon retention tank	20	48
Burner	35	84
Cooling tower	15	36
Cooling tower pumps	3	7
Tower, 6-ft diam x 12 ft	178	427
Bag filter, 1500 cfm	30	72
Structure, 3591 ft ²	200	480
Soot filter	8	19
Bag filter, 7000 cfm	76	182
Soot filter	2	5
Spray chamber scrubber	6	14
Centrifugal pump, 5 gpm	3	7
NaOH tanks, 250 gal (2)	16	38
Rotary drum filter, 1/2 ft ²	2	5
Soot filter	1	2
Process piping	2	5
Ducts	9	22
Structure, 411 ft ²	23	55
Soot filter	11	26
Spray chamber, NaOH	39	94
Rotary drum filter, 1/2 ft ²	3	7
Tanks, 250 gal, SS (2)	16	38
Centrifugal pump, 5 gpm	6	14
Soot filter	11	26
Spray chamber, 4000 cfm	33	79
Rotary drum filter, 1/2 ft ²	3	7
Centrifugal pump, 5 gpm	6	14
Tanks, 250 gal, SS (2)	16	38
Soot filter, 17,000 cfm	14	34
Blowers, 20,000 cfm (2)	26	62
Ducts	82	197
Process piping	4	10
Structure, 729 ft ²	40	96
TOTAL	1621	3886

^aCapital cost is sum of direct and indirect costs.

Table 6.3. Installed cost of equipment for waste treatment system - FFP-2

Item	Cost (\$1000)	
	Direct	Capital ^a
HF scrubber, 1 ft diam x 12 ft, Monel	15	36
Rotary drum filter, 1/2 ft ²	2	5
Centrifugal pump, 5 gpm	6	14
KOH tanks, 750 gal (2)	16	38
Liquid waste line, 1 in., SS	24	58
Process piping	2	5
Soot filter, 15 cfm	2	5
Burner	5	12
Bag filter, 100 cfm	6	14
Cooler, 75 ton	22	53
Spray scrubber	17	41
Rotary drum filter, 1/2 ft ²	2	5
Centrifugal pump, 5 gpm	6	14
NaOH tanks, 750 gal (2)	16	38
Process piping	2	5
Rotary drum filter, 1/2 ft ²	2	5
Soot filter, 3000 cfm	46	110
Burner	20	48
Cooler, 100-ton unit (2)	40	96
Bag filter	37	89
Structure, 1494 ft ²	82	197
Spray chamber, 4 cfm	1	2
Radon retention tank, 250 gal, SS	8	19
Rotary drum filter, 1 ft ²	3	7
Rotary drum filter, 1/2 ft ²	2	5
Sump tank, 250 gal, SS	8	19
HEPA filter, 20,000 cfm	280	672
Bag filter, 200 cfm	9	22
Radon retention tank	20	48
Burner	35	84
Cooling tower	15	36
Cooling tower pumps	3	7
Tower, 6-ft diam x 12 ft	178	427
Bag filter, 1500 cfm	30	72
Structure, 3591 ft ²	200	480
Soot filter	8	19
Bag filter, 7000 cfm	76	182
Soot filter	2	5
Spray chamber scrubber	6	14
Centrifugal pump, 5 gpm	3	7
NaOH tanks, 250 gal (2)	16	38
Rotary drum filter, 1/2 ft ²	2	5
Soot filter	1	2
Process piping	2	5
Ducts	9	22
Structure, 411 ft ²	23	55
Soot filter	11	26
Spray chamber, NaOH	39	94
Rotary drum filter, 1/2 ft ²	3	7
250-gal tanks, SS (2)	16	38
Centrifugal pump, 5 gpm	6	14
Soot filter	11	26
Spray chamber, 4000 cfm	33	79
Rotary drum filter, 1/2 ft ²	3	7
Centrifugal pump, 5 gpm	6	14
250-gal tanks, SS (2)	16	38
Soot filter, 17,000 cfm	14	34
Blowers, 20,000 cfm (2)	26	62
Ducts	82	197
Process piping	4	10
Structure, 729 ft ²	40	96
Solar evaporator, 70,000 ft ²	265	636
TOTAL	1885	4520

^aCapital cost is sum of direct and indirect costs.

Table 6.4. Installed cost of equipment for waste treatment system - FFP-3

Item	Cost (\$1000)	
	Direct	Capital ^a
Impingement baffle plate scrubber	36	86
Rotary drum filter, 1/2 ft ²	2	5
Centrifugal pump, 5 gpm	6	14
KOH tanks, 750 gal (2)	16	38
Process piping	2	5
Soot filter, 15 cfm	2	5
Impingement baffle plate scrubber	2	5
Rotary drum filter, 1/2 ft ²	2	5
Perclene clean-up and cooler	61	146
Soot filter, 100 cfm	6	14
Impingement baffle plate scrubber	2	5
Centrifugal pump, 5 gpm	6	14
Rotary drum filter, 1/2 ft ²	2	5
NaOH tanks, 750 gal (2)	16	38
Process piping	2	5
Burner	20	48
Cooler, 100-ton units (2)	40	96
Bag filter	189	454
Evaporator, 35 ft ²	534	1282
Cooling tower	15	36
Cooling tower pumps	3	7
Structure, 2193 ft	121	290
Impingement baffle plate scrubber	1	2
Radon retention tank, 250 gal, SS	8	19
Rotary drum filter, 1 ft ²	3	7
Rotary drum filter, 1/2 ft ²	2	5
Sump tank, 250 gal, SS	8	19
HEPA filter, 20,000 cfm	280	672
Bag filter, 200 cfm	9	22
Radon retention tank, 10,000 gal	20	48
Burner	35	84
Cooling tower	15	36
Cooling tower pumps	3	7
Tower, 6 ft diam x 12 ft	178	427
Bag filter, 1500 cfm	30	72
Acid fractionator	8	19
Condenser	2	5
Anaerobic digester	25	60
Hold tank, 250 gal	1	2
Lime storage tank, 250 gal	1	2
Lime screw conveyor	1	2
Lime mix tank	1	2
NH ₃ still	1	2
Condenser-absorber	1	2
Radon retention tank	31	74
Structure, 5487 ft ²	300	720
Bag filter, 9000 cfm	88	211
Spray chamber	2	5
Perclene clean-up and cooler	61	146
Bag filter, 9000 cfm	88	211
Ducts	9	22
Structure, 426 ft ²	23	55
Bag filter, 11,000 cfm	100	240
Impingement baffle plate scrubber	36	86
Centrifugal pump, 50 gpm	3	7
NaOH tanks, 750 gal (2)	16	38
Rotary drum filter, 1 ft ² (2)	6	14
Bag filter, 17,000 cfm	130	312
Impingement baffle plate scrubber	19	46
Centrifugal pump, 15 gpm	2	5
NaOH tanks, 750 gal (2)	16	38
Rotary drum filter, 1 ft ²	3	7
Ducts	82	197
Process piping	4	10
Bag filter, 2000 cfm	36	86
Blowers, 20,000 cfm (2)	26	62
Structure, 987 ft ²	54	130
TOTAL	2853	6841

^aCapital cost is sum of direct and indirect costs.

Table 6.5. Installed cost of equipment for waste treatment system - FFP-4

Item	Cost (\$1000)	
	Direct	Capital ^a
Venturi scrubber, 3 cfm	1	2
Centrifugal pump, 1 gpm	1	2
KOH tanks, 250 gal (2)	4	10
Rotary drum filter, 1/2 ft ²	2	5
Bag filter, 30 cfm	3	7
Venturi scrubber, 60 cfm	3	7
Perclene system and cooler	61	146
Venturi scrubber, 215 cfm	7	17
Centrifugal pump, 5 gpm	6	14
Rotary drum filter, 1/2 ft ²	2	5
Venturi scrubber, 60 cfm	3	7
Rotary drum filter, 1/2 ft ²	2	5
Bag filter, 80 cfm	5	12
Burner	20	48
Cooler, 100-ton units (2)	40	96
HEPA filter	644	1546
HEPA filter	644	1546
NaOH tanks, 750 gal (2)	16	38
Evaporator	534	1282
Cooling tower	15	36
Cooling tower pumps	3	7
Structure, 9465 ft ²	520	1248
Venturi scrubber, 4 cfm	1	2
Radon retention tank, 250 gal, SS	8	19
Rotary drum filter, 1 ft ²	3	7
Sump tank, 250 gal, SS	8	19
Acid fractionator	8	19
Condenser	2	5
Cooler, 10 ton	8	19
Bag filter, 200 cfm	9	22
Burner	35	84
Cooler	178	427
Cooling tower	15	36
Cooling tower pumps	3	7
Bag filter, 1500 cfm	30	72
Charcoal filters	2	5
HEPA filter, 20,000 cfm	280	672
HEPA filter, 20,000 cfm	280	672
Structure, 6249 ft ²	350	840
Bag filter, 9000 cfm	88	211
HEPA filter, 9000 cfm	152	365
HEPA filter, 6000 cfm	36	86
HEPA filter, 3000 cfm	24	58
HEPA filter, 1300 cfm	15	36
Impingement baffle plate scrubber	1	2
Perclene system and cooler	61	146
Structure, 1364 ft ²	75	180
Bag filter	100	240
Venturi scrubber	20	48
Centrifugal pump, 50 gpm	3	7
NaOH tanks, 750 gal (2)	16	38
Rotary drum filter, 1 ft ² (2)	6	14
Bag filter	130	312
Venturi scrubber	20	48
Centrifugal pump, 15 gpm	2	5
NaOH tanks, 750 gal (2)	16	38
Rotary drum filter, 1 ft ²	3	7
Ducts	82	197
Process piping	4	10
HEPA filter	74	178
Structure, 982 ft ²	54	130
TOTAL	4738	11,369

^aCapital cost is sum of direct and indirect costs.

Table 6.6. Installed cost of equipment for waste treatment system - FRP-1

Item	Cost (\$1000)	
	Direct	Capital ^a
Spray chamber scrubber	2	5
Perclene system and cooler	61	146
Controlled combustion furnace	14	34
Cooler, 3 ton	20	48
HEPA filters, 23,000 cfm	300	720
Manipulators (2)	30	72
Bridge crane, 10 ton	32	77
Structure, 684 ft ²	479	1150
Impingement baffle plate scrubber	10	24
Safe tank, 3-1/2-in. pipe	21	50
Perclene still	6	14
Perclene condenser	2	5
Heaters	2	5
Pumping tank, 500 gal, SS	12	29
Centrifugal pump, 5 gpm, SS	3	7
Process piping	4	10
Instrumentation	5	12
Cooling tower	5	12
Cooling tower pumps	1	2
Centrifuge, 5 hp	15	36
Spray chamber scrubber	7	17
Safe tank, 3-1/2-in. pipe	21	50
Pumping tank, 250 gal, SS (2)	16	38
Centrifugal pump, 5 gpm, SS	3	7
Process piping	4	10
Instrumentation	5	12
Centrifuge, 5 hp	15	36
Refrigeration units, 5 ton (2)	38	91
Mixer	1	2
Hydrogen burner	10	24
Charcoal trap system	238	571
HEPA filter system	297	713
Combustion cooler, 100 ton (2)	20	48
Final cooler	19	46
Soot filter	16	38
Manipulators (5)	75	180
Bridge crane, 10 ton	32	77
Structure, 1368 ft ²	958	2299
Radon retention tank, 3000 gal	8	19
HEPA filter	41	98
HEPA filter	41	98
Waste line	2	5
Bridge crane, 10 ton	32	77
Manipulators (2)	30	72
Structure, 270 ft ²	189	454
Bag filter	7	17
Radon retention tank, 10,000 gal	15	36
HEPA filter	4	10
Second HEPA filter	4	10
Dampers and drives	14	34
Blowers	2	5
Duct	1	2
Cooler, 3 ton	3	7
Evaporator	165	396
Cooling tower	18	43
Cooling tower pumps	4	10
Drum handling equipment	210	504
Bridge crane, 10 ton	32	77
Manipulators (5)	75	180
Structure, 726 ft ²	508	1219
TOTAL	4204	10,090

^aCapital cost is sum of direct and indirect costs.

Table 6.7. Installed cost of equipment for waste treatment system - FRP-2

Item	Cost (\$1000)	
	Direct	Capital ^a
Soot filter	2	5
Spray chamber scrubber	2	5
Perclene system and cooler	61	146
Controlled combustion furnace	14	34
Cooler, 3 ton	20	48
HEPA filters, 23,000 cfm	300	720
Manipulators (2)	30	72
Bridge crane, 10 ton	32	77
Structure, 684 ft ²	479	1150
Impingement baffle plate scrubber	10	24
Safe tank, 3-1/2-in. pipe	21	50
Perclene still	6	14
Perclene condenser	2	5
Heaters	2	5
Pumping tank, 500 gal, SS	12	29
Centrifugal pump, 5 gpm, SS	3	7
Process piping	4	10
Instrumentation	5	12
Cooling tower	5	12
Cooling tower pumps	1	2
Centrifuge, 5 hp	15	36
Spray chamber scrubber	7	17
Safe tank, 3-1/2-in. pipe	21	50
Pumping tank, 250 gal, SS (2)	16	38
Centrifugal pump, 5 gpm, SS	3	7
Process piping	4	10
Instrumentation	5	12
Centrifuge, 5 hp	15	36
Refrigeration unit, 5 ton (2)	38	91
Mixer	1	2
Hydrogen burner	10	24
Charcoal trap system	238	571
HEPA filter system	297	713
Combustion cooler, 100 ton (2)	20	48
Final cooler	19	46
Manipulators (5)	75	180
Bridge crane, 10 ton	32	77
Structure, 1368 ft ²	958	2299
Radon retention tank, 3000 gal	8	19
HEPA filter	41	98
HEPA filter	41	98
Waste line	2	5
Bridge crane, 10 ton	32	77
Manipulators (2)	30	72
Structure, 270 ft ²	189	454
Bag filter	7	17
Radon retention tank, 10,000 gal	15	36
HEPA filter	4	10
Second HEPA filter	4	10
Dampers and drives	14	34
Blowers	2	5
Duct	1	2
Cooler, 3 ton	3	7
Evaporator	165	396
Cooling tower	18	43
Cooling tower pumps	4	10
Drum handling equipment	210	504
Bridge crane, 10 ton	32	77
Manipulators (5)	75	180
Structure, 726 ft ²	508	1219
HEPA filter	41	98
TOTAL	4231	10,155

^aCapital cost is sum of direct and indirect costs.

Table 6.8. Installed cost of equipment for waste treatment system - FRP-3

Item	Cost (\$1000)	
	Direct	Capital ^a
Soot filter	2	5
Spray chamber scrubber	2	5
Perclene system and cooler	61	146
Controlled combustion furnace	14	34
Cooler, 3 ton	20	48
HEPA filters, 23,000 cfm	300	720
Manipulators (2)	30	72
Bridge crane, 10 ton	32	77
Structure, 684 ft ²	479	1150
Impingement baffle plate scrubber	10	24
Safe tank, 3-1/2-in. pipe	21	50
Perclene still	6	14
Perclene condenser	2	5
Heaters	2	5
Pumping tank, 500 gal, SS	12	29
Centrifugal pump, 5 gpm, SS	3	7
Process piping	4	10
Instrumentation	5	12
Cooling tower	5	12
Cooling tower pumps	1	2
Centrifuge, 5 hp	15	36
Spray chamber scrubber	7	17
Safe tank, 3-1/2-in. pipe	21	50
Pumping tank, 250 gal, SS (2)	16	38
Centrifugal pump, 5 gpm, SS	3	7
Process piping	4	10
Instrumentation	5	12
Centrifuge, 5 hp	15	36
Refrigeration unit, 5 ton (2)	38	91
Mixer	1	2
Hydrogen burner	10	24
Charcoal trap system	238	571
HEPA filter system	297	713
Combustion cooler, 100 ton (2)	20	48
Final cooler	19	46
Ion exchange columns	6	14
Centrifugal pumps, 1 gpm (2)	2	5
Tank, 250 gal, SS	8	19
Process piping	2	5
Instrumentation	10	24
Safe tank	10	24
Manipulators (6)	90	216
Cranes, 10 ton (2)	64	154
Structure, 1488 ft ²	1042	2500
Radon retention tank, 3000 gal	8	19
HEPA filter	41	98
HEPA filter	41	98
Waste line	2	5
Bridge crane, 10 ton	32	77
Manipulators (2)	30	72
Structure, 270 ft ²	189	454
Bag filter	7	17
Radon retention tank, 10,000 gal	15	36
HEPA filter	4	10
Second HEPA filter	4	10
Dampers and drives	14	34
Blowers	2	5
Duct	1	2
Cooler, 3 ton	3	7
Evaporator	165	396
Cooling tower	18	43
Cooling tower pumps	4	10
Drum handling equipment	210	504
Bridge crane, 10 ton	32	77
Manipulators (5)	75	180
Structure, 726 ft ²	508	1219
TOTAL	4359	10,462

^aCapital cost is sum of direct and indirect costs.

Table 6.9. Installed cost of equipment for waste treatment system - FRP-4

Item	Cost (\$1000)	
	Direct	Capital ^a
HEPA filters (recycle)	116	278
Venturi scrubber	2	5
Perclene system and cooler	61	146
Controlled combustion furnace	14	34
Cooler, 3 ton	20	48
Radon retention tank, 1500 gal	5	12
HEPA filters	300	720
Structure, 1650 ft ²	1155	2772
Manipulators (4)	60	144
Bridge crane, 10 ton (2)	64	154
Venturi scrubber	6	14
Safe tank, 3-1/2-in. pipe	21	50
Perclene still	6	14
Perclene condenser	2	5
Heaters	2	5
Pumping tank, 500 gal, SS	12	29
Centrifugal pump, 5 gpm, SS	3	7
Process piping	4	10
Instrumentation	5	12
Cooling tower	5	12
Cooling tower pumps	1	2
Centrifuge, 5 hp	15	36
Venturi scrubber	5	12
Safe tank, 3-1/2-in. pipe	21	50
Pumping tank, 250 gal, SS (2)	16	38
Centrifugal pump, 5 gpm	3	7
Process piping	4	10
Instrumentation	5	12
Centrifuge, 5 hp	15	36
Refrigeration units, 5 ton (2)	38	91
Mixer	1	2
Hydrogen burner	10	24
Charcoal trap system	238	571
HEPA filter	297	713
Combustion cooler, 100 ton (2)	20	48
Final cooler	19	46
HEPA filter	126	302
Structure, 1608 ft ²	1126	2702
Manipulators (5)	75	180
Bridge crane, 10 ton	32	77
Soot filter	1	2
Bag filter	7	17
HEPA filter	4	10
Second HEPA filter	4	10
Radon retention tank, 10,000 gal	15	36
Charcoal trap system	118	283
Dampers and drives	14	34
Blowers	2	5
Duct	1	2
Cooler, 3 ton	3	7
Evaporator	165	396
Cooling tower	18	43
Cooling tower pumps	4	10
Third HEPA filter	93	223
Drum handling equipment	210	504
Bridge crane, 10 ton	32	77
Manipulators (5)	75	180
Structure, 876 ft ²	613	1472
TOTAL	5309	12,741

^aCapital cost is sum of direct and indirect costs.

Table 7.1. Latitude-longitude coordinates used to derive
data sets for population distribution

	<u>Latitude (N)</u>	<u>Longitude (W)</u>
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° 56' 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	2,007	1,037	19,193	108,738	96,229	46,889
NNE	0	0	0	0	0	816	847	7,688	40,643	347,330	300,030	300,804
NE	0	0	0	0	0	709	936	23,608	22,601	77,981	625,661	575,054
ENE	0	0	0	0	652	1,197	1,906	1,377	8,737	85,826	192,983	110,272
E	0	0	0	365	0	452	3,506	254	1,824	10,629	14,875	24,482
ESE	0	0	0	0	69	2	799	972	3,323	4,470	8,449	4,378
SE	0	0	0	13	537	482	1,022	696	3,241	23,827	5,080	15,453
SSE	0	0	0	0	0	0	1,796	706	10,056	41,868	4,461	7,339
S	0	0	0	87	0	72	1,498	908	30,234	100,668	10,935	17,328
SSW	0	0	0	0	0	98	626	586	3,588	6,416	7,425	3,933
SW	0	0	146	0	0	0	2,233	428	2,614	6,862	1,717	3,257
WSW	0	0	0	0	526	0	907	202	1,380	8,621	2,690	4,601
W	0	0	0	0	0	0	3,128	655	4,400	8,192	14,438	8,317
WNW	0	0	0	0	132	77	505	402	1,424	6,379	4,908	3,646
NW	0	260	0	0	0	0	346	1,083	8,288	5,991	6,220	4,146
NNW	0	0	0	0	544	0	579	829	5,823	5,027	28,615	20,359
Total (by distance)	0	260 ±449 ^a	146 ±220	465 ±804	2,460 ±1,453	4,157 ±4,280	22,641 ±8,469	40,498 ±49,447	167,369 ±42,111	848,825 ±378,192	1,324,696 ±1,536,279	1,150,618 ±1,698,458
Cumulative	0	260	406	871	3,331	7,488	30,129	70,627	237,996	1,086,821	2,411,517	3,562,135
Density (ind./mile ²)	<div> <div>← 95 →</div> <div>96</div> <div>← 126 →</div> <div>← 440 →</div> </div>											

^aStandard deviation of the mean (total).

Table 7.3. Representative population distribution at successive distances for coastal plain site

Sector	Radial distance (miles)											
	0-0.5	0.5-1	1-2	2-3	3-4	4-5	5-10	10-15	15-25	25-35	35-45	45-55
N	0	0	0	151	0	46	10,358	7,761	3,512	4,060	4,835	9,942
NNE	0	0	0	0	0	0	965	1,147	1,978	3,115	5,985	17,515
NE	0	0	0	0	0	0	438	284	1,139	6,646	27,892	7,382
ENE	0	0	0	0	443	0	847	1,119	4,112	6,321	12,413	9,022
E	0	0	0	0	0	239	2,539	801	1,553	17,556	4,215	5,544
ESE	0	0	0	0	0	0	1,726	420	660	2,463	4,700	6,466
SE	0	0	0	0	246	213	1,710	933	1,453	3,261	2,909	4,130
SSE	0	0	0	35	282	0	5,954	1,780	3,546	2,991	3,247	3,380
S	0	0	0	0	250	570	12,327	1,095	2,803	9,367	2,829	2,744
SSW	0	0	0	0	0	0	0	318	1,518	2,978	5,556	4,590
SW	0	0	0	0	0	0	710	990	1,620	3,953	4,320	4,846
WSW	0	1,112	0	0	0	0	0	470	732	3,309	2,833	13,724
W	0	0	0	0	0	0	1,313	669	1,975	5,684	7,106	10,573
WNW	0	0	0	0	0	0	1,568	4,341	5,456	42,402	24,875	7,668
NW	0	0	0	0	0	7	7,970	11,817	8,353	13,856	4,110	7,239
NNW	0	0	0	0	421	310	15,334	22,775	4,024	8,447	5,564	9,189
Total (by distance)	0	1,112 ±1,926 ^a	0 -	186 ±237	1,642 ±927	1,385 ±1,555	63,759 ±54,948	56,720 ±79,376	44,434 ±17,548	136,409 ±93,262	123,389 ±30,247	123,954 ±29,498
Cumulative	0	1,112	1,112	1,298	2,940	4,325	68,084	12,804	169,238	395,631	42,902	552,974
Density (ind./mile ²)	55						289	61		51		

^aStandard deviation of the mean (total).

Table 7.4. Maximum committed annual dose to individuals from airborne effluents from a model HTGR fresh fuel fabrication plant at 0.5 mile on a coastal and a midwestern site

Radwaste treatment case	Maximum total body dose (millirem)	Maximum adult organ dose (millirem) ^a									
		GI tract	Bone	Thyroid	Lungs	Muscle	Kidneys	Liver	Spleen	Testes	Ovaries
Midwestern site											
1	1.4E-1	9.0E-2	1.9E+0	1.4E-1	6.9E-1	1.3E-1	4.9E-1	1.4E-1	1.2E-1	1.4E-1	1.1E-1
2	1.4E-1	9.0E-2	1.9E+0	1.4E-1	6.9E-1	1.3E-1	4.9E-1	1.4E-1	1.2E-1	1.4E-1	1.1E-1
3	3.3E-2	2.2E-2	4.3E-1	3.4E-2	1.7E-1	3.2E-2	1.0E-1	3.2E-2	2.9E-2	3.5E-2	2.7E-2
4	8.5E-5	5.8E-5	1.2E-3	8.7E-5	4.6E-4	8.2E-5	4.0E-4	9.5E-5	7.5E-5	8.8E-5	7.0E-5
Coastal site											
1	9.5E-2	6.3E-2	1.3E+0	9.8E-2	4.8E-1	9.2E-2	3.4E-1	9.7E-2	8.3E-2	9.9E-2	7.7E-2
2	9.5E-2	6.3E-2	1.3E+0	9.8E-2	4.8E-1	9.2E-2	3.4E-1	9.7E-2	8.3E-2	9.9E-2	7.7E-2
3	2.3E-2	1.6E-2	3.0E-1	2.4E-2	1.2E-1	2.2E-2	7.3E-2	2.2E-2	2.0E-2	2.4E-2	1.9E-2
4	6.0E-5	4.1E-5	8.1E-4	6.1E-5	3.2E-4	5.7E-5	2.8E-4	6.7E-5	5.2E-5	6.2E-5	4.9E-5

^aIf fresh fuel contains 10 ppm ²³⁰Th, these doses may be multiplied by a factor of 0.86.

Table 7.5. Summary of annual doses to the population from airborne effluents from a model HTGR fresh fuel fabrication plant on a coastal and a midwestern site

Radwaste treatment case	Total body dose (person-rem) ^a	Population organ doses (person-organ-rem) ^a									
		GI tract	Bone	Thyroid	Lungs	Muscle	Kidneys	Liver	Spleen	Testes	Ovaries
Midwestern site											
1	5.24E-1	3.44E-1	6.37E+0	5.43E-1	2.30E+0	5.00E-1	1.67E+0	5.07E-1	4.43E-1	5.45E-1	4.05E-1
2	5.24E-1	3.44E-1	6.37E+0	5.43E-1	2.30E+0	5.00E-1	1.67E+0	5.07E-1	4.43E-1	5.45E-1	4.05E-1
3	1.29E-1	8.52E-2	1.48E+0	1.34E-1	5.55E-1	1.23E-1	3.60E-1	1.19E-1	1.08E-1	1.35E-1	9.83E-2
4	3.21E-4	2.16E-4	3.91E-3	3.30E-4	1.49E-3	3.06E-4	1.31E-3	3.38E-4	2.73E-4	3.34E-4	2.51E-4
Coastal site											
1	3.04E-1	1.93E-1	3.86E+0	3.14E-1	1.45E+0	2.90E-1	1.01E+0	2.99E-1	2.58E-1	3.16E-1	2.36E-1
2	3.04E-1	1.93E-1	3.86E+0	3.14E-1	1.45E+0	2.90E-1	1.01E+0	2.99E-1	2.58E-1	3.16E-1	2.36E-1
3	7.41E-2	4.78E-2	8.89E-1	7.68E-2	3.50E-1	7.06E-2	2.15E-1	6.94E-2	6.27E-2	7.73E-2	5.70E-2
4	1.87E-4	1.23E-4	2.38E-3	1.93E-4	9.53E-4	1.79E-4	8.12E-4	2.02E-4	1.61E-4	1.95E-4	1.48E-4

^aDose to population within 55 miles of the model plant.

Table 7.6. Contribution of exposure modes to total-body dose from the airborne effluents of a model HTGR fresh fuel fabrication plant^a

Exposure mode	Maximum annual dose (millirem)	Percent of total dose
Submersion in air	7.1E-4	0.01
Contaminated ground	5.5E-2	39.6
Inhalation ^b	3.6E-2	25.7
Ingestion ^c	4.9E-2	34.7

^aMaximum total-body dose at 0.5 mile; midwestern site, treatment Case 1.

^bDaily intake assumed to be 20 m³ of air.

^cDaily intake assumed to be 0.25 kg of vegetables, 1 liter of milk, and 0.3 kg of meat. 100% of food consumed is assumed to be grown or produced at the location of residence.

Table 7.7. Major contributors to total-body and organ dose to individuals at 0.5 mile from airborne release of a model HTGR fresh fuel fabrication plant^a

Radionuclide ^b	Percent of total-body and organ dose			
	Total body	Bone	Kidney	Lung
²³⁴ U	46.9	47.0	42.9	70.0
²³⁵ U	27.6	4.5	6.6	6.7
²³⁰ Th	17.0	45.1	37.2	14.7
²³² Th	5.0	1.0	1.2	2.2
²²⁰ Rn ^c	2.3	1.3	11.4	4.8
²²⁸ Ra	0.7	0.4	0.2	0.1
²²⁸ Th	0.4	0.5	0.2	1.1
²²⁶ Ra	0.1	0.1	<0.1	<0.1
²³⁸ U	0.1	0.1	0.1	0.2

^aMidwestern site; Case 1.

^bRadionuclides contributing <1% not included.

^cIncludes daughter ²¹²Pb.

Table 7.8. Major radionuclides contributing to dose to individuals from airborne effluents via terrestrial pathways at 0.5 mile from a model HTGR fresh fuel fabrication plant^a

Radionuclide	Percent of total-body dose			
	Submersion in air	Contaminated ground	Inhalation	Ingestion
²³⁴ U		18.4	30.7	91.6
²³⁵ U	0.3	66.7	0.9	3.0
²³⁶ U			0.1	
²²⁸ Th		0.3	0.9	
²³⁰ Th		0.5	63.6	1.3
²³² Th		11.5	1.0	
²²⁸ Ra			0.2	1.9
²²⁶ Ra				0.3
²²⁰ Rn ^b	92.9	2.6	2.9	1.6
²²² Rn ^c	6.6			

^aCase 1, midwestern site.

^bIncludes ²¹²Pb daughter.

^cIncludes ²¹⁴Pb and ²¹⁸Po daughters.

Table 7.9. Percent contribution of inhaled and ingested radionuclides from the airborne effluent of a model HTGR fresh fuel fabrication plant^a

Radionuclide	Bone		Kidney		Lungs	
	Inhaled	Ingested	Inhaled	Ingested	Inhaled	Ingested
²³⁴ U	16.5	91.5	16.1	82.7	72.4	91.6
²³⁵ U		3.0	0.5	2.6	2.3	3.0
²³⁶ U		0.2		0.2	0.2	
²²⁸ Th	0.9		0.3		1.3	1.9
²³⁰ Th	79.6	2.8	69.9	2.9	16.8	1.3
²³² Th	1.1		0.3		1.5	
²²⁶ Ra				0.1		0.3
²²⁸ Ra		0.9		0.5		
²²⁰ Rn ^b	1.4	1.3	12.9	11.0	5.2	1.6
²²² Rn ^c					0.1	

^aCase 1, midwestern site.

^bIncludes daughter ²¹²Pb.

^cIncludes daughters ²¹⁸Po and ²¹⁴Pb.

Table 7.10. Annual dose (millirem) from aquatic pathways from waters around a model HTGR fresh fuel fabrication plant^a at a midwestern and a coastal site

Pathway	Midwestern site				Coastal site			
	15-cfs stream		1300-cfs river		15-cfs stream		Estuary	
	Total body	Bone	Total body	Bone	Total body	Bone	Total body	Bone
Submersion in water ^b	2.7E-3	-	3.1E-5	-	2.7E-3	-	2.3E-3	-
Ingestion of water ^c	1.4E+0	1.8E+1	1.6E-2	2.1E-1	1.5E+0	1.8E+1	-	-
Eating fish ^d	7.7E-8	1.3E-6	8.8E-10	1.5E-8	4.5E-6	1.6E-4	3.8E-6	1.3E-4
Totals	1.4E+0	1.8E+1	1.6E-2	2.1E-1	1.5E+0	1.8E+1	2.3E-3	1.3E-4

^aTreatment Case 1.

^bAssume swimming in water for 1% of year.

^cAssume individual drinks 1.2 liters of water per day. No drinking water is taken from coastal estuary.

^dIngestion of 20 g of fish per day.

Table 7.11. Major radionuclides contributing to dose to individuals via aquatic pathways at a model HTGR fresh fuel fabrication plant^a

Radionuclide	Percent of total body dose			
	Drinking water	Eating fish		Swimming ^d
		F ^b	S ^c	
²¹² Pb	37.7	49.0	0.8	42.2
²¹² Bi	-	-	-	54.4
²²⁴ Ra	1.2	2.5	-	-
²²⁶ Ra	0.9	1.8	-	-
²²⁸ Ra	5.8	12.0	-	-
²²⁸ Th	-	-	1.2	-
²³⁰ Th	12.8	15.9	90.7	-
²³² Th	0.9	1.1	6.7	-
²³⁴ U	40.7	16.8	0.3	-
²³⁵ U	1.4	0.6	-	1.0

^aTreatment Case 1.

^bFreshwater.

^cSaline water.

^dFresh and saline water.

Table 7.12. Annual dose (mrad) to biota from liquid effluents from a HTGR fresh fuel fabrication plant^a

	Aquatic plants	Invertebrates	Fish	Muskrats and/or waterfowl
In 15-cfs stream ^b	1.1E+7	1.1E+7	2.2E+4	2.3E+3
In 1300-cfs river ^b	1.3E+5	1.3E+5	2.2E+2	2.6E+1
In 15-cfs stream ^c	1.1E+7	1.1E+7	1.0E+5	1.9E+3
In estuary ^c	9.2E+6	9.2E+6	8.4E+4	1.6E+3

^aTreatment Case 1.

^bFreshwater at midwestern site.

^cSaline water at coastal site.

Table 7.13. Percent contribution of radionuclides to dose to biota in waters around a fresh fuel fabrication plant^a

Radionuclide	Plants		Invertebrates		Fish		Muskrat and/or Waterfowl	
	F ^b	S ^c	F ^b	S ^c	F ^b	S ^c	F ^b	S ^c
²¹² Bi	~100	~100	~100	~100	7.7	1.7	29.1	35.2
²¹² Pb	-	-	-	-	86.3	19.0	2.8	17.3
²³⁰ Th	-	-	-	-	0.8	64.0	-	-
²³⁴ U	-	-	-	-	1.0	-	-	-
²²⁴ Ra	-	-	-	-	-	-	10.8	-
²²⁸ Ra	-	-	-	-	-	-	36.5	-
²³² Th	-	-	-	-	-	1.7	17.8	45.2
²²⁸ Th	-	-	-	-	-	14.0	-	-

^aTreatment Case 1.

^bFreshwater.

^cSaline water.

Table 7.14. Curies of long-lived radionuclides released in airborne effluents during the twenty-year life of the model fresh fuel fabrication plant^a

Radionuclide	Total Ci released	Ci/m ^{2b}
²²⁶ Ra	2.0E-7	8.1E-18
²³⁰ Th	1.0E-2	4.1E-13
²³² Th	5.9E-4	2.4E-14
²³⁴ U	5.4E-1	2.2E-11
²³⁵ U	1.9E-2	7.7E-13
²³⁶ U	1.2E-3	4.9E-14
²³⁸ U	1.8E-4	7.3E-15

^aTreatment Case 1.

^b2.461E+10 m² in an area of 55-mile radius.

Table 7.15. Contribution of radionuclides in airborne effluents and exposure modes to the annual total-body dose^a to individuals from the time of cessation of the fresh fuel fabrication plant^b operation until significant decay of all radionuclides occurs

Radionuclide	Exposure mode			
	Contaminated ground (millirem)	Inhalation (millirem)	Ingestion (millirem)	Total
²²⁶ Ra	9.1E-12	2.5E-12	2.6E-10	2.7E-10
²³⁰ Th	9.1E-7	4.4E-7	4.9E-8	1.4E-6
²³² Th	5.0E-8	3.2E-8	2.9E-9	8.3E-8
²³⁴ U	5.8E-5	2.1E-7	6.2E-7	5.9E-5
²³⁵ U	4.8E-5	6.6E-9	5.5E-8	4.8E-5
²³⁶ U	1.2E-7	4.5E-10	3.8E-9	1.3E-7
²³⁸ U	3.1E-8	6.2E-11	5.0E-10	3.2E-8
Total	1.1E-4	6.9E-7	7.3E-7	1.1E-4

^aDose is average total-body dose of the individual out to a distance of 55 miles.

^bA 20-year lifetime is assumed for plant.

Table 7.16. Annual dose to individuals^a (resulting from the radionuclides released in airborne effluents during the operating lifetime of the model fresh fuel fabrication plant)^b from the time of cessation of plant operation until significant decay of all radionuclides occurs

Radionuclide	Organ dose (millirem) per exposure mode					
	Bone		Kidney		Lung	
	Inhalation	Ingestion	Inhalation	Ingestion	Inhalation	Ingestion
²²⁶ Ra	2.4E-11	2.5E-9	2.5E-12	2.6E-10	2.1E-11	2.6E-10
²³⁰ Th	1.6E-5	1.7E-6	4.4E-7	4.9E-7	2.0E-6	4.9E-8
²³² Th	1.1E-6	9.1E-8	1.7E-6	1.9E-7	1.1E-7	2.9E-9
²³⁴ U	3.5E-6	9.9E-6	2.1E-7	2.4E-6	9.1E-6	6.2E-7
²³⁵ U	1.1E-7	9.1E-7	6.6E-9	2.1E-7	2.7E-7	5.6E-8
²³⁶ U	7.4E-9	6.1E-8	4.5E-10	1.5E-8	1.9E-8	3.8E-9
²³⁸ U	9.9E-10	9.9E-9	6.2E-11	1.9E-9	2.5E-9	5.0E-10
Total	2.1E-5	1.3E-5	2.4E-6	3.3E-6	1.2E-5	7.3E-7

^aDose is the average organ dose to the individual out to a distance of 55 miles.

^bA lifetime of 20 years is assumed.

Table 7.17. Annual dose to the population^a (resulting from radionuclides released in airborne effluents from the model fresh fuel fabrication plant) from the time of cessation of plant operations until significant decay of all radionuclides occurs

Radionuclide	Dose (person-rem per 3.6×10^6 persons) ^b			
	Total body	Bone	Kidney	Lung
²²⁶ Ra	9.1E-7	9.1E-6	9.1E-7	9.9E-7
²³⁰ Th	5.0E-3	6.3E-2	3.3E-3	7.3E-3
²³² Th	3.0E-4	4.2E-3	6.6E-3	4.0E-4
²³⁴ U	2.1E-1	4.8E-2	9.1E-3	3.5E-2
²³⁵ U	1.7E-1	3.6E-3	7.9E-4	1.2E-3
²³⁶ U	4.8E-4	2.5E-4	5.5E-5	8.2E-5
²³⁸ U	1.2E-4	3.3E-5	7.1E-6	1.1E-5
Total	3.9E-1	1.2E-1	2.0E-2	4.4E-2

^aDose to population is average total-body and organ dose out to a distance of 55 miles.

^bActual population within the 55-mile radius of the midwestern plant site.

Table 7.18. Maximum committed annual dose to individuals from airborne effluents from a model HTGR fuel refabrication plant^a at 0.5 mile on a midwestern and a coastal site

Radwaste treatment case	Maximum total-body dose (millirem)	Maximum adult organ dose (millirem) ^b									
		GI tract	Bone	Thyroid	Lungs	Muscle	Kidneys	Liver	Spleen	Testes	Ovaries
Midwestern site											
1	2.0E-1	1.7E-1	5.8E-1	1.9E-1	2.8E-1	2.0E-1	1.8E-1	1.8E-1	1.5E-1	1.4E-1	1.8E-1
2	2.0E-2	1.7E-2	5.8E-2	1.9E-2	2.9E-2	2.0E-2	1.9E-2	1.8E-2	1.5E-2	1.4E-2	1.8E-2
3	1.8E-2	1.4E-2	4.2E-2	1.7E-2	2.4E-2	1.8E-2	1.6E-2	1.6E-2	1.3E-2	1.2E-2	1.6E-2
4	2.7E-5	2.1E-5	6.5E-5	2.6E-5	3.6E-5	2.7E-5	2.4E-5	2.4E-5	2.0E-5	1.8E-5	2.5E-5
Coastal site											
1	1.6E-1	1.4E-1	4.7E-1	1.6E-1	2.1E-1	1.6E-1	1.5E-1	1.5E-1	1.3E-1	1.2E-1	1.5E-1
2	1.6E-2	1.4E-2	4.8E-2	1.6E-2	2.2E-2	1.6E-2	1.6E-2	1.5E-2	1.3E-2	1.2E-2	1.5E-2
3	1.5E-2	1.2E-2	3.5E-2	1.4E-2	1.8E-2	1.5E-2	1.3E-2	1.3E-2	1.1E-2	1.0E-2	1.4E-2
4	2.3E-5	1.8E-5	5.4E-5	2.2E-5	2.8E-5	2.3E-5	2.0E-5	2.0E-5	1.7E-5	1.5E-5	2.1E-5

^aMaximum dose at 0.5 mile from plant effluents. Highest dose to individual occurs at 0.56 mile (900 meters) from the plant effluents and is approximately 12% higher than the maximum dose at 0.5-mile distance.

^bFor fuel containing 10 ppm ²³⁰Th, these doses may be multiplied by 0.31.

Table 7.18a. Maximum committed annual dose to individuals from airborne effluents from a model HTGR fuel refabrication plant at 1 mile on a midwestern and a coastal site

Radwaste treatment case	Maximum total-body dose (millirem)	Maximum adult organ dose (millirem)									
		GI tract	Bone	Thyroid	Lungs	Muscle	Kidneys	Liver	Spleen	Testes	Ovaries
Midwestern site											
1	1.5E-1	1.3E-1	4.3E-1	1.4E-1	2.1E-1	1.5E-1	1.3E-1	1.3E-1	1.1E-1	1.0E-1	1.4E-1
2	1.5E-2	1.3E-2	4.4E-2	1.4E-2	2.1E-2	1.5E-2	1.4E-2	1.3E-2	1.1E-2	1.0E-2	1.4E-2
3	1.3E-2	1.0E-2	3.2E-2	1.3E-2	1.8E-2	1.3E-2	1.2E-2	1.2E-2	1.0E-2	9.0E-3	1.2E-2
4	2.0E-5	1.6E-5	4.9E-5	1.9E-5	2.6E-5	2.0E-5	1.8E-5	1.8E-5	1.5E-5	1.4E-5	1.9E-5
Coastal site											
1	1.2E-1	1.0E-1	3.5E-1	1.2E-1	1.7E-1	1.2E-1	1.1E-1	1.1E-1	9.2E-2	8.4E-2	1.1E-1
2	1.2E-2	1.0E-2	3.6E-2	1.2E-2	1.7E-2	1.2E-2	1.2E-2	1.1E-2	9.2E-3	8.4E-3	1.1E-2
3	1.1E-2	8.3E-3	2.6E-2	1.0E-2	1.4E-2	1.1E-2	9.7E-3	9.7E-3	8.1E-3	7.3E-3	1.0E-2
4	1.7E-5	1.3E-5	4.0E-5	1.6E-5	2.2E-5	1.7E-5	1.5E-5	1.5E-5	1.2E-5	1.1E-5	1.5E-5

Table 7.18b. Maximum committed annual dose to individuals from airborne effluents from a model HTGR fuel refabrication plant at 1.5 miles on a midwestern and a coastal site

Radwaste treatment case	Maximum total-body dose (millirem)	Maximum adult organ dose (millirem)									
		GI tract	Bone	Thyroid	Lungs	Muscle	Kidneys	Liver	Spleen	Testes	Ovaries
Midwestern site											
1	1.5E-1	1.3E-1	4.4E-1	1.4E-1	2.1E-1	1.5E-1	1.4E-1	1.4E-1	1.2E-1	1.1E-1	1.4E-1
2	1.5E-2	1.3E-2	4.4E-2	1.4E-2	2.1E-2	1.5E-2	1.5E-2	1.4E-2	1.2E-2	1.1E-2	1.4E-2
3	1.4E-2	1.0E-2	3.2E-2	1.3E-2	1.8E-2	1.4E-2	1.2E-2	1.2E-2	1.0E-2	9.2E-3	1.3E-2
4	2.1E-5	1.6E-5	5.0E-5	2.0E-5	2.7E-5	2.1E-5	1.8E-5	1.8E-5	1.5E-5	1.4E-5	1.9E-5
Coastal site											
1	1.3E-1	1.1E-1	3.9E-1	1.3E-1	1.8E-1	1.3E-1	1.2E-1	1.2E-1	1.0E-1	9.3E-2	1.3E-1
2	1.3E-2	1.2E-2	3.9E-2	1.3E-2	1.8E-2	1.3E-2	1.3E-2	1.2E-2	1.0E-2	9.4E-3	1.3E-1
3	1.2E-2	9.3E-3	2.9E-2	1.2E-2	1.5E-2	1.2E-2	1.1E-2	1.1E-2	9.1E-3	8.2E-3	1.1E-1
4	1.8E-5	1.4E-5	4.4E-5	1.8E-5	2.3E-5	1.8E-5	1.6E-5	1.7E-5	1.4E-5	1.2E-5	1.7E-5

Table 7.19. Summary of annual doses to the population from airborne effluents from a model HTGR fuel refabrication plant on a midwestern and a coastal site

Radwaste treatment case	Total-body dose (person-rem)	Population organ doses (person-organ-rem) ^a									
		GI tract	Bone	Thyroid	Lungs	Muscle	Kidneys	Liver	Spleen	Testes	Ovaries
Midwestern site											
1	7.54E+0	6.08E+0	1.83E+1	7.21E+0	1.10E+1	7.54E+0	6.73E+0	6.74E+0	5.65E+0	5.11E+0	7.01E+0
2	7.57E-1	6.11E-1	1.85E+0	7.23E-1	1.12E+0	7.56E-1	7.05E-1	6.79E-1	5.67E-1	5.13E-1	7.02E-1
3	7.24E-1	5.61E-1	1.53E+0	6.91E-1	9.67E-1	7.24E-1	6.34E-1	6.47E-1	5.36E-1	4.82E-1	6.71E-1
4	1.09E-3	8.47E-4	2.32E-3	1.04E-3	1.45E-3	1.09E-3	9.54E-4	9.74E-4	8.08E-4	7.27E-4	1.01E-3
Coastal site											
1	2.68E+0	2.16E+0	6.42E+0	2.56E+0	3.77E+0	2.68E+0	2.38E+0	2.39E+0	2.00E+0	1.81E+0	2.49E+0
2	2.68E-1	2.17E-1	6.48E-1	2.56E-1	3.83E-1	2.68E-1	2.50E-1	2.41E-1	2.01E-1	1.82E-1	2.49E-1
3	2.57E-1	1.99E-1	5.39E-1	2.45E-1	3.33E-1	2.57E-1	2.24E-1	2.30E-1	1.90E-1	2.38E-1	2.38E-1
4	3.87E-4	3.01E-4	8.15E-4	3.69E-4	5.02E-4	3.86E-4	3.38E-4	3.45E-4	2.86E-4	2.58E-4	3.58E-4

^aTo entire population within 55 miles of the model plant.

Table 7.20. Contribution of exposure modes to total-body dose from the airborne effluents of a model HTGR fuel refabrication plant^a

Exposure mode	Maximum annual total-body dose (millirem)	Percent of total-body dose
Submersion in air	2.9E-9	<0.1
Contaminated ground	1.2E-1	82.6
Inhalation ^b	2.4E-3	1.6
Ingestion ^c	2.4E-2	15.8

^aMaximum total-body dose at 1.5 mile; midwestern site; radwaste treatment Case 1.

^bDaily intake assumed to be 20 m³ of air.

^cDaily intake assumed to be 0.25 kg of vegetables, 1 liter of milk, and 0.3 kg of meat. All food is assumed to be produced at the location of residence.

Table 7.21. Major contributors to total-body and organ dose to individuals at 1.5 miles from airborne release of a model HTGR fuel refabrication plant^a

Radionuclide	Percent of total-body and organ dose			
	Total body	Bone	Kidney	Lung
²³² U	89.3	68.1	85.4	80.8
²³³ U	0.8	3.4	2.6	2.5
²³⁴ U	0.2	0.7	0.5	0.5
²²⁸ Th	1.0	5.5	1.7	9.1
²²⁴ Ra	8.1	22.0	8.9	6.5
²¹² Pb	0.1	0.2	1.4	0.4

^aCase 1; midwestern site.

Table 7.22. Major radionuclides contributing to dose to individuals from airborne effluents via terrestrial pathways at 1.5 miles from a model HTGR fuel refabrication plant^a

Radionuclide	Percent of total-body dose			
	Submersion in air	Contaminated ground	Inhalation	Ingestion
²³² U	<0.1	99.1	60.1	44.4
²²⁸ Th	<0.1	0.6	31.4	0.1
²³³ U	<0.1	0.2	4.4	3.3
²³⁴ U	<0.1	<0.1	1.0	0.7
²²⁴ Ra	<0.1	<0.1	1.8	51.4
²¹² Pb	12.3	<0.1	1.1	0.2
²¹² Bi	3.0	<0.1	<0.1	<0.1
²⁰⁸ Tl	84.5	<0.1	<0.1	<0.1
²²⁰ Rn	<0.1	<0.1	<0.1	<0.1

^aCase 1; midwestern site.

Table 7.23. Percent contribution of inhaled and ingested radionuclides from the airborne effluents of a model HTGR fuel refabrication plant^a

Radionuclide	Bone		Kidney		Lung	
	Inhaled	Ingested	Inhaled	Ingested	Inhaled	Ingested
²³² U	44.6	56.9	41.5	48.3	63.1	44.4
²²⁴ Ra	0.8	36.7	0.8	37.0	2.1	51.4
²²⁸ Th	49.1	0.4	31.3	0.3	26.2	0.1
²³³ U	3.8	4.9	7.7	9.1	6.2	3.3
²³⁴ U	0.8	1.1	1.7	2.0	1.4	0.7
²¹² Pb	0.8	0.2	16.0	3.2	1.1	0.2
²¹² Bi	<0.1	<0.1	1.0	<0.1	<0.1	<0.1

^aCase 1; midwestern site; 1.5 miles from plant effluents.

Table 7.24. Curies of long-lived radionuclides released in airborne effluents during the twenty-year life of the model HTGR fuel refabrication plant^a

Radionuclide	Total Ci released	Ci/m ^{2b}
²²⁶ Ra	9.0E-10	3.7E-20
²³⁰ Th	4.2E-6	1.7E-16
²³² Th	2.4E-7	9.8E-18
²³⁸ Pu	4.4E-8	1.8E-18
²³² U	2.4E-1	9.8E-12
²³³ U	9.8E-2	4.0E-12
²³⁴ U	2.2E-2	8.9E-13
²³⁵ U	8.2E-6	3.3E-16
²³⁶ U	2.2E-5	8.9E-16
²³⁸ U	2.8E-7	1.1E-17

^aCase 1.

^b2.461E+10 m² in an area of 55-mile radius.

Table 7.25. Contribution of radionuclides in airborne effluents and exposure modes to the annual total-body dose^a to individuals from the time of cessation of the model HTGR fuel refabrication plant^b operation until significant decay of all radionuclides occurs

Radionuclide	Exposure mode			Total
	Contaminated ground (millirem)	Inhalation (millirem)	Ingestion (millirem)	
²²⁶ Ra	1.6E-19	1.1E-14	1.1E-12	1.1E-12
²³⁰ Th	3.8E-10	1.7E-10	2.0E-11	5.7E-10
²³² Th	2.1E-11	1.3E-11	1.2E-12	3.5E-11
²³⁸ Pu	4.7E-12	1.9E-12	2.6E-14	6.6E-12
²³² U	4.9E-3	5.3E-7	4.4E-6	4.9E-3
²³³ U	6.9E-6	3.8E-8	3.2E-7	7.3E-6
²³⁴ U	2.4E-6	9.9E-9	6.1E-8	2.5E-6
²³⁵ U	2.1E-8	2.9E-12	2.5E-11	2.1E-8
²³⁶ U	2.2E-9	8.2E-12	6.7E-11	2.3E-9
²³⁸ U	5.0E-11	9.9E-14	7.8E-13	5.0E-11
Total	4.9E-3	5.8E-7	4.8E-6	4.9E-3

^a Dose is average total-body dose of the individual out to a distance of 55 miles.

^b A 20-year lifetime is assumed for the plant.

Table 7.26. Annual dose to individuals^a (resulting from the radionuclides released in airborne effluents during the operating lifetime of the model HTGR fuel refabrication plant)^b from the time of cessation of plant operation until significant decay of all radionuclides occurs

Radionuclide	Organ dose (millirem) per exposure mode					
	Bone		Kidney		Lung	
	Inhalation	Ingestion	Inhalation	Ingestion	Inhalation	Ingestion
²²⁶ Ra	1.1E-13	1.1E-11	1.1E-14	1.1E-12	9.1E-14	1.1E-12
²³⁰ Th	6.6E-9	7.2E-10	1.4E-9	2.9E-10	8.2E-10	2.9E-11
²³² Th	4.3E-10	3.6E-11	6.9E-10	7.6E-11	4.5E-11	1.2E-12
²³⁸ Pu	7.6E-11	1.1E-12	8.1E-12	1.1E-13	2.5E-12	2.6E-14
²³² U	7.6E-6	6.2E-5	8.2E-7	6.6E-6	1.7E-5	4.4E-6
²³³ U	6.4E-7	5.2E-6	1.5E-7	1.2E-6	1.6E-6	3.2E-7
²³⁴ U	1.4E-7	1.2E-6	3.3E-8	2.7E-7	3.6E-7	6.1E-8
²³⁵ U	4.9E-11	4.0E-10	1.2E-11	8.3E-11	1.2E-10	2.5E-11
²³⁶ U	1.3E-10	1.1E-9	3.2E-11	2.6E-10	3.4E-10	6.7E-11
²³⁸ U	1.7E-12	1.3E-11	3.7E-13	3.0E-12	4.0E-12	7.8E-13
Total	8.4E-6	6.8E-5	1.0E-6	8.1E-6	1.9E-5	4.8E-6

^aDose is the average organ dose to the individual out to a distance of 55 miles.

^bA lifetime of 20 years is assumed.

Table 7.27. Annual dose to the population^a (resulting from radionuclides released in airborne effluents from the model HTGR fuel refabrication plant) from the time of cessation of plant operations until significant decay of all radionuclides occurs

Radionuclide	Dose (person-rem per 3.6×10^6 persons) ^b			
	Total body	Bone	Kidney	Lung
²²⁶ Ra	3.9E-9	3.9E-8	3.9E-9	4.2E-9
²³⁰ Th	2.1E-6	2.6E-5	5.8E-6	3.1E-6
²³² Th	1.2E-7	1.7E-6	2.8E-6	1.7E-7
²³⁸ Pu	2.4E-8	2.8E-7	3.0E-8	9.1E-9
²³² U	1.7E+1	2.5E-1	2.6E-2	7.5E-2
²³³ U	2.6E-2	2.1E-2	5.0E-3	6.8E-3
²³⁴ U	9.1E-3	4.7E-3	1.1E-3	1.5E-3
²³⁵ U	7.4E-5	1.7E-6	3.4E-7	5.4E-7
²³⁶ U	8.3E-6	5.2E-6	1.1E-6	1.5E-6
²³⁸ U	1.8E-7	5.4E-8	1.2E-8	1.7E-8
Total	1.7E+1	2.8E-1	3.2E-2	8.3E-2

^aDose to the population is average total-body and organ dose out to a distance of 55 miles.

^bActual population within the 55-mile radius of the midwestern plant site.

Table 8.1. Radiation dose from airborne effluents and annual cost of radwaste treatment at a model HTGR fresh fuel fabrication plant

Airborne radwaste case	Maximum annual individual dose at 0.5 mile (millirem)					Annual total body dose to population out to 55 miles (person-rem)	Annual cost of airborne radwaste treatment (dollars)
	Total body	Bone	Liver	Kidneys	Lungs		
<u>Midwestern site</u>							
1 ^a	1.4E-1	1.9E+0	1.4E-1	4.9E-1	6.9E-1	5.24E-1	1.39E+6
2 ^a	1.4E-1	1.9E+0	1.4E-1	4.9E-1	6.9E-1	5.24E-1	1.39E+6
3	3.3E-2	4.3E-1	3.2E-2	1.0E-1	1.7E-1	1.29E-1	2.01E+6
4	8.5E-5	1.2E-3	9.5E-5	4.0E-4	4.6E-4	3.21E-4	3.66E+6
<u>Coastal site</u>							
1 ^a	9.5E-2	1.3E+0	9.7E-2	3.4E-1	4.8E-1	3.04E-1	1.39E+6
2 ^a	9.5E-2	1.3E+0	9.7E-2	3.4E-1	4.8E-1	3.04E-1	1.39E+6
3	2.3E-2	3.0E-1	2.2E-2	7.3E-2	1.2E-1	7.41E-2	2.01E+6
4	6.0E-5	8.1E-4	6.7E-5	2.8E-4	3.2E-4	1.87E-4	3.66E+6

^a Cases 1 and 2 are identical for airborne radwaste effluents.

Table 8.2. Incremental airborne radwaste treatment cost and total body and bone dose between case studies at a model HTGR fresh fuel fabrication plant

Case increment	Decrease in maximum annual individual dose at 0.5 mile (millirem)		Increase in annual cost for treatment of airborne radwaste (dollars)	Cost/benefit (\$1000/millirem)	
	Total body	Bone		Total body	Bone
<u>Midwestern site</u>					
0/1 ^a	1.13E+3	1.54E+4	1.39E+6	1.23E+0	9.03E-2
1/2 ^b	-	-	-	-	-
2/3	1.07E-1	1.47E+0	6.16E+5	5.76E+3	4.19E+2
3/4	3.29E-2	4.29E-1	1.65E+6	5.02E+4	3.85E+3
<u>Coastal site</u>					
0/1 ^a	7.70E+2	1.05E+4	1.39E+6	1.81E+0	1.32E-1
1/2 ^b	-	-	-	-	-
2/3	7.20E-2	1.00E+0	6.16E+5	8.56E+3	6.16E+2
3/4	2.29E-2	2.99E-1	1.65E+6	7.21E+4	5.52E+3

^aThis case increment illustrates the effectiveness of the final airborne radwaste treatment system for the basic model plant (Case 1).

^bCases 1 and 2 are identical for airborne radwaste effluents.

Table 8.3. Radiation dose from liquid effluents and annual cost of radwaste treatment at a model HTGR fresh fuel fabrication plant

Liquid radwaste case	Annual individual dose from 15-cfs stream (millirem)		Annual individual dose from 1300-cfs river ^{a,b} (millirem)		Annual individual dose from coastal estuary ^{c,d} (millirem)		Annual cost of liquid radwaste treatment (dollars)
	Total body	Bone	Total body	Bone	Total body	Bone	
<u>Midwestern site</u>							
1	1.4E+0	1.8E+1	1.6E-2	2.1E-1	-	-	2.20E+4
2 ^e	0	0	0	0	-	-	2.31E+5
3 ^f	0	0	0	0	-	-	4.83E+5
4 ^f	0	0	0	0	-	-	4.83E+5
<u>Coastal site</u>							
1	1.5E+0	1.8E+1	-	-	2.3E-3	1.3E-4	2.20E+4
2 ^e	0	0	-	-	0	0	2.31E+5
3 ^f	0	0	-	-	0	0	4.83E+5
4 ^f	0	0	-	-	0	0	4.83E+5

^aDose is from drinking water, fish consumption, and swimming.

^bRiver is involved only at midwestern site.

^cDose is from fish consumption and swimming only.

^dEstuary is involved only at the coastal site.

^eLiquid effluents are discharged to a lined lagoon for concentration by solar evaporation.

^fSeveral chemical compounds are recycled or converted into innocuous compounds before release to the environment.

Table 8.4. Incremental liquid radwaste treatment cost and total body dose between case studies at a model HTGR fresh fuel fabrication plant

Case increment	Decrease in maximum annual individual total-body dose ^a (millirem)			Increase in annual cost for treatment of liquid radwaste (dollars)	Cost/benefit (\$1000/millirem)		
	15-cfs stream	1300-cfs river	Coastal estuary		15-cfs stream	1300-cfs river	Coastal estuary
<u>Midwestern site</u>							
0/1 ^b	8.4E+1	9.6E-1	-	2.20E+4	2.62E-1	2.29E+1	-
1/2	1.4E+0	1.6E-2	-	2.09E+5	1.49E+2	1.31E+4	-
1/3 ^c	1.4E+0	1.6E-2	-	4.61E+5	3.29E+2	2.88E+4	-
1/4 ^c	1.4E+0	1.6E-2	-	4.61E+5	3.29E+2	2.88E+4	-
<u>Coastal site</u>							
0/1 ^b	9.0E+1	-	1.4E-1	2.20E+4	2.44E-1	-	1.57E+2
1/2	1.5E+0	-	2.3E-3	2.09E+5	1.39E+2	-	9.09E+4
1/3 ^c	1.5E+0	-	2.3E-3	4.61E+5	3.07E+2	-	2.00E+5
1/4 ^c	1.5E+0	-	2.3E-3	4.61E+5	3.07E+2	-	2.00E+5

^aDose is from drinking water, fish consumption, and swimming.

^bThis case increment illustrates the effectiveness of the final liquid radwaste treatment system for the basic model plant (Case 1).

^cCases 3 and 4 have same liquid radwaste treatment.

Table 8.5. Radiation dose from airborne effluents and annual cost of radwaste treatment at a model HTGR refabrication plant

Airborne radwaste case	Maximum annual individual dose at 1.5 miles (millirem)					Annual total body dose to population out to 55 miles (person-rem)	Annual cost of airborne radwaste treatment (dollars)
	Total body	Bone	Liver	Lung	Kidney		
<u>Midwestern site</u>							
1	1.5E-1	4.4E-1	1.4E-1	2.1E-1	1.4E-1	7.54E+0	3.79E+6
2	1.5E-2	4.4E-2	1.4E-2	2.1E-2	1.5E-2	7.57E-1	3.82E+6
3	1.4E-2	3.2E-2	1.2E-2	1.8E-2	1.2E-2	7.24E-1	3.93E+6
4	2.1E-5	5.0E-5	1.8E-5	2.7E-5	1.8E-5	1.09E-3	4.76E+6
<u>Coastal site</u>							
1	1.3E-1	3.9E-1	1.2E-1	1.8E-1	1.2E-1	2.68E+0	3.79E+6
2	1.3E-2	3.9E-2	1.2E-2	1.8E-2	1.3E-2	2.68E-1	3.82E+6
3	1.2E-2	2.9E-2	1.1E-2	1.5E-2	1.1E-2	2.57E-1	3.93E+6
4	1.8E-5	4.4E-5	1.7E-5	2.3E-5	1.6E-5	3.87E-4	4.76E+6

Table 8.6. Incremental radwaste treatment cost and total body and bone dose between case studies at a model HTGR refabrication plant

Case increment	Decrease in maximum annual individual total dose at 1.5 miles (millirem)		Increase in annual cost for treatment of airborne radwaste (dollars)	Cost/benefit (\$1000/millirem)	
	Total body	Bone		Total body	Bone
	<u>Midwestern site</u>				
0/1 ^a	7.65E+4	2.24E+5	3.79E+6	4.95E-2	1.69E-2
1/2	1.35E-1	3.96E-1	2.40E+4	1.78E+2	6.06E+1
2/3	1.00E-3	1.20E-2	1.12E+5	1.12E+5	9.33E+3
3/4	1.40E-2	3.20E-2	8.30E+5	5.93E+4	2.59E+4
<u>Coastal site</u>					
0/1 ^a	6.63E+4	1.99E+5	3.79E+6	5.72E-2	1.90E-2
1/2	1.17E-1	3.51E-1	2.40E+4	2.05E+2	6.84E+1
2/3	1.00E-3	1.00E-2	1.12E+5	1.12E+5	1.12E+4
3/4	1.20E-2	2.90E-2	8.30E+5	6.92E+4	2.86E+4

^a This case increment illustrates the effectiveness of the final airborne radwaste treatment system for the basic model plant (Case 1).

Fig. 2.1. HTGR fuel components.

Fig. 2.2. Typical HTGR fuel element.

	FISSILE PARTICLE	FERTILE PARTICLE	RECYCLE PARTICLE
COMPOSITION	$^{235}\text{UC}_2$	ThO_2	$^{233}\text{UC}_3\text{O}_{0.5}$
KERNEL DIAM., μm	200	500	370
COATING THICKNESS, μm			
BUFFER	100	85	50
INNER DENSE COATING	25	—	35
SILICON CARBIDE	25	—	30
OUTER DENSE COATING	35	75	35
TOTAL PARTICLE DIAM., μm	570	820	670
DENSITY, g/cc	2.3	3.3	2.2

Fig. 2.3. Diagrammatic representation of fissile, fertile, and recycle particles.

Fig. 3.1. Fabrication of fuel for high-temperature gas-cooled reactors.

PHOTO 1666-75

Fig. 3.2. Artist's conception of General Atomic Company's fresh fuel fabrication facility.

Fig 33 Cell bank for the recycle fuel fabrication pilot plant at ORNL

ORNL-DWG 68-13847

Fig 3 4 Elevation of operating cells for the recycle fuel fabrication pilot plant at ORNL

Fig. 3.5. HTGR fuel cycle.

FP = FISSION PRODUCTS

Fig. 3.6. HTGR fuel cycle modes.

Fig. 3.7. Typical sample system - Summary.

Fig. 4.1. Process and waste treatment system for the production of fissile particles - Cases 1 and 2. (FRESH FUEL FABRICATION PLANT)

Fig. 4.2. Process and waste treatment system for the production of fertile particles - Cases 1 and 2. (FRESH FUEL FABRICATION PLANT)

Fig. 4.3. Process and waste treatment system for the production of matrix material – all cases.

Fig. 4.5. Process and waste treatment system for fissile scrap recovery - Cases 1 and 2.
(FRESH FUEL FABRICATION PLANT)

Fig. 4.6. Plant ventilation, off-gas, and gaseous treatment systems - Case 1. (FRESH FUEL FABRICATION PLANT)

Fig. 4.8. Process and waste treatment system for the production of resin fuel kernels - Cases 1 and 2. (REFABRICATION PLANT)

Fig. 4.9. Process and waste treatment system for the production of resin fuel kernels - Alternate Case 1 (under development). (REFABRICATION PLANT)

Fig. 4.10. Process and waste treatment system for the production of recycle coated fuel kernels - Cases 1 and 2. (REFABRICATION PLANT)

Fig. 4.11. Process and waste treatment system for the production of recycle fuel rods and elements - Cases 1 and 2. (REFABRICATION PLANT)

Fig. 4.12. Process and waste treatment system for scrap recovery - Cases 1 and 2. (REFABRICATION PLANT)

Fig. 4.13. Plant ventilation, off-gas, and gaseous treatment systems - Case 1.
(REFABRICATION PLANT)

Fig. 4 14. Decay chain for thorium, uranium, and daughters.

ORNL DWG 75-5251

Fig. 4.15. Variation of thorium alpha activity with time.

ORNL DWG 74-11682R1

Fig. 4.16. Increase in activity with time for ^{232}U and daughters.

Fig. 4.17. Radioactive release rate for the fresh fuel fabrication plant - Cases 1 and 2.

Fig. 4.18. Miscellaneous liquid waste treatment system - all cases.

Fig. 4.19. Solid waste treatment system - all cases. (BOTH PLANTS)

Fig. 4.20. Radioactive release rate for the fresh fuel fabrication plant - Case 3.

Fig. 4.21. Process and waste treatment system for the production of fissile particles - Case 3. (FRESH FUEL FABRICATION PLANT)

Fig. 4.22. Process and waste treatment system for the production of fertile particles - Case 3. (FRESH FUEL FABRICATION PLANT)

Fig. 4.23. Process and waste treatment system for the production of fuel rods and elements - Case 3. (FRESH FUEL FABRICATION PLANT)

Fig. 4.24. Process and waste treatment system for scrap recovery - Case 3. (FRESH FUEL FABRICATION PLANT)

NO RADIOACTIVE LIQUID WASTES DISCHARGED

Fig. 4.25. Radioactive release rate for the fresh fuel fabrication plant - Case 4.

Fig. 4.26. Process and waste treatment system for the production of fissile particles - Case 4. (FRESH FUEL FABRICATION PLANT)

Fig. 4.27. Process and waste treatment system for the production of fertile particles – Case 4. (FRESH FUEL FABRICATION PLANT)

Fig. 4.28. Process and waste treatment system for the production of fuel rods and elements - Case 4. (FRESH FUEL FABRICATION PLANT)

Fig. 4.29. Process and waste treatment system for scrap recovery - Case 4. (FRESH FUEL FABRICATION PLANT)

Fig. 4.30. Process and waste treatment system for the production of recycle fuel particles – Case 4. (REFABRICATION PLANT)

Fig. 4.31. Process and waste treatment system for the production of recycle fuel rods and elements - Case 4. (REFABRICATION PLANT)

Fig. 4.32. Process and waste treatment system for scrap recovery - Case 4. (REFABRICATION PLANT)

○ STREAM NUMBER, TABLE 5.1

Fig. 5.1. Water usage and overall liquid flowsheet - Case 1. (FRESH FUEL FABRICATION PLANT)

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

Fig. 8.1. Annual cost for reduction of maximum annual dose from airborne effluents at 0.5-mile distance from the model HTGR fresh fuel fabrication plant. (Doses are for the midwestern location.)

Fig. 8.2. Annual cost for reduction of annual population dose out to a radius of 55 miles from airborne effluents from the model HTGR fresh fuel fabrication plant.

Fig. 8.3. Annual cost for reduction of maximum annual dose from airborne effluents at 1.5-mile distances from the model HTGR refabrication plant. (Doses are for the midwestern location.)

Fig. 8.4. Annual cost for reduction of annual population dose out to a radius of 55 miles from airborne effluents from the model HTGR refabrication plant.

APPENDIX A. PREPARATION OF COST ESTIMATES

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 the 450-metric ton/year model fresh fuel fabrication plant (FFP) and the 245-metric ton/year model fuel refabrication plant (FRP). The details of the methods used for estimating the annual fixed charges 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 for the model fuel refabrication plant to cover the cost of drums and cement to solidify and contain the radioactive liquid waste. Operating costs include the surveillance and monitoring of the lagoon and the ventilation ducts to control the build-up of fissile material and decay products.

The capital and annual costs for all of the radwaste treatment cases are summarized in Table 6.1.

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, erections, 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 below for each treatment case. Flowsheets (Figures 4.1 to 4.12) and equipment lists (Tables 6.2 to 6.9) are found in Sections 4 and 6 for each case.

FFP Radwaste Treatment Case 1. - The flowsheets for the Fresh Fuel Plant (FFP) Case 1 are shown in Figs. 4.1 to 4.5. The four systems, fissile particle production, fertile particle production, fuel rod and element fabrication, and scrap recovery, consist of gas scrubbing, filtration, and a settling basin for "holdup" of the liquid waste. Costs for the process equipment and tanks were obtained from 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 in ref. 1 using a unit cost of \$1400/ft², a size exponent of 0.63, and a field installation factor of 1.60.

The cost of the settling basin is based on the recent (1973) experience of the General Engineering Division at Oak Ridge National Laboratory.² The basin is 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 x 10⁶ gallon capacity. The costs that are used are based on volume factors.

The vapor cleaning equipment costs were taken from ref. 1 and were based on volume factors. Duct costs were based on 1973 General Engineering Division experience.² Blower costs were obtained from the special equipment graph in ref. 1 using a unit cost of \$7/ft³, a size exponent of 0.8, and a field installation factor of 1.59.

FFP Radwaste Treatment Case 2. - The flowsheets for FFP Case 2 are shown in Figs. 4.1 to 4.5. The equipment is the same as that for Case 1. However, in Case 2, no liquid wastes are released from the settling basin. Water is removed from the basin by solar evaporation. The capacity and size of the solar evaporation basin are based on the solar heating data as set forth in ref. 3. The location is assumed to be at the coastal site (approximately 35° latitude). Costs are based on the experience of the Baker Pool Company in the construction of swimming pools.

FFP Radwaste Treatment Case 3. - The flowsheets for FFP Case 3 are shown in Figs. 4.21 to 4.24. FFP Case 3 includes much of the equipment used in the two previous cases, but with more sophisticated vapor cleaning and filtration equipment. Additional equipment includes an ammonia still, acid evaporator and fractionating tower, nitrate digestion plant, and lime handling equipment.

The special equipment graph in ref. 1 is used for the ammonia still with a unit cost of \$1200/ft², 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, i.e., 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/ft², 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 included 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.-diameter tower is required for the 1400-ft³/min water vapor flow rate. 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/ft², a size exponent of 0.53, and a field installation factor of 1.90.

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 "perclene" clean-up system is based on an existing similar system located at the Y-12 plant at Oak Ridge, Tennessee, but designed to be critically safe for ²³³U as well as ²³⁵U. The use of storage tanks consisting of 3-1/2-in. pipe on 24-in. centers rather than conventional vessels poisoned with borosilicate rings is considered by production personnel to be superior in terms of criticality safety. Costs of equipment were taken from appropriate graphs in ref. 1.

FFP Radwaste Treatment Case 4. - The flowsheets for FFP Case 4 are shown in Figs. 4.26 to 4.29. More efficient vapor cleaning equipment is utilized in this case, and 95% of the process off-gas and cell ventilation is recycled through one stage of HEPA filtration. The remaining effluent is treated with retention tanks and additional HEPA filtration.

FRP Radwaste Treatment Case 1. - The flowsheets for the Fuel Recycle Plant (FRP) Case 1 are shown in Figs. 4.8 to 4.13. The four systems, fissile particle production, fertile particle production, fuel rod and element fabrication, and scrap recovery consist of vapor cleaning, filtration, and evaporation of liquid waste. Since ²³³U with several hundred parts per million ²³²U and ²³⁵U with residual fission products will be processed in these operations, remotely-operated, concrete shielded, contained "hot cells" will be required. The structure cost of \$700/ft² was estimated by J. R. Parrott (ORNL) and was based on ORNL 1973 experience with two massive concrete structures. The total area required was obtained by summing the areas required for individual equipment and using a 1.5 size factor for clearances between equipment. Manipulator costs were supplied by C. D. Wicker (ORNL).

Liquid wastes are concentrated in all cases in an evaporator to achieve volume reduction. Costs associated with the evaporator are taken from appropriate tables in ref. 1.

A special operating cost is incurred in the solidification of the concentrated liquid waste, which requires 55-gal black-iron drums at \$20/drum and cement at \$2.96/ft³. This solidification cost is added to the total annual cost.

As in the FFP cases, costs of equipment were taken from ref. 1.

FRP Radwaste Treatment Case 2. - The flowsheets for FRP Case 2 are shown in Figs. 4.8 and 4.10-4.12. As in FRP Case 1, equipment costs were taken from ref. 1. The cost of the additional HEPA was obtained by scaling.

FRP Radwaste Treatment Case 3. As in the first two cases, equipment costs were taken from ref. 1. The costs of the ion exchange columns for the removal of daughter products and the safe storage system were obtained by scaling.

FRP Radwaste Treatment Case 4. - The flowsheets for FRP Case 4 are shown in Figs. 4.30 to 4.32. As in the other cases, equipment costs were obtained from ref. 1 or by scaling.

1.2 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. L. B. Shappert, *Cask Designers Guide*, ORNL-NSIC-68 (1970), pp. 129-32.

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