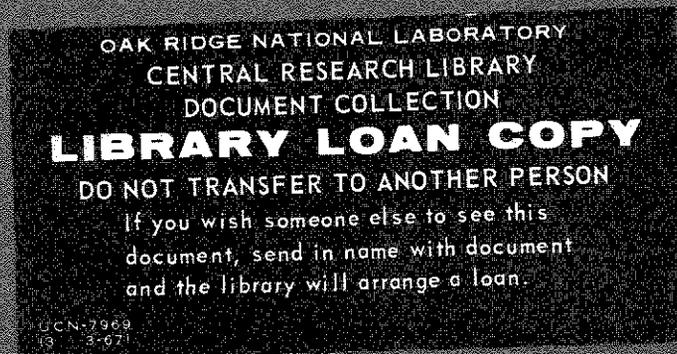


Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle— Conversion of Recycle Uranium to UF_6

J. W. Roddy
R. E. Blanco
B. C. Finney

G. S. Hill
R. E. Moore
J. P. Witherspoon

Prepared for the U.S. Nuclear Regulatory Commission
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CHEMICAL TECHNOLOGY DIVISION

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J. W. Roddy
R. E. Blanco
B. C. Finney
G. S. Hill*
R. E. Moore*
J. P. Witherspoon*

Project Manager: R. E. Blanco

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*Health and Safety Research Division

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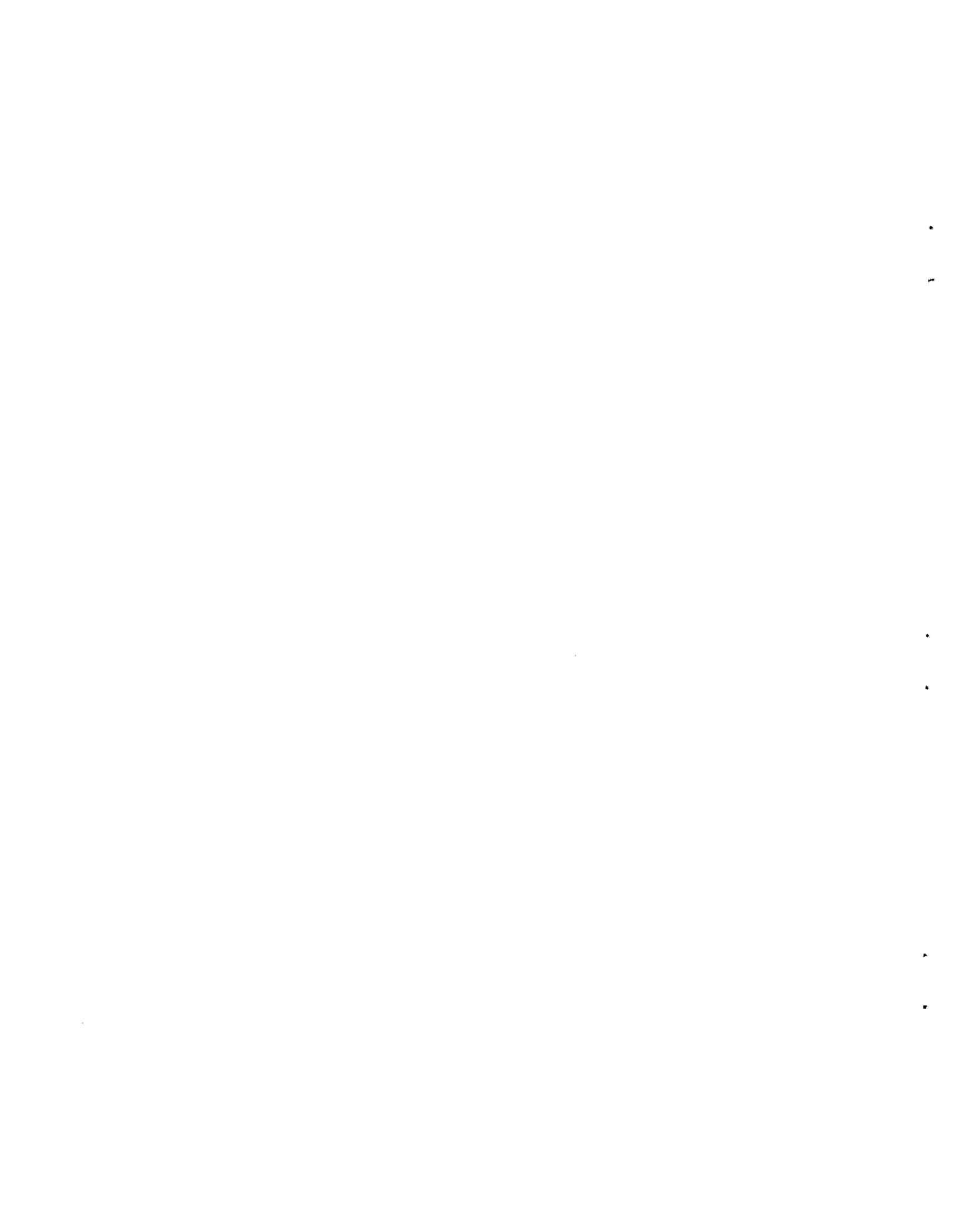
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CORRELATION OF RADIOACTIVE WASTE TREATMENT COSTS AND THE ENVIRONMENTAL IMPACT OF WASTE EFFLUENTS IN THE NUCLEAR FUEL CYCLE - CONVERSION OF RECYCLE URANIUM TO UF₆

J. W. Roddy, R. E. Blanco, B. C. Finney, G. S. Hill,
R. E. Moore, and J. P. Witherspoon

ABSTRACT

A cost/benefit study was made to determine the cost and effectiveness of various radioactive waste (radwaste) treatment systems for decreasing the amount of radioactive materials released from a model recycle uranium conversion and uranium hexafluoride (UF₆) production plant and to determine the radiological impact (dose commitment) of the released radioactive materials on the environment. This 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 case model plant is representative of a licensable UF₆ production plant and has an annual capacity of 1500 metric tons of uranium. Additional radwaste treatment systems are added to the base case plant in a series of case studies to decrease the amounts of radioactive materials released and to reduce the radiological dose commitment to the population in the surrounding area. The cost for the added waste treatment operations and the corresponding dose commitments is calculated for each case. In the final analysis, radiological dose is plotted vs the annual cost for treatment of the radwastes. The status of the radwaste treatment methods used in the case studies is discussed. The methodology used in estimating the costs is presented in Appendix A.

1.0 SUMMARY

A study was made to determine the dollar cost and effectiveness of radioactive waste treatment systems for decreasing the amount of radioactive materials released from a model recycle uranium conversion and uranium hexafluoride (UF₆) production plant and to determine the radiological impact (dose commitment) of the released radioactive materials on the environment. The purpose of the recycle UF₆ facility is to convert the purified uranyl nitrate product of a reprocessing plant to UF₆ suitable for feed to the enrichment plants. The model UF₆ plant processes 1500 metric tons of uranium per year operating on a 300-day-per-year basis. The plant feed is produced by an adjacent model reprocessing plant. About 5500 Ci of radioactivity enters the plant each year, and about 47% of this is alpha activity. The feed also contains minute amounts of fission products and transuranium elements which have not been completely removed at the reprocessing plant. It is assumed that the model recycle uranium conversion plant will be sited adjacent to a fuel reprocessing plant and that the boundary of

the plant is the same for the two units, i.e. at a distance of 1.5 miles (the typical site boundary distance for a reprocessing plant).

The waste treatment systems have been selected: (1) to remove radioactive materials from the airborne effluents, (2) to remove noxious chemicals (fluoride, nitrogen oxides, and sulfur dioxide) from the airborne effluents, (3) to permit the recycle of treated liquid streams, and (4) to provide for the isolation of solid radioactive wastes from the environment. Offsite releases of radioactive materials occur only in the airborne effluents. No liquids containing radioactivity of process origin are discharged from the site during normal operation of the plant.

Five conceptual case studies, each chosen to reflect a decreasing release of radioactivity for an increasing sophistication of radioactive waste treatment, have been selected for the recycle UF_6 plant. Inclusion of specific treatment techniques was not based on cost, but on the effectiveness in reducing the radioactivity of plant effluents. The general plan and objectives are summarized in Table 1.1. Case 1 is the "base case" and represents a plant which is designed to operate under present licensing regulations. The objectives in Case 2 are to reduce the quantity of dry materials released in the airborne effluent from the dust control system by the addition of secondary bag filters. Case 3 includes additional treatment for the airborne effluents from both the dust control and process off-gas systems. Additional treatment equipment is added to all sections of the effluent system in Case 4. The Case 5 study is selected to demonstrate the cost of a complete treatment system for the building ventilation effluent (Case 5a) and a method for isolation of solid waste containing radioactivity (Case 5b). All costs are estimated in mid-1973 dollars for the construction of a new plant (Sect. 6.0), and do not include the development costs of the advanced cases. Backfitting of existing plants is not evaluated. The costs are estimated in 1973 dollars so that this survey will be comparable to previous fuel cycle surveys in this series (Sect. 2.1).

The amounts of radioactive materials and chemicals released (Sect. 4.0), the capital, annual, and contribution to power costs (Sect. 6.0), and the radiological impact (the doses, Sect. 7.0) are calculated for each case. The annual cost of treatments which reduce the amount of airborne radioactive materials released is correlated with the maximum annual individual dose commitments (mrem) at 1.5 miles and with the annual population dose commitment out to 55 miles (person-rem, Sect. 8.0). The dose commitments for each case are estimated for total body, bone, lung, kidney, GI tract, thyroid, muscle, liver, spleen, testes, and ovaries (Sect. 7.0). The model plant is assessed at a rural midwestern site and a rural southeastern coastal site. Meteorologic data are derived from nearby first-order weather stations, while the population distribution is taken from census tapes for the region around several fuel reprocessing and fuel fabrication facilities. Realistically conservative assumptions are used in estimating source terms, selecting efficiency ratings for equipment, estimating costs, defining movement of radionuclides in the environment, and selecting food and liquid consumption patterns to be consistent with similar assessments of other segments of the nuclear fuel cycle.

The total annual costs for reduction of the radiological dose commitment to the population surrounding the model recycle UF_6 plant are summarized in Table 1.2. The annual costs include annual operating and maintenance costs as well as annual fixed charges for radioactive and chemical waste treatment of airborne and liquid effluents and for packaging solid wastes preparatory to offsite shipment. These costs do not include the expense of onsite storage, shipment, permanent disposal of solid wastes, decommissioning of the plant, or charges

Table 1.1. Conceptual waste treatment case studies for the model recycle uranium--UF₆ plant

	Case 1	Case 2	Case 3	Case 4	Case 5
Level of waste treatment	Meets present licensing regulations	Similar to recently completed plant	Near limits of present technology	Uses technology which is not fully developed	Applies technology to large gas flows
Airborne effluent treatment systems					
Particulates	Porous metal filter, centrifugal separator, bag filter, HEPA filter	Case 1 plus additional bag filter	Same as Case 2	Case 2 plus HF-resistant HEPA filter, venturi scrubber	Case 4 plus bag filter on ventilation system
Gases	Cold traps for UF ₆ , condenser for H ₂ O and HNO ₃ (NO _x)	Same as Case 1	Case 1 plus KOH coke-packed tower	Same as Case 3	Same as Case 3
	Burner for H ₂ and H ₂ S	Same as Case 1	Same as Case 1	Case 1 plus KOH venturi scrubber	Same as Case 4
	Scrubber systems for HF and F ₂	Same as Case 1	Case 1 plus KOH coke-packed tower	Case 3 plus KOH venturi scrubber	Same as Case 4
Liquid effluent treatment systems					
Nonradioactive	Monitored and released	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1
Radioactive	Concentrated in evaporators and treated as solid radwaste	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1
Solid radwaste treatment systems					
	All liquids evaporated to dryness, evaporator bottoms and other solids packaged in drums for disposal	Same as Case 1	Same as Case 1	Same as Case 1	Incorporated in cement and packaged in drums for disposal (Case 5b)

Table 1.2. Costs of reducing the total-body dose for the model recycle uranium--UF₆ plant

	Case 1	Case 2	Case 3	Case 4	Case 5a
Annual cost increase over base, \$(mid-1973)	Base	9.60E+4	1.51E+5	3.18E+5	9.35E+5
			<u>Midwestern site</u>		
Annual population total-body dose within 55 miles from airborne effluents, person-rem ^a	1.4E00	5.5E-1	3.8E-1	2.6E-1	2.1E-3
Incremental cost per reduction in population total-body dose between successive case studies, \$/person-rem	Base	1.1E+5	3.2E+5	1.4E+6	2.4E+6
			<u>Coastal site</u>		
Annual population total-body dose within 55 miles from airborne effluents, person-rem ^a	7.5E-1	3.0E-1	2.0E-1	1.4E-1	1.1E-3
Incremental cost per reduction in population total-body dose between successive case studies, \$/person-rem	Base	2.1E+5	5.9E+5	2.6E+6	4.4E+6

^aPopulation dose from natural background radiation; midwestern site - 4.6E+5 person-rem, coastal site - 7.2E+4 person-rem.

for developing advanced treatment methods. The annual cost for Case 2 is \$96,000 (mid-1973 dollars) more than that for the base case; for Case 5b, which is the most expensive, it is about \$1.14 million more than the base case.

The doses to the population out to 55 miles and the cost/benefit ratio are presented in Table 1.2 for the midwestern and the coastal sites. The individual total-body dose from airborne effluents at the midwestern site is reduced from 0.061 to 0.025 millirem from Case 1 to Case 2 and the bone dose from 0.54 to 0.22 millirem. The population total-body dose is reduced from 1.39 to 0.55 person-rem between Cases 1 and 2. The incremental Case 1/Case 2 cost/benefit is \$110,000 per person-rem total body and \$14,000 per person-rem bone. Individual and population doses at the coastal site are slightly lower than at the midwestern site due to differences in meteorology and population. Further dose reductions to lower levels are possible, but the incremental cost/benefit is high (i.e., \$1.4 million per person-rem total body from Case 3 to 4 and \$2.4 million per person-rem between Cases 4 and 5a). The added cost to incorporate solid wastes containing radioactive material into cement between Cases 5a and 5b is \$205,000. This treatment does not decrease the dose commitment but does reduce the potential for leaching radioactive materials by natural waters after the waste has been placed in storage. The amount of gaseous HF released in Case 1 is 4.6 kg/day, but is reduced to 2.8 kg/day in Case 5. The major fraction of this release (2.75 kg/day) originates from the production of fluorine and is the same for all cases.

The capital cost of the total model plant for the base case is estimated at \$20 million including the Case 1 off-gas treatment system. The unit conversion cost is estimated at \$4.85 per kg of uranium for the base plant. The capital costs for the airborne radioactive waste treatment in advanced cases range from \$0.341 to \$3.59 million, or up to about 18% of the capital cost of the base case. The annual cost increases over the base plant range from \$0.096 to \$1.14 million and are equivalent to increased power costs of 0.00026 to 0.0031 mill/kWhr. Thus, the cost of airborne radioactive waste treatment is a small fraction of total capital and power generation costs although the absolute dollar costs are high.

2.0 INTRODUCTION

This study was performed to determine the cost and the effectiveness of additional or alternative radioactive waste treatment systems that could be used at recycle uranium conversion and UF_6 production plants to decrease the amount of radioactive materials and chemicals released to the environment. A second objective is to determine the radiological impact (dose commitment) of these releases on the environment. The effectiveness of the alternative 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 radioactive waste treatment costs as the basis for a cost/benefit analysis.

During operation of a commercial nuclear power plant, a portion of the uranium-235 content is not consumed by fissioning. Fuel elements must be removed from the reactor before the fuel values have been completely consumed, primarily because of fission product buildup. Fission products have a high affinity for the parasitic capture of neutrons which are necessary to sustain the chain fission reaction. In the interest of economic utilization of nuclear fuels and the conservation of valuable resources, the residual uranium and plutonium values contained in the spent fuel elements are recovered at a fuel reprocessing plant. A fraction of the recovered uranium may be used in plutonium-base recycle fuels. However, the fraction that can be used in this way is small. The bulk of the uranium will require reenrichment to about 3% uranium-235, since spent fuel normally contains less than 1% uranium-235. This reenrichment is accomplished at a diffusion plant such as those located at Oak Ridge, Tennessee, and Paducah, Kentucky, where the feed material is UF_6 . Since the purified uranium product from a reprocessing plant is normally in the form of a uranyl nitrate solution, the uranium must be converted to UF_6 to be a suitable feed for the enrichment plants. The purpose of the recycle uranium conversion and UF_6 production facility is to convert uranyl nitrate into UF_6 .

The radioactive materials entering the plant consist of isotopes of uranium and daughter products. In addition, the feed material also contains fission products and transuranium materials which have not been completely separated from the recycle uranium. A small fraction of the radioactive materials and noxious chemicals is suspended in the gaseous waste streams from processing areas as dust or aerosols. Treatment systems are used to minimize the release of these materials in the gaseous effluents from the plant. Liquid process streams are treated to recover nonradioactive materials such as nitric acid and water, and to recycle these materials to the reprocessing plant. No liquids containing radioactivity of process origin are released from the plant. Residues from the treatment of liquid wastes containing radioactivity are solidified. These wastes, along with other solids containing radioactivity, are either prepared for shipment offsite or are impounded in onsite storage bins for later disposal.

A model plant that is typical of current designs for UF_6 production plants is used as the base case for this report. Flowsheets that serve to illustrate the waste treatment methods are developed from the best available information, but are not necessarily representative of any one specific plant. The radiological impact of the plant is considered at two typical sites, i.e., the

model midwestern location and the model southeastern coastal plain. Case I serves as the base for the cost/benefit analysis and contains the minimum treatment necessary for economical operation of the process, including treatment for noxious fumes. Increasingly efficient radioactive waste treatment systems are added to the "base" plant, and the annual cost and environmental impact of each case are calculated. It is not feasible to include all possible variations of base plants and radioactive waste treatment systems, but sufficient information is provided in this study to permit the costs and impacts for other radioactive waste treatment systems to be estimated by extrapolation or interpolation from the data provided. The base case study illustrates important features of plants currently being designed. No sizable production operation exists at this time. All of the treatment equipment is presently available. However, some additional development may be required for the design and operation of air control systems and in the construction and maintenance of sealed filter bank enclosures.

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,¹ milling uranium ores,² fabricating LWR fuels containing enriched uranium,³ fabricating LWR fuels containing plutonium,⁴ reprocessing HTGR fuels,⁵ fabricating HTGR fuels,⁶ and converting yellow cake to UF₆.⁷

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3.0 OBJECTIVES AND ASSUMPTIONS

3.1 Objectives

The objectives of this study are to determine: (1) the dollar cost of using advanced treatment systems to reduce to very low levels the amount of radioactive materials and noxious chemicals released to the environment from a base plant containing the minimum treatment necessary to operate the process and (2) 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 increased 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. Consequently, a greater amount of radioactive material is released by the larger system when operating on the same type, but larger volume, of radioactive effluent. The incremental and absolute values derived in this study for a single size of conceptual plant can thus be extrapolated to larger or smaller plants. The calculated total amounts of radioactive materials released are also defined, but are less important in this study since they are expected to vary with plant size. The volumes and compositions of radioactive wastes are based on model flowsheets developed from the best available information.

Estimates are made of the average radioactive and nonradioactive releases and the annual cost of waste treatment over the 30-year operating lifetime of the plant. In a similar study for nuclear power reactors, emphasis was placed on maintaining continuous operation of the power plant.¹ Consequently, the more complex radioactive waste treatment systems contained redundant (parallel) treatment units to ensure continued operation in case one of the units should become inoperable. In the recycle uranium conversion study, less emphasis is placed on continuous operation since the plant could temporarily cease operations in the event that a major radioactive waste treatment unit failed. Only potential releases from normal operations have been considered in this study.

3.2 Selection of the Model Plant

The model plant selected for the Case I study is similar to a commercial plant being constructed in the southeastern United States.² An artist's conception of this plant is presented in Fig. 3.1. The major structures consist of two buildings, both of standard chemical plant construction. The main building is a multistory structure containing the principal process areas. A second building located near the main process area is used for fluorine generation. The model UF₆ facility is located near a reprocessing facility to eliminate the shipment of uranyl nitrate to a distant conversion plant. The elimination of the shipping requirement saves time, reduces the cost to the nuclear power industry, and lessens the radiological hazards to the public.

The model plant is selected to have an annual capacity of 1500 metric tons of uranium. The various processes are assumed to operate 24 hr per day for 300 days a year with the exception of the scrap uranium recycle operation, which operates on an intermittent basis. The plant has been designed such that there is sufficient surge capacity to continue operation when one section is down. Costs are amortized over 15 years, although the assessment of long-term environmental impact is based on a 30-year operating life.

A simplified flow scheme for the conversion of uranyl nitrate to uranium hexafluoride is depicted in Fig. 3.2. The individual process steps are:

- (1) receipt of purified uranyl nitrate solution from a reprocessing plant;
- (2) concentration of the uranyl nitrate feed solution via evaporation;
- (3) conversion of the uranyl nitrate to UO_3 by denitration;
- (4) hydrogen reduction of UO_3 to UO_2 ;
- (5) hydrofluorination of UO_2 to UF_4 using gaseous HF;
- (6) fluorination of UF_4 to UF_6 using electrolytically generated F_2 ;
- (7) freezing and then resubliming UF_6 in a series of cold traps; and
- (8) packaging of the UF_6 product into standard transport cylinders.

All processing steps which involve radioactive materials are performed inside equipment maintained at negative pressures relative to the adjacent areas of the conversion 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, while the conversion building forms the second level. Pressure differentials are maintained by automatically controlled zoned ventilation systems. Spare ventilation fans and required controls, which are provided, are connected to independent or installed emergency power systems in the event of loss of normal plant power and to ensure that the required pressure differentials are maintained.

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 effluents. No liquid wastes containing radioactivity are released from the plant.

3.3.1 *Airborne effluents*

Airborne effluents from process vessels contain radioactive particles that are produced directly as solids or are formed from aerosols of process solutions that subsequently dry to become solids. These effluents are treated with filters and wet scrubbers to retain increasingly larger fractions of the radioactive particulates, and noxious fumes. The off-gases from the processing steps each receive a separate pretreatment and are discharged through a 50-m stack. Two additional stacks are used for gaseous discharge; one, which is 30 m high, is used for the general building ventilation system; the second is a special ventilation stack (40 m) for the fluorination and decontamination areas.

3.3.2 *Liquid effluents*

Liquid radioactive wastes from process vessels and other miscellaneous liquids from wet scrubbers contain dissolved and suspended compounds of uranium and uranium daughter products, as well as traces of fission products and transuranium elements. Consideration of the chemistry involved indicates that, in most of the process systems, the relative proportion of these materials in the liquid will be the same as in the solids formed in a given operation. An exception occurs in the production and subsequent filtration of gaseous UF_6 where less volatile fission product and transuranic fluorides are removed as solids which are concentrated in the solid waste streams. The liquid radioactive wastes are evaporated to dryness, and the residues are stored in drums for final disposal. In the most advanced case study (Case 5b), the residues are incorporated in cement. The concentration of radioactive material in the condensate from the evaporation step is lower by a factor of 10,000 than that of the original wastes.³

3.3.3 *Solid wastes*

The principal solid wastes containing significant quantities of radioactive materials are the filter fines generated during fluorination of UF_4 . Smaller amounts of radioactivity are found in the miscellaneous wastes that are generated in other parts of the plant. The latter consist of rags, clothing, floor sweepings, 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. The residue from the scrap recovery system and other miscellaneous wastes are packaged in drums and stored onsite or shipped to a licensed burial ground. In the most advanced case study, 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 plasticized product in case the drum should fail and solidified waste should be exposed to water.^{4,5} The case studies do not address the cost of final disposal such as shipping and burial of the wastes or of decommissioning of the plant since these costs will vary with the location of the plant.

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 30 years. The costs are based on conceptual designs for new model plants, and no attempt is

made to estimate backfitting costs for present plants. The capital cost of the base 1500-metric-ton-per-year UF₆ conversion plant is estimated as \$20 million in 1973 based on an extrapolation from the estimated costs of a proposed plant.² These costs are used in 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 are to be treated by the radioactive waste treatment equipment; that is, 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 plant is located at each of two sites which have environments characteristic of contemporary nuclear fuel reprocessing and fuel fabrication facilities. Site 1 is located on a plain in a rural southeastern coastal area adjacent to a continuously flowing stream that empties into an ocean estuary. Cities with moderate populations are located a short distance from the site. Site 2 is located on a plain in a rural midwestern area adjacent to a continuously flowing stream which empties into a large river. Cities with moderate populations and a large city are located within the survey area. Meteorological data for Sites 1 and 2 are derived from first-order weather stations in the coastal southeastern (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

The AIRDOS⁶ computer code is used to estimate annual population doses (person-rem) and the maximum annual individual doses in an area surrounding the model fuel cycle plants. 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 exposure. In this study, no radioactive materials are released in the liquid effluents.

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

3.8 References

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4.0 SOURCE TERMS FOR RADIOACTIVE RELEASES

4.1 Origin of the Radioactive Wastes in Recycle Uranium Hexafluoride Plants

Periodically, the fuel elements of a nuclear power facility must be removed to prevent loss of reactivity in the reactor due to the accumulation of fission product poisons, to prevent or repair irradiation damage to the fuel elements, and to recover new fuel bred from fertile material. Fuel burnup per cycle ranges from a fraction of a percent to about half of the total amount of fissionable and fertile material. Typically, the fuel is replaced after generating about 25,000 to 35,000 MWd of heat per metric ton of contained fuel. Each year, about 32.4 (from a charge of about 33.5) metric tons of heavy metal in spent fuel per 1000 MW(e), on the average, are discharged from typical large light-water-cooled reactors of 500- to 1200-MW(e) rating [1500 to 3600 MW(t)]. In this study, both PWRs and BWRs are assumed to be discharging fuel with average burnups of 33,000 and 27,500 MWd/ton, respectively, to the reprocessing plant. The capacity of the recycle uranium conversion and UF₆ production facility is 1500 metric tons of uranium annually, corresponding to the fuel from about 50 power reactors. Because of economic considerations, the residual uranium and plutonium in spent fuel are recovered in a fuel reprocessing plant.

The function of the recycle uranium facility is to convert uranyl nitrate solution into UF₆ that can be used as feed for either an enrichment plant or a commercial fuel fabrication plant. The purified uranyl nitrate solution is piped directly from an adjacent reprocessing plant to the UF₆ facility. The total storage time is assumed to be 160 days before reprocessing, which permits short-lived nuclides to decay to valuable or less troublesome products and lessens the amount of heat released by fission product decay. An additional 10 days of storage is assumed after reprocessing, but before UF₆ production, to allow for supplementary decay of ²³⁷U and other isotopes.

Two commercial plants in the United States produce UF₆ – the Allied Chemical Plant at Metropolis, Illinois,¹ and the Kerr-McGee Plant at Sequoyah, Oklahoma.² However, both of these plants operate with natural uranium only and are not designed or licensed to operate with enriched uranium. Allied-General Nuclear Services³ has a UF₆ facility under construction at their reprocessing plant site (Barnwell, South Carolina) that will convert low-enriched uranyl nitrate to UF₆. Nuclear Fuel Services⁴ had applied for a license to construct a similar facility at their West Valley, New York, site (NFS notified the Nuclear Regulatory Commission in September 1976⁵ that it has decided to withdraw from nuclear fuel reprocessing and will no longer pursue their application for amendment to their operating license), and Exxon^{6,7} has applied for a license to construct a reprocessing plant and an adjacent UF₆ conversion plant in eastern Tennessee.

The model UF₆ conversion plant consists of two buildings of standard chemical plant construction. The main process operations are housed in a multistory structure which is approximately 100 ft wide by 150 ft long by 125 ft high above the foundation. The building is designed such that the initial processing steps occur on the top floor of the structure. This arrangement maximizes the use of gravity transfers between processing steps, and thereby minimizes the use of potentially troublesome mechanical conveyors and facilitates the

maintenance of the particulate filters. Each level is separated from adjacent levels by solid floors except for equipment and piping penetrations. Fluorine is produced in a smaller building adjacent to the process building. It is a one-story structure with an area of about 7500 square feet (50 ft wide by 150 ft long by 35 ft high). The following sections describe the processing steps that produce the radioactive waste effluents. The processing techniques are similar to those used by the ERDA facilities at Paducah, Kentucky,⁸ and Portsmouth, Ohio.⁹ The flowsheets for the production of UF₆ from uranyl nitrate are shown in Figs. 4.1 and 4.2, and the amounts of material flowing through the processes are listed in Tables 4.1 and 4.2 for all case studies.

4.1.1 *Feed storage*

Uranyl nitrate solution, containing about 350 g of uranium per liter, is pumped directly to the UF₆ facility from the adjoining reprocessing plant where it has been recovered from spent fuel. The solution is received in an accountability tank where it is measured, sampled, and then transferred to the storage tanks. This storage area represents the first potential source of radioactive discharge since a small intermittent air stream is used to vent the system when the tank is filled or material is transferred.

4.1.2 *Concentration*

The first processing step at the UF₆ plant is the concentration via thermosiphon evaporation^{10,11} of the uranyl nitrate solution to uranyl nitrate hexahydrate (UNH) containing about 1300 g of uranium per liter. This step removes the excess water and some nitric acid. The vapor is condensed, and the resulting water is recycled to the reprocessing plant. The concentrated material has a melting point above 60°C and is held above this temperature to prevent solidification and to provide a uniform liquid feed to the subsequent denitrator.

4.1.3 *Denitration and nitric acid recovery*¹²⁻²⁰

The UNH is calcined to uranium trioxide (UO₃) in a bed of UO₃ fluidized by superheated steam at 300°C to 430°C (570°F to 805°F). A controlled discharge of UO₃ is withdrawn from the bed and fed to the next process step. The decomposition produces a superheated vapor containing steam, nitrogen oxide, nitrogen dioxide, nitric acid, and oxygen. This vapor is vented out of the top of the denitrator to a condenser where the nitrate values are recovered as nitric acid and returned to the reprocessing plant. The UO₃ powder continuously overflows into a centrally located disposal tube where it flows into a feed hopper on the UO₃ pulverizer. The pulverized powder falls to a feed hopper in the reduction area.

4.1.4 UO_3 reduction²¹⁻²⁴

The UO_3 product from the denitration step is reduced with dissociated ammonia to UO_2 powder in a fluidized-bed reduction system. Uranium trioxide powder is collected in a feed hopper which provides surge storage in the process and is transferred from the hopper into the first-stage reduction reactor via a screw feeder. Fluidization is accomplished in the reactor with a reducing atmosphere consisting of a mixture of hydrogen and nitrogen obtained from dissociation of ammonia plus additional nitrogen gas to achieve a thermal balance. The gases and powder flow from the first stage to a similar second-stage reduction reactor where the powder is fluidized by additional dissociated ammonia. The conversion to UO_2 is completed in the second-stage reactor, and the powder is collected in a surge storage hopper. The UO_2 powder is fed from the hopper on demand to the hydrofluorination system.

4.1.5 Hydrofluorination²⁵⁻²⁹

Uranium dioxide from the fluidized-bed reduction units is screw fed into the first of two fluidized-bed hydrofluorinators where it is contacted with the gas from the second hydrofluorinator. Powder and gas flow together from the first hydrofluorinator to an interstage hopper-filter unit. The partially reacted solids are then fed by means of a screw conveyor to the second fluidizer-bed hydrofluorinator where they are reacted with anhydrous HF. The gas feed to the second hydrofluorinator is generated by vaporizing liquid anhydrous HF in a steam-heated vessel. The vapor flows successively through a steam-heated superheater, which increases the temperature from 55°C to 175°C (130°F to 350°F), and two electrically heated exchangers, which raise the temperature to 425°C (800°F). The UF_4 product is screw fed to a mill-blender system for further size reduction and then directed to the fluorination area.

4.1.6 Fluorine generation³⁰⁻³⁴

Fluorine is produced onsite in electrolytic cells similar to units that are used to generate fluorine gas throughout the chemical industry. Gaseous HF is fed to the electrolytic cells containing fused potassium bifluoride from a central vaporizing station. The delivery rate at each cell is controlled separately by electrolyte-level sensing devices. A direct current passing through the electrolyte evolves fluorine at the anodes and hydrogen at the cathodes. The fluorine gas is directed to a porous metal filter to remove trace quantities of airborne electrolyte material, to a surge tank, and then to the fluorination reactors where it is used to convert UF_4 to UF_6 . The hydrogen generated in the cells is oxidized to form water vapor, then passed through a high-energy venturi scrubber and a packed tower to remove any fluorides prior to its release to the atmosphere. Periodic cell maintenance and cell recharging are performed on a routine basis. Fumes from the cell maintenance area are collected through hoods and subsequently released to the environment. The sludge is collected, neutralized, and buried onsite. The process sequence is shown schematically in Fig. 4.3; the amounts of material flowing through the process are listed in Table 4.3.

4.1.7 Fluorination³⁵⁻⁴¹

Two techniques have been considered commercially for the preparation of UF_6 from UF_4 . One of these utilizes a fluidized-bed fluorinator containing fused CaF_2 as the bed material. (Allied-General Nuclear Services will use such a system.³) The other technique incorporates a flame tower reactor that is similar to units used at government-owned gaseous diffusion plants. Although both systems will be discussed, the fluidized-bed fluorinator has been selected as the reference method in this study because it presents greater problems in controlling the environmental impact.

The initial bed material in the reference method is fused CaF_2 in the -40 +200-mesh size range. The UF_4 feed solids are charged by means of a screw conveyor through the side of the reactor wall at a point slightly above the surface of the bed. Fluorine enters the reactor through a conical inlet section equipped with a ball check valve to prevent backflow of solids. A small amount of CaF_2 is added continuously with the UF_4 feed to replace ejected material and also to help purge fluorination residues. The effluent gas is removed from the reactor through a large conical settling chamber to minimize powder entrainment to the UF_6 recovery system. The process off-gases contain UF_6 , excess F_2 , HF, nitrogen, and particulates. The gases are filtered through sintered porous metal filters and directed to a refrigerated cold trap system where the bulk of the UF_6 is condensed in a primary cold trap. The secondary and tertiary traps operate at lower temperatures and remove additional UF_6 . The product is removed intermittently from the cold traps by melting and is transferred as a liquid into approved UF_6 cylinders through surge tanks.

In the flame tower reactor system, UF_4 is fed into the tower through a high-speed mixing unit which provides a finely divided powder as feed. From the dispenser, the powder falls by gravity into the top of the tower where it is mixed with preheated ($\sim 320^\circ C$) fluorine. The UF_4 fluorine reaction is highly exothermic, producing a flame temperature in excess of $1100^\circ C$ ($2000^\circ F$). A small percentage (1 to 2%) of the UF_4 passes through the reaction zone and is collected at the base of the tower in a small container or ash receiver. Periodically, the ash material is either recycled to the reactor or sent to a scrap recovery system. Vent gases remaining after cold trapping of product UF_6 are processed through a cleanup reactor containing an excess of UF_4 powder to ensure maximum consumption of the excess fluorine gas. The remainder of the system is as described above.

Exxon plans to produce UF_6 by the direct fluorination of UO_3 in a fluidized bed of UO_3 and alumina.⁷ The UF_6 product will be collected in conventional UF_6 cold traps and purified by trapping fission product fluorides and transuranic fluorides on selective absorbent beds and distilling the product in a fractionating column.

4.1.8 Scrap recovery

Most of the uranium feed material will be converted into UF_6 during the first pass through the plant; but small quantities of uranium will be sent to a uranium recovery step prior to returning it to the process (Fig. 4.4). The scrap is dissolved in nitric acid, filtered to remove any insoluble impurities, and transferred to the precipitation system where uranium

tetroxide is precipitated by adding ammonia (pH increased to 3.0) and hydrogen peroxide. In this system, the principal objective is to recover the uranium rather than achieve a high degree of separation from impurities since few impurities are present in the scrap. Consequently, the reaction is performed at a relatively high pH where precipitation is more complete for the uranium. The uranium tetroxide is separated from the mother liquor in centrifuges and clarifiers. The precipitate is calcined and returned to the reduction feed process step. The quantities of materials flowing through the process are listed in Table 4.4.

4.1.9 *Scrubber systems*

Scrubber systems are an integral part of a UF_6 production facility and are used to remove both chemical and radioactive material from the process off-gas stream. The resulting liquids, containing uranium and uranium daughter products, are transferred to a recovery system to regenerate potassium hydroxide, which is then recycled to the scrubber system.

4.1.10 *Miscellaneous liquid wastes*

Miscellaneous liquid wastes are generated by the laundering of clothing, personnel showers, floor drains, laboratory drains, etc. Since all processing operations are carried out in reactor vessels, this liquid waste is normally free of radioactive contamination. The potential for contamination exists, however; thus a miscellaneous liquid waste treatment system exists to monitor and treat this waste (Fig. 4.5). When radioactivity is detected in this stream, the liquid is piped to a holding basin and then transferred to a reverse osmosis unit and the permeate is sent to an evaporator where the water is removed and discharged through a stack and the bottoms are stored in drums for disposal.

4.1.11 *Miscellaneous solid wastes*

Miscellaneous solid wastes, including gloves, cleaning materials, filters, etc., are separated into combustible and noncombustible materials. An incinerator is used to reduce combustible wastes to a residue which is packaged into drums for disposal. 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 radioactive waste treatment system for packaging. Fluorides collected in the scrubber solution are converted to insoluble CaF_2 , separated from the scrubber solution, and placed in drums for disposal.

4.1.12 *Process airborne effluent*

The processing units in the UF_6 production and waste treatment systems are connected to the process airborne effluent treatment system. These combined effluents contain 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, and from ventilation of laboratory hoods and other special areas by resuspension of settled particles. These airborne effluents are combined and discharged through a separate 50-m stack. The process gaseous flow rate is ~ 368 std m^3/min (scmm) ($\sim 13,000$ scfm).

4.1.13 *Ventilation airborne effluent*

The air from the operating areas contains small amounts of radioactive particulates of uranium, transuranics, and fission products. The suspension of these particles occurs during such operations as loading material into a process reactor or transferring material from one process to another, or may result from the leakage and drying of process solutions from pipes or packing glands. Current designs for UF_6 production facilities use high ventilation and process air flow rates; hence the ventilation flow rate of the model UF_6 facility is 5300 scmm (186,000 scfm), which is exhausted through a separate 30-m stack. A separate ventilation stack (40 m) discharges air from the fluorination and decontamination areas (425 scmm or 15,000 scfm). The quantities of materials flowing through the ventilation system are listed in Table 4.5; a schematic flowsheet of the system is shown in Fig. 4.6.

4.2 Composition and Amount of Radioactive Material Entering the Model Plant⁴²⁻⁴⁷

The model UF_6 production plant processes 1500 metric tons of uranium per year in the form of a uranyl nitrate solution produced by an adjacent reprocessing plant. This amount of feed represents about 5500 Ci of radioactivity of which approximately 47% is alpha activity. A list of the radionuclides considered in this study is given in Table 4.6, and the criteria for the selection of this list are as follows:

1. The feed to the UF_6 plant is directly related to the material received by the reprocessing plant. The feed to the reprocessing plant is assumed to be a composite product from the two different types of model 1000-MW(e) light-water reactors (60% from pressurized water reactors with an average burnup of 33,000 MWd/MTHM and 40% from boiling water reactors with an average burnup of 27,500 MWd/MTHM). This material has passed through the model reactors, the reprocessing plant, and the

enrichment cascades twice. In an enrichment facility utilizing only natural uranium as feed material, the enriched product contains the three naturally occurring isotopes ^{234}U , ^{235}U , and ^{238}U . When spent fuels are reprocessed and the recycled uranium is returned to the diffusion plants as UF_6 feed, the minor isotopes, ^{232}U , ^{233}U , and ^{236}U , which are formed in reactors during the process of irradiation, are introduced to the enrichment plant. The concentration of these isotopes in the product will depend on the final ^{235}U concentration. The Minor Uranium Isotope Flowsheet Analyzer computer program^{42,45} calculates minor isotope concentrations in product and waste streams of a matched $^{235}\text{U}/^{238}\text{U}$ abundance ratio cascade, given the minor isotope concentrations of all feed and withdrawal streams. The program also calculates the ratio of virgin uranium to recycle uranium required by the cascades. In the second passage through the cascades, the recycled material is diluted by 5.4 parts of virgin uranium to one part of recycled uranium. A cooling period of 160 days occurs before reprocessing.

2. The feed has aged 10 days since passing through the reprocessing plant. This allows sufficient time for the ^{237}U to decay by approximately 64%, or to about one-third of its initial value.
3. Extremely small amounts of fission products and transuranium elements follow the uranium through the reprocessing plant and are associated with the uranium feed. The amounts present in the feed to the UF_6 production facility are based on the calculated average amounts of fission products and transuranic elements in the spent reactor fuel that enters the fuel reprocessing plant and the degree of removal of these materials in the reprocessing operation [i.e., the plant decontamination factor (DF)]. The decontamination factor is defined as the ratio of material in the plant feed to that in the uranium product. The following plant DFs are used in this study: 10^7 for Zr, Nb, Ru, and Rh; 25 for Tc; 10^8 for all other fission products, Am, and Cm; 10^6 for Th and Pu; and 300 for Np.

The relative inhalation hazard for each nuclide is estimated by dividing the curies present in 1 metric ton of feed to the model plant by the Radiation Concentration Guide (Code of Federal Regulations, Title 10, Part 20, Appendix B, Table II, Column I) for that nuclide (Table 4.7). Nuclides whose contribution to the total relative inhalation hazard is $<0.01\%$ 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 0.01% of the total-body dose for individuals in the case studies as the result of bioaccumulation in the environment. Table 4.7 also lists the radionuclides selected as constituents of the source terms, along with their specific activities.

4.3 Description of Waste Treatment Methods

This section contains a general description of waste treatment methods that have been applied to the model UF_6 facility. DFs are given for each of the systems, where appropriate.

4.3.1 Airborne radioactive waste treatment systems

During normal operation of the UF₆ facility, small amounts of radioactive materials are entrained in the process effluent streams. These particles are generated by the drying of entrained droplets of process liquids and by the entrainment of fine droplets in the various 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, and scrubbers. All of these treatment methods are in use or are in the development stage. Each of the case studies represents increasingly efficient treatment systems. The costs for each off-gas treatment system in the advanced case studies have been estimated (see Sect. 6.0). The treatment methods that have been considered for the airborne effluents are described in the following sections.

Dry dust collectors. The recovery of uranium-bearing particulate material from the process off-gas streams is an important part of any waste treatment system. Since the particles have such a diversity of properties, several waste treatment methods have been used.

(a) *Centrifugal separators.*⁴⁸⁻⁴⁹ Centrifugal separators, commonly called cyclones, separate particulate matter from a carrier gas by transforming the velocity of an inlet stream to a descending outer vortex and an ascending inner vortex, both confined within the upper cylinder and lower cone of the cyclone. The rapidly rotating descending vortex holds the heavier dust against the walls of the cyclone by centrifugal force and throws it into the hopper from where it is periodically removed. The ascending inner vortex of cleaned gas, which is fed its entire length by the inner surface of the descending vortex, leaves the cyclone through the vortex finder at the top of the cylinder. Because of its simplicity, reliability, and high efficiency, the cyclone collector has been widely used. A fines educator-type cyclone has been used for the vacuum cleaner and maintenance systems with an assumed overall collection efficiency of 75% (DF = 4).

(b) *Bag filters.*⁵⁰⁻⁵⁵ One of the most versatile collectors for the removal of dry, solid particulate matter from an air or gas stream is the fabric dust collector in which the dust-bearing gas is passed unidirectionally through a fabric filter medium of woven or felted cloth. The medium is usually hung in a vertical position to facilitate the removal of the deposited dust. The mechanisms acting in bag filters are considered to be:

1. *Direct interception:* If the center of a spherical particle follows faithfully the flow line around a fiber, and the flow line 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.
2. *Diffusion:* The bombardment of particles by gas molecules causes them to deviate from the flow lines, thus increasing the chance of capture. Diffusion effects increase with smaller particles and lower velocities.
3. *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.
4. *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.

5. *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.
6. *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 that 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 associated 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 the large size of the filters, the high maintenance requirements due to plugging of the filters by moisture when operating below the dew point, and the cost of bag replacement.

Of the many ways to classify bag filters, the most common is that describing their method of cleaning. Such systems as mechanical shaking, automatic reverse air flow, traveling reverse ring jet, and automatic reverse pulsed jet have found the broadest commercial application. However, the pulsed jet type has proved to be the most reliable in UF₆ plants, exhibiting long life and relatively low maintenance in contrast to the mechanical problems associated with the reverse ring jet method.

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. However, overall process efficiencies are somewhat lower, due to dust losses during initial layer formation.

Two types of bag filters have been selected for this study. A cleaner bag filter is used to remove the coarse material from the two feed preparation steps and has been assigned an efficiency of 75% (DF = 4). A single pulse jet bag filter or the first one in a series is assumed to have an efficiency of 99.9% (DF = 1000). The second pulse jet filter in a series is assumed to have an efficiency of 86% (combined efficiency of 99.986% and an estimated DF for two filters in series of 7000).

(c) *Porous metal filters.*⁵⁶⁻⁵⁸ Porous metal filters have been used extensively in the nuclear industry for removing airborne particulates from gas streams. The filters are made by first producing a uniform powder by a procedure in which a molten stream of alloy is atomized by high-pressure water jets impinging on it. The jets are located on the periphery of a wheel rotating at high speed. A porous metallic sheet is fabricated by spreading the powder out into a thin layer and passing it through a furnace in a strongly reducing atmosphere at a temperature just below the melting point. The points of contact between particles develop into bridges of a diameter about one-fifth to one-third of the particle diameter, thereby bonding the assembly into a sheet of residual porosity approximately equal to the spaces that initially

existed between the metal powder particles. Virtually all the pore openings formed in this manner are interconnected, resulting in a high flow capacity. The efficiency of the filters is very high; for example, a 1/8-in.-thick filter with a mean pore size of 10 μm will remove 98% of 0.7- μm particles ($\text{DF} = 50$).

Porous stainless steel filters are used on the reduction off-gas, and either Monel or nickel porous filters are used on the fluorination off-gas to recover uranium in the model plant. The parallel train of filters contains a primary system which is equipped with automatic blowback devices to return trapped material directly to the process and a secondary system which removes particulates that have bypassed the primary system.

(d) *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- by 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- μm particles and a maximum resistance (when clean) of 1.0 in. H_2O pressure when operated at rated airflow. Tests of filter efficiency are conducted in special facilities which ensure that no significant leakage occurs around the sides of the filter or through other bypasses. 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 size in field operations.⁵⁹

Several tests have been carried out with plutonium aerosols on a small scale in laboratories and on a large scale in 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.⁶⁰ 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, which is about 15 years old, does not represent the latest design practice for HEPA installations.⁶¹⁻⁶² Ettinger et al. have performed laboratory tests using plutonium aerosols in small installations that are tightly sealed and tested periodically for leaks with DOP.⁶³⁻⁶⁵ 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.⁶⁶ 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 tested with DOP.

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.⁶⁴ 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.⁶⁷ 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 99.95% has been assigned a single bank of HEPA filters which are tested periodically in place with DOP and are 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 4.0×10^5 is used in this study.

(e) *HF-resistant HEPA filters.*^{68,69} Experimental filter assemblies have been tested at the Rocky Flats Division of Dow Chemical Company in a stream containing an estimated 40 to 100 μg of HF per liter as well as nitric acid and plutonium and were found to exhibit efficiencies approaching 99.9% with a resistance of about 1.3 in. of H_2O . With additional development, these filters should become available for commercial application. For this study the assumption has been made that a 99.95% efficient HEPA filter which is resistant to a HF concentration of $\sim 1 \mu\text{g}/\text{liter}$ will be achieved.

Gas scrubbing.^{70,71} 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 gaseous, from the gas. The mechanisms involved in a particular process may be some or all of the following:

1. *Impaction:* The collision and absorption of aerosol particles by the liquid droplets.
2. *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 $0.05 \mu\text{m}$.
3. *Condensation:* Vapors at temperatures below their dew points condense readily on nuclei, such as aerosol particles, which may thereby be agglomerated.
4. *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 is that the temperature and the moisture content of the inlet gas are essentially unlimited. Some of the disadvantages 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 the inherent characteristic of all aqueous scrubber stacks discharging to the atmosphere without downstream gas conditioning.

Most conventional scrubbers, when used in the conventional way, have a limited capability for retaining fine particulates.⁷² This is because most conventional scrubbers depend on some form of inertial collection of particulates as their primary mechanism of capture. Because of this, collection efficiency decreases rapidly as particulate size is decreased to the point where inertial forces become insignificantly small. As a result, the energy input into a scrubber must be increased significantly to improve its ability to collect smaller particulates. The energy can be introduced either in the water cycle or the gas cycle. In most commercial collectors, almost 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 for particles in the submicron range are not satisfactory. For example, the orifice- or baffle-type collector is 93% efficient on 5- μm particles, 75% on 2- μm particles, and only 40% on 1- μm particles.⁷³ However, high-energy-demanding scrubbers such as the venturi customarily exhibit efficiencies of 99% on 2- μm particles.

(a) *Spray tower scrubber.*⁷⁴⁻⁷⁶ The spray tower scrubbers are the most elemental of wet scrubbers. They are empty towers utilizing liquid introduced via a bank of spray nozzles at the top. Gases passing countercurrent to the falling drops are scrubbed clean of particulate matter. These towers may also be used as coolers or as primary cleaners. The spray tower is used at the model plant to scrub the UF_6 , HF, and F_2 from the fluorination off-gas stream. In this study, the efficiency of the KOH system is assumed to be 80% for UF_6 removal and 80% for F_2 and HF removal by analogy to UF_6 and HCl.

(b) *Wetted packed tower.*⁷⁶⁻⁷⁹ The packed tower is a vertical vessel in which various fill material is wetted. Surface area provided by the various packings offers a basis for inducing interaction between the liquid and gas phases. The air or gas enters the bottom of the tower and receives a preliminary washing as the scrubbing liquid drains in an opposing flow from the packed, irrigated bed. This liquid, which is pumped into the top of the tower, flows down over the packed bed. Enroute, it covers the surface areas of the packing with a liquid film that accomplishes the major work of collection. Finally, the airstream passes through a mist eliminator section before it is exhausted. In this study, the KOH packed tower is assumed to have an efficiency of 99% for UF_6 removal and an efficiency of 99% for HF and F_2 removal by analogy to UF_6 and HCl. Since the packed tower is primarily used as a gas absorption system, it has been assumed that its effect on particulate removal is negligible.

(c) *Venturi scrubber.*^{76,80-83} The venturi's basic construction and principles of operation are noncomplex in nature. Atomization of the scrubbing liquid takes place in the throat of the venturi. Here, the liquid is introduced at relatively low pressure and is shattered into minute droplets by the onrushing gas flow. For coarse particles, efficient collection may be attained with lower velocities and water rates than those needed for the collection of submicron particles. The basic advantages of a venturi scrubber are: relatively small size, high efficiency, no moving parts, and ease of recirculation of liquids containing solids. In this study, efficiencies for the high-energy KOH venturi scrubber are assumed to be 98% for SO_2 , 99% for HF by analogy to HCl and Cl_2 , and 99% for particulates.

(d) *Coke-packed tower.*⁸⁴ Activated charcoal and coke have been used extensively to remove pollutants from process streams. Recently, Bergbaw-Forschung, the research institute

of the West German coal mining industry, has developed a process for the adsorption of SO_2 and the oxides of nitrogen on activated charcoal.⁸⁵ Gaseous effluent streams at many nuclear power plants contain charcoal adsorber systems to remove radioactive iodine, and studies are now in progress to apply these systems to the removal of the radioactive noble gases.⁸⁶⁻⁸⁹ The Allied Chemical Corporation has developed a scrubber system to remove traces of UF_6 , HF, and F_2 from process effluent streams of their UF_6 plant.³ This proprietary system consists of a specially designed tower packed with "coke" and utilizes a KOH solution as the scrubber medium. Since this system is proprietary and its efficiency for removal of fluoride-bearing impurities has not been published, it has been assigned a relatively low removal efficiency of 90% (i.e., a DF of 10). Proprietary technology is generally avoided in generic studies, but this system is a developed technique and appears to have technical advantages over the known alternative that uses consumable wet mineral wool filters.⁹⁰

Hydrogen burner and flame arrestor. In all case studies, a hydrogen burner and a flame arrestor are used on the reduction off-gas stream to convert all forms of sulfur to SO_2 and hydrogen to water.

4.3.2 *Liquid radioactive waste treatment systems*

The model UF_6 facility generates liquid effluents which contain uranium, transuranics, their daughter products, and fission products. These liquids are produced in the scrap recovery operations and are found in the scrubbers that are used in the airborne radioactive waste treatment systems. The major objectives of the liquid waste treatment systems are: (1) to return the uranium to the process along with a minimum amount of impurities, where economically practical; and (2) to prevent the release of small quantities of uranium and other radionuclides. Various unit process operations are used to treat liquid effluents. The scrap recovery system utilizes a peroxide precipitation to separate the uranium from undesirable impurities and to prevent its release to the environment. Liquids containing radioactivity are evaporated to retain both soluble and insoluble impurities, and the purified condensate is recycled for reuse. Liquids containing radioactivity of process origin are not released to the environs. Miscellaneous liquid wastes are normally free of radioactivity. When radioactivity is detected in this stream, the liquid is transferred to a storage area for subsequent evaporation. The treatment methods that have been considered for the liquid effluents are described in the following sections.

*Holding and settling.*⁹¹ 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. The amount of uranium 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 holdup time of 16 to 20 hr significantly increases the amount of uranium that can be removed by filtration. Where the holding technique is utilized, gravity sedimentation allows the waste to be separated into a solids-rich portion and a relatively clear supernate.

*Filtration and centrifugation.*⁹²⁻⁹⁴ Filtration is used to remove the insoluble uranium from liquid waste streams. The operations are of the type known as clarification, since only a relatively small (100 ppm or less) amount of solids is present in the 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 charges associated with waste treatment (Sect. 6.0).

In those cases where the waste stream is held for 16 to 20 hr 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.

*Evaporation.*⁹⁵⁻⁹⁷ 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.⁹⁸ 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 surface of the boiling liquid. 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, maintenance is less expensive and operation is more satisfactory for simple evaporators equipped with adequate auxiliaries to achieve the required DF. 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 (overhead 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 waste containing detergents or other foam-producing materials must be given a pretreatment before evaporation. Liquid waste evaporators should be tested before being used 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; a value of 10,000 was assumed in this study.

4.3.3 *Solid radioactive waste treatment methods*⁹⁹⁻¹⁰¹

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 onsite or shipment to a licensed commercial burial ground. The wastes include aqueous residues, sludge from evaporative processes, incinerator ash, and nonburnable items that are slightly contaminated with radioactive materials. In Cases 1-5a, the solid waste residues from the scrap recovery operation, along with other miscellaneous wastes, are packaged in drums for storage onsite or shipment to a licensed commercial burial ground. In Case 5b, the solid wastes and the concentrated bottoms from the evaporation of radioactive liquids 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 UF₆ plants.¹⁰² Part of the waste may be shipped for storage in Federal repositories, if the proposed new Federal regulations¹⁰³ are adopted, since the material (filter fines and spent bed material) is slightly contaminated with plutonium.

4.4 Selection of Case Studies

Five conceptual case studies, each chosen to reflect a decreasing release of radioactivity for an increasing sophistication of radioactive waste treatment, were selected for the recycle uranium conversion and UF₆ plant. Inclusion of specific treatment techniques was not based on cost, but on the effectiveness in reducing the radioactivity of plant effluents. All of the treatment methods included have been utilized in either pilot-plant or industrial scale operations, although no existing recycle 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 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 is the "base case" for the model plant and represents a facility which could be operated under present licensing regulations. Additional treatment systems are added in each succeeding case study. The principal objective of each treatment system is to decrease the quantity of radioactivity released to the environment, although noxious chemical releases have also been reduced in some instances. The cases studied, along with the treatment systems, are summarized in Table 4.8.

4.5 Description of Case Studies and Calculation of Source Terms

The treatment methods used in the individual case studies are discussed in the following sections. 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 in Table 4.9. The parameters used in calculating the source terms are presented in Sect. 4.5.12. The amounts of nonradioactive noxious materials (nitrate, fluoride, etc) are listed in the material balance tables (Tables 4.1-4.4).

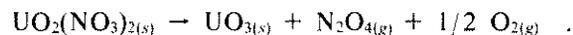
4.5.1 Feed storage and concentration

An adjoining fuel reprocessing plant furnishes the feed to the UF₆ facility via direct pipeline to an accountability tank and then to a storage and feed tank. Only small quantities of water and nitric acid are found in the purge streams emanating from these areas. These air streams are released directly to the environment in all case studies.

Concentration of the uranyl nitrate solution is performed in a thermosiphon evaporator where the uranium is concentrated by a factor of 4. The off-gas vapors report to a condenser for removal of water, which is returned to the reprocessing plant for reuse. No treatment systems are required for the sparge air streams from the condensate storage tanks for any of the case studies.

4.5.2 Denitration and nitric acid recovery

The denitration process is based on the thermal decomposition of uranyl nitrate hexahydrate to uranium trioxide by the following series of reactions:



The product of the dehydration and denitration reaction is usually a tetragonal type of UO₃. This form is the most stable of the UO₃ structures at the elevated temperatures employed for denitration. These temperatures generally lie between 300°C and 400°C, a range chosen for two principal reasons. Below 300°C, rapid and efficient denitration is difficult to achieve. Moreover, hydrated types of UO₂ can form at low temperatures. Above 430°C, UO₃ begins to dissociate into O₂ and U₃O₈.

Of the three methods generally used for the thermal denitration of UNH (viz., batch, stirred bed, and fluidized bed), the fluidized-bed technique was selected as the reference method. Superheated steam is used as the fluidizing medium, and the UNH, atomized by air, is sprayed into the fluidized bed. Uranyl nitrate is converted to UO₃ particles which overflow to a collection vessel. The waste off-gas treatment system consists of a standard condenser and a condensate storage system.

4.5.3 Feed preparation for UO_3 reduction

The preparation of the UO_3 feed material for the reduction step is very important in obtaining a high-quality UO_2 product for hydrofluorination. The process variables that must be carefully controlled are temperature, particle size, rate of dehydration, sulfate content, and stoichiometry.

The rate of reduction increases with an increase in temperature, but an excessively high temperature can produce a refractory UO_2 product. The particle size of the UO_3 influences both the particle size of the UO_2 product and the rate of reduction. In general, the particle size of the UO_2 resembles that of the parent UO_3 and a high interfacial area produces the most rapid reduction. A more reactive oxide is produced if the thermal denitration is performed such that hydrated oxides are formed first by low-temperature denitration followed by complete dehydration at a somewhat higher temperature. The addition of sulfate (2000 to 3500 ppm) before denitration improves the reactivity of the UO_3 product. Although the mechanism is not clearly understood, the sulfate ion apparently increases lattice strains in the UO_3 and, in turn, increases its surface area. During its production or during subsequent handling, UO_2 can become oxidized. Thus, at elevated temperatures under a partial pressure of oxygen, the UO_3 content of the UO_2 increases. The presence of UO_3 is not desirable because of the adverse effects in the subsequent fluorination step: (1) a higher consumption of fluorine, (2) the evolution of more heat, and (3) the possibility that some of the UO_3 may not be completely fluorinated because of the relatively slow fluorination rate of UO_3 .

Feed preparation off-gas treatment, Case 1. The preparation of the feed for the reduction of UO_3 involves the typical mechanical operations for producing particles of a uniform size (i.e., milling, mixing, and screening). Large amounts of small particles are dispersed into the process off-gas during these operations. An efficient filtration system utilizing a cleaner bag filter and a pulse jet bag filter in series is used to remove 99.975% (DF = 4000) of these particles. The pulse jet bag filter is also used in conjunction with a centrifugal separator (same rated overall efficiency) to remove dry waste material discharged by the vacuum cleaner and maintenance system.

The gaseous effluent from the Case 1 off-gas treatment system consists of 1.17×10^5 standard liters per minute (slm) of N_2 (4140 scfm), 3.15×10^4 slm of O_2 (1110 scfm), 18 slm of water vapor (0.7 scfm), and small amounts of uranium as particulate material. The water released amounts to 21.4 kg (47.2 lb) per day, and the uranium released totals approximately 97 g per day, which represents a major fraction of the total uranium released from the facility.

Feed preparation off-gas treatment, Case 2. The objective in this case study is to reduce the quantity of particulates in the off-gas stream by additional treatment methods. A second pulse jet bag filter is added, which removes an additional 86% of the uranium dust to produce an overall removal efficiency of 99.9965% (DF = 28,570). The uranium content of the off-gas stream is reduced by a factor of 7 to 13.6 g/day.

Feed preparation off-gas treatment, Cases 3-5. A HEPA filter bank is added as a final treatment system to reduce the uranium content of this process stream to trace amounts. The overall process containment is now greater than 5×10^7 , and the amount of uranium released has been reduced to less than 7 mg per day.

4.5.4 UO_3 reduction

Uranium dioxide is prepared by the reduction of UO_3 with hydrogen, utilizing the fluidized-bed reactor technique developed at Oak Ridge by the Union Carbide Corporation Nuclear Division.^{26,28} The reaction is represented by the equation



The reference method employs two consecutive beds (or stages), although some single-stage units are used in the industry. The reduction gases are produced by dissociating ammonia at 900°C (1650°F); usually excess nitrogen is added to secure sufficient gas velocities of about 1 fps for satisfactory fluidization. Twice the stoichiometric amount of H_2 (100% excess) is used. Heat is applied to the reactor at the beginning of a cycle to increase its temperature from ambient to a value in the range of 540°C to 620°C (1000°F to 1150°F). Once the reaction has been initiated, heat must be removed from the system because of the exothermic nature of the reduction. Careful control of the temperature is essential for the production of an easily fluorinated product.

Reduction off-gas treatment, Cases 1-3. The most troublesome materials found in this waste stream include H_2S , H_2 , and uranium dust. Uranium is removed by passing the off-gas through two porous metal filters in series, which reduces the uranium content by a factor of 10^5 . Hydrogen and H_2S are oxidized by burning in 50% excess air. A flame arrestor is located in front of the burner in the process gas stream to prevent flashback. The effluent released to the environment consists of 1070 slm of N_2 (38 scfm), 96 slm of O_2 (3.4 scfm), 725 slm of H_2O (26 scfm), 7.3 slm of SO_2 (0.3 scfm), and 5 g of uranium per day.

Reduction off-gas treatment, Cases 4-5. A high-energy venturi scrubber utilizing a KOH recirculating system operating between 10 and 2% KOH is added to the process waste treatment system to remove 98% of the SO_2 and 99% of the remaining uranium. The scrubber is operated at 70°C (158°F) to prevent dilution of the scrubber liquid by water formed during combustion and to achieve an acceptable reaction rate between the caustic solution and the gaseous effluents. Approximately 600 g of SO_2 and 50 mg of uranium per day are released to the environment.

Reduction scrub liquor, Cases 4-5. About 1100 liters (300 gal) of spent KOH scrub liquor containing ~5 g of uranium is regenerated daily by treating it with lime to precipitate $CaSO_4 \cdot 1/2H_2O$ (Fig. 4.4). The mixture is centrifuged to produce a clean KOH stream suitable for recycle and a waste sludge that is sent to a spray evaporator for removal of water, which is exhausted as vapor through the process stack.

4.5.5 Hydrofluorination of UO_2 to UF_4

Uranium tetrafluoride is prepared by the reaction of HF with UO_2 at temperatures of 350°C to 600°C (625°F to 1100°F) according to the equation



Reaction conditions must be carefully controlled because of (1) the highly exothermic nature of the reaction (43.2 kcal/mole), (2) the reversible characteristics of the reaction, and (3) the variations that may occur in the preparation of the UO_2 feed. A temperature that is too low will reduce the reaction rate and may lead to HF-water condensation and resultant corrosion problems. An excessively high temperature may produce a sintered UF_4 coating on the UO_2 particles, with an accompanying reduction in reaction rate. Both the history of the starting UO_3 and its reduction (Sect. 4.5.4) have a marked effect on the hydrofluorination rate. The difference in volume between the reactants and the products can create problems in controlling gas flow in fluidized beds.

The model plant uses a fluidized-bed reactor, which is the preferred technique in the United States. The anhydrous HF flow (present in 10% excess over stoichiometric) is supplemented with nitrogen (2830 slm or 100 scfm) to improve the fluidizing characteristics of the bed. Two fluidized beds in series are used, with the first stage performing the function of a cleanup reactor for HF and the second stage for UO_2 . Approximately 70% of the conversion occurs in the primary hydrofluorinator. To prevent sintering at localized hot spots, external cooling is required in this reactor where most of the heat is liberated. Depending on the process system, heating or cooling may be needed for the secondary hydrofluorinator. Conversion efficiencies approaching 100% are quite common in the hydrofluorination process.

Hydrofluorination off-gas treatment, Cases 1-3. Particulates are removed from the process off-gas stream by two porous metal filters in series which have a combined trapping efficiency of 99.999% ($\text{DF} = 10^5$). These filters are provided with a timed cycled blowback which returns the collected dust to the hydrofluorinator. The process off-gases are then treated for removal of HF by passage through a packed tower which utilizes a KOH recirculating system operating between 10 and 2% KOH. A HF removal efficiency of 99% and a zero efficiency for particulate removal are assumed in this study.

The gaseous effluent released to the atmosphere consists of 2830 slm of N_2 (100 scfm), 1.3 slm of HF (0.05 scfm), and 700 slm of water vapor (25 scfm). The quantities of HF and uranium released are 1.7 kg/day (3.7 lb) and 0.60 g/day, respectively.

Hydrofluorination scrub liquors, Cases 1-3. Approximately 5400 liters (1440 gal) of untreated scrub liquors per day containing 158 kg (348 lb) of fluoride, 406 kg (895 lb) of potassium, and negligible quantities of uranium are recycled to the KOH regeneration system. Fluoride is removed by a lime treatment, the KOH solution is separated by centrifugation, and the remaining moist solid is transported to a spray dryer for complete removal of water; the resulting solids are drummed for disposal. The water vapor from the dryer is discharged from the process stack.

Hydrofluorination off-gas treatment, Cases 4-5. Further treatment is included to reduce the HF and uranium concentrations of this stream by a factor of 100 by adding a high-energy venturi scrubber utilizing a recirculating KOH solution. The uranium content of this off-gas stream after treatment is 6 mg/day, while the content of HF is 17 g/day. The gaseous flow rates are the same as in the previous case studies.

Hydrofluorination scrub liquors, Cases 4-5. Liquid flow rates are about the same as in the preceding cases. A slightly larger amount of fluoride (168 kg or 370 lb/day) and approximately 0.6 g of uranium are found in the untreated scrub liquors. The uranium is removed in a separate step, and the fluoride is precipitated as CaF_2 and stored in 55-gal drums for ultimate disposal. Water is discharged as vapor from the process stack.

4.5.6 Feed preparation for UF₄ fluorination

A feed preparation step is required to obtain the optimum use of fluorine in the fluorination of UF₄. The most critical part of this operation is to produce a uniform feed that will mix easily with the bed material and will fluorinate at a constant rate. A mill and blender system is used to prepare such a mixture.

Feed preparation off-gas treatment, Case 1. Considerable quantities of airborne particulates are generated and enter the process off-gas treatment system. A cleaner bag filter and a pulse jet bag filter in series are used to remove the particulates from the process off-gas. A pulse jet bag filter is also used in conjunction with a centrifugal separator to recover the dust collected by a vacuum cleaner and maintenance system. The dust removal efficiency for both systems is 99.975%.

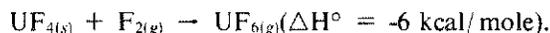
The gaseous effluent released to the environment from this system is composed of 40,000 slm of N₂ (1400 scfm), 10,700 slm of O₂ (380 scfm), and small amounts of uranium dust. The uranium content discharged to the environs (15.6 g/day) is approximately 10% of the total that is released from the plant.

Feed preparation off-gas treatment, Cases 2-3. An additional pulse jet bag filter with an estimated efficiency of 86% has been added to the treatment system. The DF of the filter train is estimated to be greater than 28,000. The uranium content in the off-gas stream discharged to the environment is about 2 g/day, which is equivalent to a sevenfold reduction when compared with the previous case study. The gas flow rates are unaltered.

Feed preparation off-gas treatment, Cases 4-5. An HF-resistant HEPA filtration system is incorporated into the process off-gas stream to increase the DF by a factor of 2000 for particulates. The uranium released to the atmosphere from the feed preparation steps has been reduced to approximately 1 mg/day.

4.5.7 Fluorination of UF₄ to UF₆

The model plant uses a fluidized-bed fluorinator as the reference method with CaF₂ as a diluent to control the highly exothermic reaction



Excellent conversion of UF₄ to UF₆ can be obtained when operating in the temperature range of 425°C to 565°C (800°F to 1050°F). The reaction rate is extremely fast under these conditions and increases rapidly with temperature. Such conditions can place a heavy load on the reactor. Hence, CaF₂ is used in the bed as a heat exchange medium and to dilute the UF₄. Air drawn from the room is used for cooling and functions as part of the building ventilation. The fluorides of most of the radioactive impurities in the UF₄ are nonvolatile and remain with the bed material or are ejected with the fines to the process off-gas stream.

Fluorination off-gas treatment, Cases 1-2. The vapors from the fluorinator contain UF₆ product, HF, excess F₂, nitrogen, and particulate material (CaF₂ fines, unreacted UF₄, and impurities). The solid material is removed by two porous metal filters in series, and the UF₆

product is removed in the cold trap system. The residual gases are discharged to a KOH scrubbing system consisting of a spray tower, absorber, and a packed tower in series to remove uranium and noxious gases. The spray tower is assumed to be 80% efficient, and the packed tower 99% efficient, for the removal of UF_6 , F_2 , and HF.

After passage through the cold traps, the fluorinator off-gases contain, by volume, 0.08% UF_6 , 6% F_2 , 16% HF, and other gases (nitrogen used to fluidize the bed, seal leakage, and oxygen from the fluorination of oxide or oxyfluoride impurities in the UF_4). The total fluoride load is 99.6 kg/day (220 lb); the uranium load is 3.3 kg/day (7.3 lb).

The gaseous effluent released to the atmosphere from the waste treatment system carries 0.2 kg (0.4 lb) of fluoride and 6.6 g of uranium per day.

Fluorination scrub liquors, Cases 1-2. About 3270 liters per day (860 gal) of spent KOH solution containing 242 kg of potassium (530 lb), 94 kg of fluoride (210 lb), and 3.3 kg of uranium (7.3 lb) are regenerated and recycled to the process by precipitating the fluoride with lime. Uranium is present as a diuranate and is removed before the lime treatment.

Fluorination off-gas treatment, Case 3. The gaseous HF release is reduced to 20 g/day and the uranium to 0.7 g/day by adding a KOH coke box which is assumed to be 90% efficient for the removal of F_2 , HF, and UF_6 . The other gaseous and liquid flow rates are the same as in the previous case studies.

Fluorination off-gas treatment, Cases 4-5. A 99.95% efficient HF-resistant HEPA filter is added as a final step to remove small particulates. The uranium content of the process off-gas stream is reduced to less than 0.4 mg/day. Flow rates for all other effluents (both gaseous and liquid) are the same as in Case 3.

4.5.8 Fluorine generation and waste treatment

Fluorine is produced by the electrolysis of HF in an anhydrous electrolyte of $KF \cdot 2HF$. Passage of a direct current through the melt liberates fluorine at the anodes and hydrogen at the cathodes. Anhydrous HF is supplied to the process on demand. A typical cell is of 6000-A capacity containing 3000 lb of electrolyte in a Monel vessel. The anodes are made of carbon and the cathodes of steel. Large quantities of heat are removed from the cells by cooling coils containing circulating water. The cells operate under corrosive conditions and must be rebuilt periodically. The life of each cell is approximately 40 million A-hr, and 20% of the charge in each cell is discharged as waste. From the 16 cells at the facility (14 operating continuously, 1 on standby, and 1 being recharged), the model plant discharges an estimated 4 metric tons of nonradioactive cell sludge per year. This material is neutralized with a lime slurry, centrifuged, and transferred to a spray dryer for the removal of water. The solids are stored in drums for disposal.

The gaseous treatment system is designed to reduce the fluoride release rate and to eliminate the possibility of a hydrogen explosion. The hydrogen stream from the cells is passed through the following treatment systems: (1) porous metal filters to remove particulates, (2) a flame arrestor to eliminate the possibility of flame propagation from the burner, (3) a burner to oxidize hydrogen to water vapor, and (4) a high-energy venturi scrubber and a packed tower in series to remove HF. The scrub liquors are treated with lime to precipitate CaF_2 and to

regenerate KOH. The ventilation air contains such low concentrations of HF and F₂ (originating from occasional small leaks and general maintenance procedures) that it is released from the stack without scrubbing. The cell maintenance ventilation air contains HF only during cell dismantling, which occurs on the average of 30 min every 3 days. Because of its sporadic nature and low HF content, this stream is released via a stack without scrubbing. The flowsheet for the treatment system and the material flows are presented in Fig. 4.3 and Table 4.3, respectively. The same treatment is used for all case studies.

4.5.9 Scrap recovery

Uranium powders collected from off-gas filters and much of the residues from fluorination reactors are returned directly to the process by placement into the powder vessels preceding the appropriate process step; however, uranium-bearing residues that contain materials undesirable in the main process are treated for uranium recovery. These wastes consist of uranium-bearing floor cleanups, potassium diuranate separated from the scrubber solutions, and other uranium containing solids. The uranium is dissolved in nitric acid, and any remaining insoluble material is removed by filtration. The metal is precipitated as the tetroxide by the addition of ammonia and hydrogen peroxide. The precipitate is removed from the mother liquor by centrifugation and clarification and subsequently calcined and returned to the process.

Scrap recovery off-gas treatment, Cases 1-3. The off-gas treatment system consists of spray dryers, evaporators, and a bank of HEPA filters. The spray dryers and evaporators generate large amounts of water vapor, and the uranium dissolver produces significant quantities of nitrogen oxides. The amount of uranium released from the scrap recovery and ash handling system is 1.2 g/day, with the majority of it originating from the ash handling system.

Scrap recovery off-gas treatment, Cases 4-5. An additional HEPA filter system with an estimated efficiency of 99.5% is added to the process off-gas treatment system. A DF of 4×10^5 is assumed as the efficiency of the filter train for particulates. The uranium released to the atmosphere has been reduced to 6 mg/day.

4.5.10 Ventilation system

The process building is serviced by a building ventilation system that consists of a pressurized supply and an exhaust through two elevated stacks. Ventilation is provided on a once-through basis with appropriate winter heating. The air change rates for the process areas are greater than those normally used in the chemical industry in order to ensure control of noxious fumes and to provide comfortable working conditions. The contributors to each of the two stacks are given in Fig. 4.6, flow rates are presented in Table 4.5, and descriptions are given below.

The exhaust stack carries the ventilation air from the fluorination section and the decontamination areas of the building. Both of these areas are separately partitioned from the rest of the processing area and are separately ventilated. In Cases 1-3, the discharged air is filtered by two banks of HEPA filters in series. Four grams of uranium is released daily in a

gas flow of 4.25×10^5 slm (15,000 scfm). A pulse jet bag filter is incorporated in Cases 4 and 5 to reduce the uranium release rate to 40 mg/day.

The second stack, which is comprised of four separate systems, carries ventilation air from the remaining parts of the building. The main process area is adequately ventilated using a system of supply and return ducts. Since the flow rate is large for this stream (3.40×10^6 slm or 1.20×10^5 scfm), no filtration units are provided in the early case studies (Cases 1-4). The uranium release rate of 30 g/day is reduced by a factor of 1000 in Case 5 by the addition of a pulse jet bag filter. The process support ventilation air (waste treatment, chemical scrubbing) is drawn in through the sides of the building and discharged without treatment. The cylinder filling section is compartmented from the other areas and has a separate supply and exhaust air system. The ventilation for this section is separate to permit shutdown in the event of a UF_6 release during transfer operations. The cold trap section is also compartmented with a separate ventilation system to permit shutdown in the event of a UF_6 release.

The fluorine generation and cell maintenance area is supplied with a ventilation system that is separate and independent from other areas. The nominal working area pressure is slightly negative. The ventilation air is distributed into the area along the floor and is extracted along the roof. Nuclear materials are not permitted in the fluorine generation area, and no process gases are released to the area ventilation system under normal operation.

4.5.11 *Solid waste treatment*

The wet and solid waste processing operations are shown in Fig. 4.4. 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. In Case 5b the liquid waste residues and solid wastes containing radioactivity are incorporated in cement. The cemented wastes are drummed and either stored onsite or transferred to a licensed burial ground. A mixture of 15% solids, 45% cement, and 40% water is generally satisfactory. Cementing of slightly soluble wastes is beneficial in reducing the potential long-term leaching of radioactive materials during storage. However, this extra cost over that of Case 5a does not reduce the amount of radioactive materials released from the plant.

4.5.12 *Calculation of source terms*

The radionuclide concentrations in the effluent streams are multiplied by the average specific activity values from Table 4.7 to calculate the source terms. 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. The source terms for the airborne effluents are listed in Table 4.9.

The design of the Case I model plant is based on contemporary designs for recycle UF_6 plants, and the generation rate for radioactive particulates in processing areas is derived from that observed in two plants which produce UF_6 from natural uranium. The estimated concentrations of alpha and beta-gamma radioactive materials in the airborne effluent from the model plant are 3.12×10^{-11} and 3.57×10^{-11} $\mu Ci/ml$, respectively. The releases from the

model plant stacks are diluted by a factor of at least 10^6 before reaching the boundary of the plant site at a distance of 1.5 miles. Thus, the model plant for Case I is well within the Federal guidelines listed for the release of radioactive materials (Code of Federal Regulations, Title 10, Part 20, Appendix B, Table II, Column 1) to unrestricted areas.

4.6 References

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5.0 NONRADIOACTIVE RELEASES

Various nonradioactive chemical compounds are released to the environment from both the recycle UF_6 facility and the fluorine production building. The chemicals that present the greatest health hazard include sulfur oxides, fluorides, and nitrogen oxides. Other off-gas constituents such as steam, nitrogen, and carbon dioxide are innocuous. The origin and treatment of these materials are discussed in Sect. 4.0 and will be summarized in the following sections.

5.1 Airborne Effluents

The most significant airborne chemical effluents released from the stacks of the two facilities are fluorine as fluoride, sulfur as sulfur oxides, and nitrogen as nitrogen oxides. Fluoride is released from the hydrofluorination process, the fluorine production process, and the fluorine facility ventilation system. Treatment of the effluent streams by scrubbing and demisting reduces the average fluoride concentration to approximately 2.5 ppm in the air released from the stacks. Sulfur is added to the feed material as sulfate to improve the reactivity of the UO_3 . The concentration of SO_x in the air released to the environment is approximately 1.5 ppm. The nitrogen oxides are produced in the various combustion operations and in the denitration process and amount to about 4 ppm in the discharged air.

As a point of reference for the chemical contaminants, the American National Standards Institute^{1,2} has recommended acceptable upper concentrations of 5 ppm¹ for NO_2 and 3 ppm² for HF for repeated daily 8-hr exposure. The releases at the stack meet these criteria.

5.2 Liquid Effluents

The design and operation of the recycle UF_6 facility are such that no release of process chemicals to the environment occurs, other than the small amounts in the gaseous effluent. Condenser condensates and recovered nitric acid are returned to the reprocessing plant for reuse. Chemicals employed in the processing operations are either consumed by the process or collected in a solid waste form. About 35 gpm of potable water is used for sanitary purposes such as drinking fountains, showers, sinks, laboratory, and sanitary facilities.³ The effluent is discharged to the sewage treatment facility. All process water is treated for recycle of useful species, and the spent liquid and waste solid are spray dried for disposal.

5.3 Thermal Releases³

Heat is released from the UF_6 facility by: (1) building ventilation exhausts, (2) process exhausts, (3) evaporated water from cooling towers, (4) water effluents, and (5) boiler effluents. The plant, when operating at design capacity, generates about 7.1×10^9 Btu/hr. Of the total energy released, approximately 30% originates from the fluorine building, 50% from the utility equipment, and 20% from the process condensers. About 80% of the cooling water (flow rate

of 940 gpm) is used in the refrigeration compressors for the cold traps, the air compressors, and the fluorine plant. Since these areas are free of radioactive material, there is no possibility of radioactivity contaminating the cooling water in these areas. The remaining 20% is utilized in the condensers for uranyl nitrate concentration and denitration. The high pressure in the cooling water system should protect it from radioactive contamination if a leak should develop in one of the condensers. No chemicals are added to the cooling water system.

5.4 References

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6.0 COSTS FOR RADWASTE TREATMENT

Costs for the gaseous radioactive waste treatment cases and incorporation of the filter fines and liquid residue wastes in cement (Case 5b) for the model 1500-metric ton/year recycle UF_6 plant are estimated as additions to the base plant. The capital costs, annual fixed charges, annual operating costs, total annual costs, unit conversion costs, and power costs for the cases are summarized in Table 6.1. The cost of converting the uranium nitrate product from the reprocessing plant to UF_6 for shipping to the enrichment plant is considered as an additional reprocessing cost.

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 presented 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 radioactive waste treatment case. The annual operating (and maintenance) expense is calculated as follows: for conventional chemical equipment, such as towers, tankage, pumps, etc., it is estimated at 40% of the annual fixed charge; for gaseous radioactive waste treatment equipment, such as bag filters and venturi scrubbers, it is calculated based on published information;²⁻⁵ and for HEPA filters, it is based on experience at ORNL.⁶⁻⁸ This cost is then divided by the annual amount of uranium processed, or by the annual amount of electricity that was produced by the processed fuel, to obtain the cost of radioactive waste treatment per unit weight of fuel converted to UF_6 or the contribution to the cost of power for each case. A recycle UF_6 plant with a nominal production rate of 1500 metric tons/year can service about 50 reactors. It is assumed that the 50 reactors are comprised of 32 PWRs and 18 BWRs, based on a burnup of 33,000 MWd/metric ton, an 80% load factor, and a 32.5% thermal efficiency for the PWRs, and a burnup of 27,500 MWd/metric ton, an 80% load factor, and a 35% thermal efficiency for the BWRs. Costs are estimated in terms of 1973 dollars to make this report consistent with other reports in this series.^{4,9-13} No attempt is made to include the effect of inflation; however, based on the Marshall and Swift (M and S) Equipment Cost Index¹⁴ for chemical equipment, the 1976 costs will be about 36% higher than the 1973 costs. The cost estimates are expected to have an accuracy of about $\pm 30\%$. The details of the cost estimates are provided in Appendix A.

6.1 Capital Costs

The capital cost of a radioactive waste treatment case is the sum of the direct cost and indirect cost. The interest during construction and the contingency allowance are included as indirect costs to simplify the calculations.

6.1.1 Direct costs

The major equipment components were sized and a base cost estimated by using either published information²⁻⁵ or the general methods for costing conventional chemical plant equipment for conceptual designs.^{15,16} The base cost for the gas treatment equipment (i.e.,

venturi scrubbers, bag filters, and HEPA filters) is the complete installed cost of the equipment. For other equipment, the base cost is the estimated purchase price. Appropriate factors are applied to the equipment cost to estimate the cost of installation, piping, instruments and controls, electrical, and quality assurance.^{15,16}

Building requirements are estimated from equipment size with allowance made for auxiliary equipment such as pumps, condensers, etc. The costs of a warehouse building and other related facilities are not included. The total direct cost for each 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	<u>140</u>

6.2 Annual Fixed Charges and Operating Costs

The annual fixed charges on invested capital are based on the Fuel Recycle Task Force¹⁷ 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%

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

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%; thus, 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 annual fixed charges for conventional chemical equipment. The annual costs of drums (\$73,600) and cement (\$47,300) in Case 5b are included as additional operating charges. The cost for onsite storage of the drums or shipping offsite for storage or burial is not included. The annual operating cost of the gaseous waste treatment systems is calculated based on published information for equipment such as bag filters and liquid scrubbers. The operating cost for HEPA filters is based on experience at ORNL.

6.3 Installed Equipment Costs

The estimated direct and capital costs for equipment in Cases 2 through 5b are presented in Table 6.2. The direct cost is the estimated installation (material and labor) cost of the equipment; the capital cost includes both direct and indirect costs.

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7.0 ENVIRONMENTAL IMPACT

The radiological impact of the model recycle uranium conversion and UF₆ plant is assessed by estimating radiation dose commitments to individuals and populations that result from 1-year exposure to the radionuclides discharged during normal operations. The effluents are dispersed in the environment by atmospheric transport. In this study, no process radioactive materials are released in liquid effluents. The resulting concentrations of radionuclides in the air and on the soil surface at various distances and directions from the model plant are then used to estimate the doses. Doses are calculated for each site and radioactive waste treatment case.

Potential pathways for radiation exposure to man from radionuclides released from a nuclear facility are presented schematically in Fig. 7.1. Although those shown are not exhaustive, they illustrate the principal pathways of exposure based on experience. External doses result from immersion in contaminated air, immersion in contaminated water, and exposure to contaminated ground surfaces. Internal doses result from the inhalation of contaminated air and the ingestion of contaminated food. Conservative assumptions which tend to maximize doses are used; for example, doses from atmospheric releases assume exposure to contaminated air and ground 100% of the time with no shielding and 100% of the food consumed is produced at the location of the dose calculation.

Radioactive materials taken into the body by inhalation and ingestion (internal exposure) continuously irradiate the body until removed by processes of metabolism and radioactive decay. A dose calculated for 1 year of radionuclide intake (internal-exposure pathways) is an estimate of the total dose an individual will receive integrated over the next 50 years of his life as a result of that 1 year of exposure (i.e., dose commitment). All of the internal doses estimated in this report represent 50-year dose commitments. For those materials which either have short radioactive half-lives or are eliminated rapidly from the body, essentially all of the dose is received in the same year that the materials enter the body (i.e., the annual dose rate is about the same as the dose commitment). This is the case for most radionuclides in this study since the uranium radionuclides are eliminated from the body fairly rapidly and the half-lives of most of the fission products are short. However, ⁹⁰Sr, ²³⁷Np, ²³⁸Pu, ²³⁹Pu, ²⁴⁰Pu, ²⁴¹Pu, and ²⁴⁴Cm are eliminated from the body very slowly and have long half-lives so that the individual will continue to receive a dose from the ingested material for many years after the exposure. Under these conditions, the approximate dose received in the year that the materials enter the body is obtained by dividing the dose commitment by 50 (i.e., approximately equal doses are received over a 50-year period). Thus the average annual dose rate from, for example, ²³⁷Np, ²³⁹Pu, or ²⁴⁴Cm is only one-fiftieth of the dose commitment. If an individual is exposed to the recycle UF₆ plant effluents for the assumed 30-year operating life of the facility, his annual dose rate during the 30th year from the radionuclides with long radiological half-lives is about 30 times the annual dose rate for one year of exposure (i.e., ~ three-fifths of the 50-year dose commitment for 1 year of exposure). These generalized dose estimates are approximately correct for the conditions cited. However, a detailed calculation must be made to determine a more precise value for the actual dose received in a given year. Assumptions, models, and codes used to estimate radiation doses are given in ORNL-4992.¹

The radiation dose to organs 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 differ 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 total-body dose estimates 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,² the person-rem estimates are based on total-body doses calculated for adults. 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. The person-organ-rem estimates are based on adult organ doses.

7.1 Radiological Impact of Airborne Effluents During Plant Operation

The release of radioactive materials to the atmosphere is the only mode of environmental contamination from the recycle UF₆ plant. In this study, no process radioactive materials are released in liquid effluents.

7.1.1 Models and assumptions

AIRDOS. The FORTRAN computer code *AIRDOS*³ is used to estimate individual and population doses resulting from the continuous simultaneous atmospheric release of airborne radioactive materials from the model plant. Pathways to man include: (1) inhalation of radionuclides in air, (2) immersion in air containing radionuclides, (3) exposure to ground surfaces contaminated by deposited radionuclides, (4) ingestion of food produced in the area, and (5) submersion (swimming) in water subjected to surface deposition from plumes. Doses are estimated for the total body as well as for the GI tract, bone, thyroid, lungs, muscle, kidney, liver, spleen, testes, and ovaries.

The area surrounding the nuclear facility is divided into 16 sectors. Each sector is bounded by radial distances of 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 10, 15, 25, 35, 45, and 55 miles from the point of release. There are 176 areas lying outside the plant boundary, within 55 miles of the plant. Human population, numbers of beef cattle, and specification as to whether each of the 176 areas is used for producing vegetable crops or is a water area are required as input data.

The first part of *AIRDOS*³ is an atmospheric dispersion model (*AIRMOD*) which estimates concentrations of radionuclides in air at ground level and their rates of deposition on ground surfaces as a function of distance and direction from the point of release. Annual average meteorological data for the area are supplied as input for *AIRMOD*.

AIRMOD is interfaced with environmental models within *AIRDOS* to estimate doses to man through the five pathways. The most complex environmental model is a terrestrial model *TERMOD*.⁴ This model estimates radionuclide intake via ingestion of radionuclides deposited on crops, soil, and pastures. The intakes result from eating beef and vegetable crops and drinking milk.

Population doses are summarized in the output tables of AIRDOS³ by nuclides, pathways, and organs. The highest individual doses in the area for the total body and for each organ are tabulated for each radionuclide, and the highest total-body and organ doses from all radionuclides in the source terms are calculated.

Meteorology. The basic equation used to estimate atmospheric transport to the terrestrial environment is Pasquill's Equation⁵ as modified by Gifford.⁶ For particulate releases, the meteorological χ/Q values are used in conjunction with dry deposition velocities and scavenging coefficients to estimate air concentrations and steady-state ground concentrations. Radioactive decay during plume travel is taken into account in AIRDOS.³ Daughters produced during plume travel must be added to the AIRDOS³ source term. Concentrations in air for each sector are used to calculate dose via inhalation and immersion in air. The ground deposits are also assimilated into food which, when ingested, results in additional dose via the food chain pathway.

The meteorological data required for the calculations are joint frequency distributions of wind velocity and direction summarized by stability class. Meteorological data⁷ from representative first-order weather stations in the Midwest (St. Louis, Mo.) and the southeast coast (Wilmington, N. C.) are used to calculate the concentrations of radioactive materials 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 of 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 10, 15, 25, 35, 45, and 55 miles from the point of release.

Radioactive particulates are removed from the atmosphere and deposited on the ground through mechanisms of dry deposition and scavenging (washout). Dry deposition, as used in this analysis, represents an integrated deposition of radioactive materials by processes of gravitational settling, adsorption, particle interception, diffusion, and chemical-electrostatic effects and is calculated from deposition velocity, V_g , for a 1-year interval. Deposition velocity values for particles and reactive gases commonly range from 0.1 to 1.0 $\text{cm}\cdot\text{sec}^{-1}$.^{8,9} A value of 1.0 $\text{cm}\cdot\text{sec}^{-1}$ is used for calculation of ground concentrations of all radioactive particles. Scavenging of radionuclides in a plume is the process through which rain or snow washes out particles or dissolves gases and deposits them on ground or water surfaces. Methods for estimating scavenging coefficients can be found in ref. 10. A scavenging coefficient for particulates of $2.0 \times 10^{-5} \text{ sec}^{-1}$ is assumed for both the midwestern and the southeastern coastal sites.

Airborne release from the model plant. The radioactive effluents from the recycle UF_6 plant are released from three separate stacks 50, 40, and 30 m high, respectively.

The 50-m stack is assumed to have a gas flow rate of $3.74 \times 10^5 \text{ slm}$ ($1.32 \times 10^4 \text{ cfm}$), and the plume rise resulting from the momentum of the released gas is calculated by assuming a stack diameter of 1.016 m. Similarly, it is assumed that the 30-m stack (effective stack height due to plume rise is 50.3 m) has a gas flow rate of $5.27 \times 10^6 \text{ slm}$ ($1.86 \times 10^5 \text{ cfm}$) and a stack diameter of 2.743 m, and that the 40-m stack (effective stack height due to plume rise is 45.9 m) has a gas flow of $4.25 \times 10^5 \text{ slm}$ ($1.5 \times 10^4 \text{ cfm}$) and a diameter of 0.762 m. The maximum χ/Q values for the long-lived radioactive particulates released from the three stacks for the 1.5-mile distances from the midwestern and coastal sites, respectively, are as follows: 50-m stack, $2.25\text{E-}7$ and $1.88\text{E-}7 \text{ sec/m}^3$; 40-m stack, $2.54\text{E-}7$ and $2.38\text{E-}7 \text{ sec/m}^3$; 30-m stack, $2.48\text{E-}7$ and $1.86\text{E-}7 \text{ sec/m}^3$. Since the stack releases are at different heights and the

corresponding χ/Q 's at 1.5 miles from the plant (and at other distances) are different, dose estimates were calculated separately for each stack release and then combined to obtain the composite total-body and organ doses resulting from all airborne releases.

7.2 Population

Population distributions which would be representative of southeastern coastal and midwestern environments were derived. 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, Missouri, and Wilmington, North Carolina, are included in the averaging because the meteorological 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 5-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 smooth the major discontinuities.

Population distributions for the two sites of the recycle UF_6 plant have somewhat different characteristics (Table 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 recycle UF_6 facility. The cumulative population in the midwestern site is approximately six times greater than for the coastal site.

7.3 Environmental Impact of the Recycle UF₆ Plant

7.3.1 Radiation dose commitments from airborne effluents of the operating plant

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 code³ to estimate doses resulting from immersion in the airborne effluent, exposure to contaminated ground surface, and intake of radionuclides into the body through inhalation and ingestion are calculated with computer codes^{12,13} which use dosimetric criteria of the International Commission on Radiological Protection.

Estimates of the intake of radionuclides by man through terrestrial food chains are made with a model and computer code (TERMOD)⁴ incorporated with AIRDOS,³ 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. Doses are calculated for the final period of plant operation when there is a 30-year accumulation of deposited radioactive materials on the ground surfaces outside the plant boundary. Reducing factors, such as shielding provided by dwellings and time spent away from the reference location specified in the calculation, are not considered. Moreover, in estimating the dose to individuals via ingestion of plants, beef, and milk, an individual is assumed to obtain all of his food at the reference location. 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 ORNL-4992.¹

Dose to individuals. The maximum annual total-body doses and organ doses to individuals from all airborne effluents at 1.5 miles from the model recycle UF₆ plant are summarized in Table 7.4 assuming that 100% of the food is produced locally. Appropriate dose reduction factors can be applied when the food production and consumption pattern are known. The average total-body doses to the individual at 1.5 miles from the plant are 55.5 and 66.7% of the maximum doses given for 1.5 miles (Table 7.4) for the midwestern and coastal sites, respectively.

The maximum doses to the individual at 0.5 mile from the plant are approximately 2.3 times those for the 1.5-mile distance shown in Table 7.4. Similarly, the maximum doses to the individual at 1 mile from the plant are approximately 1.5 times those for the 1.5-mile distance.

The maximum doses for the total body and organs at the midwestern site are slightly higher than the comparable doses at the coastal site (Table 7.4). In all cases, the annual doses at the 1.5-mile boundary were less than 1 millirem. The bone receives the highest organ dose, which is approximately nine times higher than the total-body dose. The doses to the lungs and kidney are, respectively, five and two times higher than the total-body dose at both sites. For organs not listed, the doses are equal to or less than those shown for the total-body doses. Radioactive waste treatment in Case 2 is effective in reducing the doses to the total body and organs to approximately one-half those for Case 1. For example, at the midwestern site the maximum annual total-body dose decreases from 6.1×10^{-2} millirem in Case 1 to 2.5×10^{-2} millirem in Case 2. Additional dose reduction to 1.2×10^{-2} millirem is illustrated for Case 4.

Dose to population. The annual dose commitments from airborne effluents to the population living within 55 miles of the model plant are summarized in Table 7.5. Although the population around the midwestern site is over six times greater than that around the coastal site, the dose to the population (person-rem) is only 1.8 times greater for the midwestern site because of meteorological differences at the two sites. At the midwestern site the annual population total-body dose decreases from 1.4 person-rem in Case 1 to 0.55 person-rem in Case 2, and the population bone dose from 11.4 person-organ-rem to 4.5 person-organ-rem.

Exposure modes and radionuclides. The relative contributions of exposure modes to the total-body dose from airborne effluents are given in Table 7.6. Internal exposure from inhalation and ingestion accounts for more than 43% of the total-body dose, and exposure from contaminated ground surfaces accounts for essentially all of the remaining 57%.

The relative contributions of the principal radionuclides to the individual doses from airborne effluents are presented in Table 7.7 and for the population in Table 7.8 (midwestern site) and Table 7.9 (southeastern coastal site). Almost 92% of the maximum total-body dose of the individual is due to the uranium radionuclides, with ^{232}U , ^{234}U , and ^{238}U accounting for more than 20% each and ^{235}U for almost 10%. The exposure pathways of the radionuclides as shown in Table 7.10 indicate that the exposure to the total body from ^{232}U , ^{235}U , and ^{238}U is primarily external, by way of contaminated ground surface, whereas the primary exposure mode of ^{234}U is by way of ingestion.

The major contributors to the organ doses (Table 7.7) are as follows: GI tract dose, ^{99}Tc (26%), ^{106}Ru (19%), and the uranium radionuclides (52%); bone dose, uranium radionuclides (76%) and ^{238}Pu (12%); lung dose, uranium radionuclides (98%); kidney dose, uranium radionuclides (82%) and ^{238}Pu (5%). The contributions to organ dose of inhaled and ingested radionuclides are presented in Table 7.11.

7.3.2 Postoperational exposure from long-lived radionuclides released into the environment from a recycle UF_6 plant

Potential releases of radionuclides during plant operations and estimations of resulting radiation doses to individuals and populations are discussed in Sect. 7.3. 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. The 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 made in areas where deficiencies of knowledge exist. These assumptions make it likely that the estimates of health consequence are well above the probable effects.

Postoperational source terms. The model recycle UF_6 plant (Case 1) releases a total of 0.17 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 be a source of exposure to people long after the plant has ceased operation. Table 7.12 lists these radionuclides and the total quantities released from the model UF₆ facility during its 30 years of operation. Except for ²³²U and ²³⁸Pu, the radionuclides listed 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. Estimates of the deposition of particulates indicate that most of the materials are deposited within a 50-mile radius, even when the release point is the top of a 100-m-high stack.⁹

The average exposure to individuals and populations is estimated using the assumption that the radionuclides deposited during the operating 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.

Postoperational pathways of exposure. Pathways by which the deposited radionuclides may result in external and internal exposure to man are discussed below.

(a) *Resuspended air activity.* After airborne particulates have been removed from the atmosphere and reach the ground by deposition and washout, they may reenter the atmosphere by resuspension processes. In this case, 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 ²³⁸U. Resuspension factors of 10^{-9} and 10^{-10} m^{-1} were obtained from recent measurements of ²³⁹Pu made at the Nevada Test Site in an area contaminated 17 years previously.¹⁴ Measurements of ²³⁹Pu in the vicinity of the Rocky Flats Plant several years after deposition indicated a resuspension factor of 10^{-9} m^{-1} .¹⁴ Discounting airborne material of industrial origin, it appears from the data concerning movement of naturally occurring ²³⁸U that a realistic estimate of the resuspension of aged radioactive material in surface soil lies between 10^{-8} and 10^{-10} m^{-1} .¹⁴ This is in agreement with the field measurements for ²³⁹Pu. An intermediate value of $1 \times 10^{-9} \text{ m}^{-1}$ is used in this study to estimate the amounts of long-lived radionuclides inhaled over a long period of time for the relatively large well-vegetated regions around a recycle UF₆ 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 the foliage of crops and pastures. For estimating intake via inhalation of resuspended radionuclides, the expression is:

$$\text{Ci intake yr}^{-1} = \text{Ci m}^{-2} \times 10^{-9} \times 7300 \text{ m}^3 \text{ air inhaled yr}^{-1} .$$

(b) *Ingestion.* The radionuclides that are not inhaled by man remain in the environment for periods 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, neptunium, and plutonium 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 study, it is assumed that plant material accumulates a concentration (C_f value) of technetium equal to 2.5×10^{-1} , uranium equal to 2.5×10^{-3} , neptunium equal to 2.5×10^{-3} , and plutonium equal to 2.5×10^{-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.⁴

(c) *Contaminated ground.* Exposure via contaminated ground is also estimated. It is assumed that there is no loss of deposited radionuclides except through radioactive decay.

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 the population doses are expressed in terms of 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.

(a) *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 recycle UF_6 plant will continue to receive some radiation above background long after the plant has ceased operating, or actually until the ultimate decay of all the radionuclides. The average annual total-body doses to the individual out to 55 miles for the various radionuclides by exposure mode are shown in Table 7.13. Almost 95% of the total-body dose (2.5×10^{-4} millirem in Case 1) results from exposure to the contaminated ground. Three of the uranium radionuclides, ^{234}U , ^{235}U , and ^{236}U , contribute more than 95% of the total-body dose. These doses are the average doses out to 55 miles. Under actual conditions of radionuclide dispersal, the dose range, as a function of distance, will vary considerably over the 55-mile area.

The average annual doses to the organs resulting from the various radionuclides and for the major internal pathways are shown in Table 7.14. The bone receives the highest dose (1.4×10^{-4} millirem, Case 1), which is more than three times the dose to the kidney and GI tract. The major contributors to the bone and kidney dose are ^{234}U , ^{236}U , and ^{238}U , while ^{99}Tc contributes about 79% of the GI tract dose.

(b) *Population dose.* The annual doses to the population, given as person-rem per 3.6 million persons, are presented in Table 7.15. The annual total-body dose (0.89 person-rem) is, as with the individual dose, due primarily to the ^{234}U , ^{235}U , and ^{236}U , which account for about 97% of the dose. The bone dose (0.51 person-organ-rem) and the kidney dose (0.14 person-organ-rem) result primarily from ^{234}U , ^{236}U , and ^{238}U , while ^{99}Tc contributes about 80% of the GI tract dose (0.15 person-organ-rem).

7.4 References

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8.0 CORRELATION OF RADIOLOGICAL DOSE WITH COST OF WASTE TREATMENT

The relationship between the annual costs of the radioactive waste treatment systems described in Sects. 4.0 and 6.0 and the radiological impact of radioactive releases (dose commitment) 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 quantity of chemicals released by the model plant has been determined; however, the waste treatment systems have not been specifically designed to retain these substances, and the cost/benefit analysis does not address them.

Case 1, which is the base case, illustrates the important features of a facility which could be operated under present licensing regulations. Waste treatment systems are added to the basic plant primarily to remove radioactive materials from the gaseous effluents. In some instances, noxious chemicals such as HF, NO_x, and SO₂ are also removed by the waste treatment systems (i.e., scrubbers using KOH solution). The advanced cases use technology which is not available for immediate use because it is still at the pilot-plant stage of development or because it is proprietary. 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 assumptions made in estimating the makeup of the feed to the plant, selecting the flows to the waste treatment system and treatment efficiency ratings for equipment, estimating costs, defining the movement of radionuclides in the environment, and selecting food and liquid consumption patterns were realistically conservative, and this conservatism is reflected in the costs and doses.

The annual costs and dose commitments for the base case (Case 1) and succeeding case studies (Cases 2 through 5) 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 radioactive waste 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 (1) the maximum annual individual total-body, bone, lung, and kidney doses (other body organs which were discussed in Sect. 7.0, but which will not be considered here, include GI tract, thyroid, muscle, liver, spleen, testes, and ovaries) at 1.5 miles from the plant, which represent the doses from all radioactive materials released from the recycle facility in each case study; (2) incremental maximum annual individual doses at 1.5 miles, which represent the differences in dose between a given case and the preceding case; and (3) the annual dose to the population out to a distance of 55 miles. Factors for calculating maximum doses at distances other than 1.5 miles are given in Sect. 7.0. For example, the individual doses at 0.5 mile from the point of release are approximately 2.3 times greater than the doses at 1.5 miles. The maximum doses for a given annulus (downwind of the prevailing wind direction) are considered rather than the average individual doses to total body, bone, lung, and kidney, 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, lung, and kidney doses because the principal radionuclides that contribute to the total-body dose also contribute to these organ doses.

Since liquids containing radioactivity of process origin are contained and isolated from the environment, the dose calculations are based only on the radioactive particulates released in the gaseous effluent from the plant. The calculated population doses for the midwestern site are slightly greater than those for the coastal site because of variations in atmospheric dispersion patterns and population densities. This difference, as applied to the annual population total-body dose, is shown in Table 8.1.

8.1 Comparison of Airborne Radioactive Waste Treatment Costs and Radiological Dose

The summary table (Table 8.1) is expanded into three separate tables (Tables 8.3-8.5) to identify the effectiveness of the individual waste treatment systems. The dust control effluent from the handling of dry materials contributes about 70% of the dose in the base case (Table 8.3), the process off-gas about 8% (Table 8.4), and the building ventilation about 21% (Table 8.5). The objectives in Case 2 are to reduce the quantity of material released with the dust control air by the addition of secondary bag filters. An 86% reduction in uranium release is obtained at a total annual cost of \$96,000. Case 3 includes additional treatment for both dust control and process off-gas streams. The total annual increase in cost of the effluent treatment system (\$55,000) includes \$29,500 for a bank of HEPA filters for dust control and \$25,400 for a venturi scrubber on one of the process off-gas streams. Case 4 includes additional treatment equipment for all three sections of the effluent system with the following increases in annual cost over Case 3: dust control, \$16,300; process off-gas, \$36,700; and selected parts of the building ventilation, \$114,000. The final case study (Case 5) was selected to demonstrate the cost of a complete treatment system for the ventilation system (Case 5a) and a more effective method for isolation of solid waste containing radioactivity (Case 5b). The addition of bag filters to the ventilation air system is expensive because of the large volume of air to be treated. The total annual cost of the system is \$617,000 for Case 5a. The total annual cost of incorporating the solid wastes in cement is \$205,000. Incorporation in cement provides an effective system for isolating wastes but does not decrease the dose from the model plant to the surrounding population.

8.1.1 *Individual total-body dose*

The maximum annual individual total-body dose is derived mostly from the uranium isotopes (about 92%). The annual costs for reducing this dose from airborne effluents at 1.5 miles are presented in Tables 8.1-8.5 and in Fig. 8.1. The total-body dose is reduced by about 60% (i.e., from 0.061 to 0.025 millirem at the midwestern site and 0.055 to 0.022 millirem at the coastal site from Case 1 to Case 2) at a total annual cost increase of \$96,000. The cost/benefit ratio for this increment is \$2.7 million per millirem (\$2.9 million per millirem at the coastal site), corresponding to an annual expenditure of about 0.5% of the \$20 million capital cost of the plant. The cost/benefit ratio increment increases from case to case (Table 8.2), with a final value of \$51 million for the Case 4/Case 5a increment for the

midwestern site. This cost is further increased to \$69 million if the expense of incorporating the solid wastes in cement is included. The high cost/benefit ratios for the advance case increments result from the small incremental reductions in the removal of radioactive materials and small reductions in dose rather than from the magnitude of the treatment costs. The coastal site shows slightly lower doses and slightly higher cost/benefit ratios.

8.1.2 *Bone dose*

The maximum annual individual bone dose is derived from the uranium isotopes (76%) and the plutonium isotopes (20%). Annual costs to reduce the bone dose are presented in Tables 8.1-8.5 and in Fig. 8.1. The initial 60% reduction in dose achieved by the final treatment system between Cases 1 and 2 provides a cost/benefit ratio of \$300,000 per millirem at the midwestern site. Further reductions in the bone dose occur between the case studies with a resultant increase in the cost/benefit ratio. The cost/benefit ratio for the most expensive increment (Case 4/Case 5a) is \$5.6 million per millirem for the midwestern site.

8.1.3 *Population dose*

The annual cost of reducing the annual total population total-body and bone doses (person-rem) out to a distance of 55 miles is presented in Tables 8.1-8.5 and in Fig. 8.2. The population dose values for Case 1 are low (i.e., 1.39 and 0.75 person-rem for total-body dose at the midwestern and coastal sites, respectively). These values are low when compared with the natural background radiation of 7.2×10^4 and 4.6×10^5 person-rem for the same populations.^{1,2} The addition of secondary bag filters on the dust control system reduces the population doses to 0.55 person-rem to the total body and 4.52 person-rem to the bone (11.4 person-rem in Case 1). The cost of this dose reduction from Case 1 to Case 2 is high - \$110,000/person-rem total body and \$14,000/person-rem bone for the general population out to 55 miles at the midwestern site (Table 8.2). Further dose reduction to very low levels using advanced technology is possible, but the incremental cost/benefit is very high (i.e., \$1.4 million/person-rem total body from Case 3 to Case 4 and \$2.4 million/person-rem total body between Cases 4 and 5a).

8.1.4 *Combined reprocessing - recycle UF₆ facility doses*

Finney et al.³ have correlated waste treatment costs and the environmental impact of a LWR fuel reprocessing plant which is expected to be located adjacent to the recycle UF₆ facility. The annual population doses in the base case of the reprocessing plant at the midwestern site are as follows: total body, 1040 person-rem; GI tract, 2430 person-rem; bone, 1710 person-rem; and thyroid, 12,300 person-rem. By comparison with corresponding base case values for the recycle UF₆ plant, namely 1.39, 2.03, 11.4, and 1.40 person-rem, respectively, it is apparent that the dose commitment due to the recycle UF₆ plant is, in all cases, less than 1% of that due to reprocessing.

8.2 Comparison of Airborne Radioactive Waste Treatment Costs and Power Costs

The capital cost of the total model plant for the base case (Case 1) is estimated at \$20 million, including the Case 1 off-gas treatment. The unit conversion cost is estimated at \$4.85 per kg of uranium for the base plant (Table 6.1). The capital costs for the airborne radioactive waste treatment in advanced cases range from \$0.341 to \$3.59 million, or up to about 18% of the capital cost of the base plant. The annual cost increases over the base case range from \$0.096 to \$1.14 million and are equivalent to contribution to power costs of 0.00026 to 0.0031 mill/kWhr, respectively. All of these values are less than 0.1% of an estimated total power generation cost of 7 to 10 mills/kWhr. Thus, the cost of airborne radioactive waste treatment is a small fraction of total capital and power generation costs.

8.3 References

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Table 4.1. Material flows for the production of uranium dioxide from recycle uranyl nitrate for the model
1500-metric ton/year recycle uranium -- UF₆ plant
(Process streams are identified in Fig. 4.1)

Case No.	Stream			Gas flow [liters/day or (scf/day)]			Liquid flow [liters/day or (gal/day)]	Flow rate [kg/day or (lb/day)]								
	Code	Type	Description	Total	N ₂	O ₂		U	H ⁺	NO ₃ ⁻	H ₂ O	N ₂ O ₄	NH ₃	SO ₂	K ⁺	OH ⁻
1-5	A	Liquid	Initial feed solution from reprocessing plant	-	-	-	1.43E+4 (3.77E+3)	5.00E+3 (1.10E+4)	5.80E-1 (1.28E+0)	2.64E+3 (5.82E+3)	1.27E+4 (2.80E+4)	-	-	-	-	-
1-5	B	Gaseous	Sparging gas streams from storage and accountability feed tanks	1.47E+7 (5.19E+5)	1.12E+7 (3.94E+5)	3.00E+6 (1.06E+5)	-	-	5.22E-4 (1.15E-3)	3.24E-2 (7.13E-2)	3.28E+2 (7.23E+2)	-	-	-	-	-
1-5	C	Gaseous	Effluent from evaporator	1.30E+7 (4.59E+5)	-	-	-	-	5.72E-1 (1.26E+0)	3.54E+1 (7.82E+1)	1.04E+4 (2.29E+4)	-	-	-	-	-
1-5	D	Liquid	Condensate from evaporator	-	-	-	1.03E+4 (2.72E+3)	-	5.72E-1 (1.26E+0)	3.54E+1 (7.82E+1)	1.03E+4 (2.27E+4)	-	-	-	-	-
1-5	E	Gaseous	Sparging gas streams from the condensate storage tanks	8.46E+6 (2.99E+5)	6.37E+6 (2.25E+5)	1.71E+6 (6.04E+4)	-	-	1.49E-4 (3.29E-4)	9.24E-3 (2.04E-2)	1.88E+2 (4.14E+2)	1.93E+1 (4.25E+1)	-	-	-	-
1-5	F	Gaseous	Steam feed to denitrator	6.36E+6 (2.25E+5)	7.96E+5 (2.81E+4)	2.14E+5 (7.54E+3)	-	-	-	-	4.29E+3 (9.46E+3)	-	-	-	-	-
1-5	G	Gaseous	Effluent stream from denitrator	9.87E+6 (3.48E+5)	7.96E+5 (2.81E+4)	4.49E+5 (1.59E+4)	-	-	-	-	6.54E+3 (1.44E+4)	1.93E+3 (4.25E+3)	-	-	-	-
1-5	H	Liquid	Condensate from denitrator	-	-	-	7.33E+3 (1.94E+3)	-	4.16E+1 (9.17E+1)	2.58E+3 (5.69E+3)	6.07E+3 (1.34E+4)	-	-	-	-	-
1	I	Gaseous	Effluent from feed preparation and vacuum cleaner maintenance system	2.16E+8 (7.63E+6)	1.69E+8 (5.96E+6)	4.53E+7 (1.60E+6)	-	9.69E-2 (2.12E-1)	-	-	2.14E+1 (4.72E+1)	-	-	-	-	-
2	I	Gaseous	Effluent from feed preparation and vacuum cleaner maintenance system	2.16E+8 (7.63E+6)	1.69E+8 (5.96E+6)	4.53E+7 (1.60E+6)	-	1.36E-2 (2.99E-2)	-	-	2.14E+1 (4.72E+1)	-	-	-	-	-
3-5	I	Gaseous	Effluent from feed preparation and vacuum cleaner maintenance system	2.16E+8 (7.63E+6)	1.69E+8 (5.96E+6)	4.53E+7 (1.60E+6)	-	6.78E-6 (1.49E-5)	-	-	2.14E+1 (4.72E+1)	-	-	-	-	-
1-5	J	Gaseous	Ammonia feed to dissociator and reductor	6.98E+5 (2.47E+4)	-	-	-	-	-	-	-	-	5.29E+2 (1.17E+3)	-	-	-
1-5	K	Solid	UO ₂ product to hydrofluorinator	-	-	-	-	5.00E+3 (1.10E+4)	-	-	-	-	-	-	-	-
1-3	L	Gaseous	Effluent from reductor	2.76E+6 (9.75E+4)	1.54E+6 (5.44E+4)	1.38E+5 (4.87E+3)	-	5.00E-3 (1.10E-2)	-	-	8.39E+2 (1.85E+3)	-	-	2.99E+1 (6.59E+1)	-	-
4-5	L	Gaseous	Effluent from reductor	2.14E+6 (7.56E+4)	1.54E+6 (5.44E+4)	1.38E+5 (4.87E+3)	-	5.00E-5 (1.10E-4)	-	-	3.44E+2 (7.58E+2)	-	-	5.98E-1 (1.32E+0)	-	-
1	M	Gaseous	Combined effluent released to the environment	2.42E+8 (8.55E+6)	1.88E+8 (6.64E+6)	5.01E+7 (1.77E+6)	-	1.02E-1 (2.25E-1)	6.71E-4 (1.48E-3)	4.16E-2 (9.17E-2)	1.38E+3 (3.04E+3)	1.93E+1 (4.25E+1)	-	2.99E+1 (6.59E+1)	-	-
2	M	Gaseous	Combined effluent released to the environment	2.42E+8 (8.55E+6)	1.88E+8 (6.64E+6)	5.01E+7 (1.77E+6)	-	1.86E-2 (4.10E-2)	6.71E-4 (1.48E-3)	4.16E-2 (9.17E-2)	1.38E+3 (3.04E+3)	1.93E+1 (4.25E+1)	-	2.99E+1 (6.59E+1)	-	-
3	M	Gaseous	Combined effluent released to the environment	2.42E+8 (8.55E+6)	1.88E+8 (6.64E+6)	5.01E+7 (1.77E+6)	-	5.01E-3 (1.10E-2)	6.71E-4 (1.48E-3)	4.16E-2 (9.17E-2)	1.38E+3 (3.04E+3)	1.93E+1 (4.25E+1)	-	2.99E+1 (6.59E+1)	-	-
4-5	M	Gaseous	Combined effluent released to the environment	2.41E+8 (8.52E+6)	1.88E+8 (6.64E+6)	5.01E+7 (1.77E+6)	-	5.68E-5 (1.25E-4)	6.71E-4 (1.48E-3)	4.16E-2 (9.17E-2)	8.81E+2 (1.94E+3)	1.93E+1 (4.25E+1)	-	5.98E-1 (1.32E+0)	-	-
4-5	N	Liquid	KOH feed stream to venturi scrubber	-	-	-	6.23E+2 (1.65E+2)	-	-	-	6.12E+2 (1.35E+3)	-	-	-	4.74E+1 (1.05E+2)	2.06E+1 (4.54E+1)
4-5	O	Liquid	Effluent stream from venturi scrubber	-	-	-	1.13E+3 (2.98E+2)	4.95E-3 (1.09E-2)	-	-	1.11E+3 (2.43E+3)	-	-	2.93E+1 ^a (6.46E+1)	4.74E+1 (1.05E+2)	5.05E+0 (1.11E+1)

^aPresent as SO₃²⁻.

Table 4.2. Material flows for the production of uranium hexafluoride from uranium dioxide
for the model 1500-metric ton/year recycle uranium -- UF₆ plant
(Process streams are identified in Fig. 4.2)

Case No.	Stream		Gas flow [liters/day or (scf/day)]			Liquid flow [liters/day or (gal/day)]	Flow rate [kg/day or (lb/day)]								
	Code	Type	Description	Total	N ₂		O ₂	U	H ₂ O	H ⁺	F ⁻	F ₂	CaF ₂ ^a	K ⁺	OH ⁻
1-5	A	Solid	UO ₂ powder from denitration process	-	-	-	5.00E+3 (1.11E+4)	-	-	-	-	-	-	-	-
1-5	B	Gaseous	Effluent from hydrofluorinators	5.21E+6 (1.84E+5)	4.08E+6 (1.44E+5)	-	6.00E+1 (1.32E+2)	7.57E+2 (1.67E+3)	8.47E+0 (1.87E+1)	1.60E+2 (3.52E+2)	-	-	-	-	-
1-3	C	Gaseous	Effluent from packed tower scrubber	5.08E+6 (1.79E+5)	4.08E+6 (1.44E+5)	-	6.00E-4 (1.32E-3)	8.03E+2 (1.77E+3)	8.47E-2 (1.87E-1)	1.60E+0 (3.52E+0)	-	-	-	-	-
4-5	C	Gaseous	Effluent from packed tower scrubber	5.08E+6 (1.79E+5)	4.08E+6 (1.44E+5)	-	6.00E-6 (1.32E-5)	8.03E+2 (1.77E+3)	8.47E-4 (1.87E-3)	1.60E-2 (3.52E-2)	-	-	-	-	-
1-5	D	Gaseous	HF feed to hydrofluorinators	2.07E+6 (7.31E+4)	-	-	-	-	9.32E+1 (2.05E+2)	1.76E+3 (3.87E+3)	-	-	-	-	-
1	E	Gaseous	Effluent from feed preparation and vacuum cleaner maintenance system	7.34E+7 (2.59E+6)	5.73E+7 (2.02E+6)	1.54E+7 (5.43E+5)	-	1.56E-2 (3.44E-2)	-	-	-	-	-	-	-
2-3	E	Gaseous	Effluent from feed preparation and vacuum cleaner maintenance system	7.34E+7 (2.59E+6)	5.73E+7 (2.02E+6)	1.54E+7 (5.43E+5)	-	2.19E-3 (4.83E-3)	-	-	-	-	-	-	-
4-5	E	Gaseous	Effluent from feed preparation and vacuum cleaner maintenance system	7.43E+7 (2.59E+6)	5.73E+7 (2.02E+6)	1.54E+7 (5.43E+5)	-	1.09E-6 (2.40E-6)	-	-	-	-	-	-	-
1-5	F	Gaseous	F ₂ feed to fluorinator	5.70E+5 (2.01E+4)	1.14E+4 (4.03E+2)	-	-	-	2.82E+0 (6.21E+0)	5.31E+1 (1.17E+2)	8.40E+2 (1.85E+3)	-	-	-	-
1-5	G	Liquid	Final UF ₆ product	-	-	-	2.10E+3 (5.55E+2)	4.99E+3 (1.10E+4)	-	2.38E+3 (5.25E+3)	-	-	-	-	-
1-5	H	Solid	Waste material from fluorinator	-	-	-	-	1.00E+1 (2.20E+1)	-	-	-	-	2.95E+2 (6.50E+2)	-	-
1-2	I	Gaseous	Effluent from fluidized-bed fluorinator cleanup system	3.16E+5 (1.12E+4)	3.04E+5 (1.07E+4)	1.24E+4 (4.37E+2)	-	6.64E-3 (1.46E-2)	7.30E+0 (1.61E+1)	1.00E-2 (2.21E-2)	1.89E-1 (4.17E-1)	-	-	-	-
3	I	Gaseous	Effluent from fluidized-bed fluorinator cleanup system	3.16E+5 (1.12E+4)	3.04E+5 (1.07E+4)	1.24E+4 (4.37E+2)	-	6.64E-4 (1.46E-3)	7.30E+0 (1.61E+1)	1.00E-3 (2.21E-3)	1.89E-2 (4.17E-2)	-	-	-	-
4-5	I	Gaseous	Effluent from fluidized-bed fluorinator cleanup system	3.16E+5 (1.12E+4)	3.04E+5 (1.07E+4)	1.24E+4 (4.37E+2)	-	3.32E-7 (7.32E-7)	7.30E+0 (1.61E+1)	1.00E-3 (2.21E-3)	1.89E-2 (4.17E-2)	-	-	-	-
1	J	Gaseous	Combined effluent released to the environment	7.88E+7 (2.78E+6)	6.17E+7 (2.18E+6)	1.54E+7 (5.44E+5)	-	2.28E-2 (5.03E-2)	8.10E+2 (1.79E+3)	9.47E-2 (2.09E-1)	1.79E+0 (3.94E+0)	-	-	-	-
2	J	Gaseous	Combined effluent released to the environment	7.88E+7 (2.78E+6)	6.17E+7 (2.18E+6)	1.54E+7 (5.44E+5)	-	9.43E-3 (2.08E-2)	8.10E+2 (1.79E+3)	9.47E-2 (2.09E-1)	1.79E+0 (3.94E+0)	-	-	-	-
3	J	Gaseous	Combined effluent released to the environment	7.88E+7 (2.78E+6)	6.17E+7 (2.18E+6)	1.54E+7 (5.44E+5)	-	3.45E-3 (7.61E-3)	8.10E+2 (1.79E+3)	8.57E-2 (1.89E-1)	1.62E+0 (3.57E+0)	-	-	-	-
4-5	J	Gaseous	Combined effluent released to the environment	7.88E+7 (2.78E+6)	6.17E+7 (2.18E+6)	1.54E+7 (5.44E+5)	-	7.42E-6 (1.64E-5)	8.10E+2 (1.79E+3)	1.85E-3 (4.07E-3)	3.49E-2 (7.69E-2)	-	-	-	-
1-3	K	Liquid	KOH feed stream to packed tower	-	-	-	5.33E+3 (1.41E+3)	-	5.24E+3 (1.16E+4)	-	-	-	-	4.06E+2 (8.95E+2)	1.78E+2 (3.92E+2)
4-5	K	Liquid	KOH feed stream to packed tower and venturi scrubber system	-	-	-	5.39E+3 (1.42E+3)	-	5.30E+3 (1.17E+4)	-	-	-	-	4.10E+2 (9.04E+2)	1.80E+2 (3.97E+2)
1-3	L	Liquid	Effluent stream from packed tower	-	-	-	5.44E+3 (1.44E+3)	-	5.35E+3 (1.18E+4)	-	1.58E+2 (3.48E+2)	-	-	4.06E+2 (8.95E+2)	3.53E+1 (7.78E+1)
4-5	L	Liquid	Effluent stream from packed tower and venturi scrubber system	-	-	-	5.50E+3 (1.45E+3)	5.94E-4 (1.31E-3)	5.40E+3 (1.19E+4)	-	1.60E+2 (3.53E+2)	-	-	4.10E+2 (9.04E+2)	3.56E+1 (7.85E+1)
1-2	M	Liquid	KOH feed stream to packed tower and spray tower system	-	-	-	3.19E+3 (8.42E+2)	-	3.13E+3 (6.90E+3)	-	-	-	-	2.42E+2 (5.34E+2)	1.06E+2 (2.34E+2)
3-5	M	Liquid	KOH feed stream to packed tower, spray tower, and coke-packed tower system	-	-	-	3.19E+3 (8.42E+2)	-	3.13E+3 (6.90E+3)	-	-	-	-	2.42E+2 (5.34E+2)	1.06E+2 (2.34E+2)
1-2	N	Liquid	Effluent stream from packed tower and spray tower system	-	-	-	3.27E+3 (8.64E+2)	3.32E+0 (7.31E+0)	3.21E+3 (7.08E+3)	-	9.44E+1 (2.08E+2)	-	-	2.42E+2 (5.34E+2)	2.21E+1 (4.87E+1)
3-5	N	Liquid	Effluent stream from packed tower, spray tower, and coke-packed tower system	-	-	-	3.27E+3 (8.64E+2)	3.32E+0 (7.31E+0)	3.21E+3 (7.08E+3)	-	9.44E+1 (2.08E+2)	-	-	2.42E+2 (5.34E+2)	2.21E+1 (4.87E+1)

^aContains essentially all the plutonium and transuranium elements.

Table 4.3. Fluorine cell waste and recycle streams and material flows for the model 1500-metric ton/year recycle uranium -- UF₆ plant
(Process streams are identified in Fig. 4.3)

Code	Type	Stream Description	Gas flow [liters/day or (scf/day)]			Liquid flow [liters/day or (gal/day)]	Flow rate [kg/day or (lb/day)]							
			Total	N ₂	O ₂		F ₂	H ₂	F ⁻	H ₂ O	Electrolyte	H ₂	K ⁺	OH ⁻
A	Gaseous	HF feed to fluorine production facility	1.10E+6 (3.88E+5)	-	-	-	-	4.96E+1 (1.09E+2)	9.36E+1 (2.06E+2)	-	-	-	-	-
B	Solid	Spent electrolyte from fluorine cells	-	-	-	-	-	-	-	-	1.37E+1 (3.02E+1)	-	-	-
C	Gaseous	Fluorine stream from fluorine cells	5.70E+5 (2.01E+4)	1.14E+4 (4.03E+2)	-	-	8.40E+2 (1.85E+3)	2.82E+0 (6.21E+0)	5.31E+1 (1.17E+2)	-	-	-	-	-
D	Gaseous	Hydrogen stream from fluorine cells	5.57E+5 (1.97E+4)	1.11E+4 (3.92E+2)	-	-	-	2.26E+0 (4.98E+0)	4.25E+1 (9.37E+1)	-	-	4.47E+1 (9.86E+1)	-	-
E	Gaseous	Fluorine product to fluorination reactor	5.70E+5 (2.01E+4)	1.14E+4 (4.03E+2)	-	-	8.40E+2 (1.85E+3)	2.82E+0 (6.21E+0)	5.31E+1 (1.17E+2)	-	-	-	-	-
F	Gaseous	Purge air stream	4.08E+6 (1.44E+5)	3.18E+6 (1.12E+5)	8.54E+5 (3.02E+4)	-	-	5.04E-3 (1.11E-2)	9.50E-2 (2.09E-1)	-	-	-	-	-
G	Liquid	Feed solution to packed tower and venturi scrubber system	-	-	-	1.44E+3 (3.80E+2)	-	-	-	1.42E+3 (3.13E+3)	-	-	1.10E+2 (2.42E+2)	4.80E+1 (1.06E+2)
H	Liquid	Effluent stream from packed tower and venturi scrubber system	-	-	-	1.38E+3 (3.65E+2)	-	-	4.28E+1 (9.44E+1)	1.35E+3 (2.98E+3)	-	-	1.10E+2 (2.42E+2)	9.71E+0 (2.14E+1)
I	Gaseous	Effluent release from packed tower and venturi scrubber system	6.23E+6 (2.20E+5)	4.57E+6 (1.61E+5)	9.78E+5 (3.45E+4)	-	-	2.26E-4 (4.98E-4)	4.27E-3 (9.41E-3)	5.04E+2 (1.11E+3)	-	-	-	-
J	Gaseous	Ventilation air from fluorine production facility	1.22E+9 (4.31E+7)	9.53E+8 (3.37E+7)	2.56E+8 (9.04E+6)	-	-	1.26E-1 (2.78E-1)	2.37E+0 (5.22E+0)	-	-	-	-	-
K	Gaseous	Cell maintenance air	7.34E+8 (2.59E+7)	5.73E+8 (2.02E+7)	1.54E+8 (5.44E+6)	-	-	1.26E-2 (2.78E-2)	2.37E-1 (5.22E-1)	-	-	-	-	-
L	Gaseous	Combined gaseous effluent from fluorine production facility	1.96E+9 (6.92E+7)	1.53E+9 (5.40E+7)	4.11E+8 (1.45E+7)	-	-	1.39E-1 (3.06E-1)	2.61E+0 (5.75E+0)	-	-	-	-	-

Table 4.4. Material flows for the scrap recovery and solid waste treatment system for the model 1500-metric ton/year recycle uranium isotope plant
(Process streams are identified in Fig. 4.4)

Code	Stream Type	Stream Description	Gas flow [liters/day or (scf/day)]			Liquid flow [liters/day or (gal/day)]	Flow rate (kg/day or (lb/day))												
			Total	H_2	O_2		H^+	NH_4^+	H_2O^+	U	NH_4^+	OH^-	H_2O_2	NO_2	CaF_2	F^-	K^+	SO_3^{2-}	Ca(OH)_2
A	Liquid	Nitric acid dissolver solution	-	-	-	6.23E+2 (1.65E+2)	1.44E+0 (3.17E+0)	1.10E+1 (1.95E+1)	3.20E+2 (1.30E+3)	-	-	-	-	-	-	-	-	-	-
B	Gaseous	Steam to promote dissolution	3.73E+4 (1.32E+3)	-	-	-	-	-	1.00E+1 (2.20E+1)	-	-	-	-	-	-	-	-	-	-
C	Solid	Uranium scrap for recovery	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
D	Liquid	Solution from dissolver	-	-	-	6.48E+2 (1.71E+2)	6.24E-1 (1.38E+0)	6.40E+1 (1.40E+2)	6.13E+2 (1.60E+3)	5.00E+1 (1.10E+2)	-	-	-	-	-	-	-	-	-
E	Liquid	pH adjustment solution	-	-	-	7.20E+1 (1.90E+1)	-	-	4.20E+1 (9.30E+1)	-	1.10E+1 (2.42E+1)	1.04E+1 (2.27E+1)	-	-	-	-	-	-	-
F	Liquid	Precipitating solution	-	-	-	1.14E+3 (3.01E+2)	-	-	1.13E+3 (2.54E+3)	-	-	-	3.04E+1 (6.70E+1)	-	-	-	-	-	-
G	Liquid	Feed solution to precipitator	-	-	-	7.14E+2 (1.89E+2)	1.34E+0 (2.95E+0)	6.38E+1 (1.41E+2)	6.00E+2 (1.62E+3)	5.00E+1 (1.10E+2)	1.10E+1 (2.42E+1)	-	-	-	-	-	-	-	-
H	Liquid	Feed solution to clarifier	-	-	-	1.83E+3 (4.85E+2)	1.34E+0 (2.95E+0)	6.23E+1 (1.37E+2)	1.20E+3 (3.20E+3)	1.50E+0 (1.10E+0)	1.07E+1 (2.36E+1)	-	1.58E+1 (3.48E+1)	-	-	-	-	-	-
I	Solid	Uranium precipitate to calciner	-	-	-	-	1.28E-2 (2.82E-2)	1.95E+0 (4.30E+0)	5.00E+1 (1.30E+2)	4.95E+1 (1.09E+2)	3.38E-1 (7.45E-1)	-	5.00E-1 (1.10E+0)	-	-	-	-	-	-
J	Solid	Uranium product	-	-	-	-	-	-	-	4.95E+1 (1.09E+2)	-	-	-	-	-	-	-	-	-
K	Liquid	Supernatant stream from clarifier	-	-	-	1.81E+3 (4.79E+2)	1.33E+0 (2.93E+0)	6.04E+1 (1.33E+2)	1.70E+3 (3.80E+3)	5.00E-1 (1.10E+0)	1.04E+1 (2.29E+1)	-	1.53E+1 (3.37E+1)	-	-	-	-	-	-
L	Gaseous	Process off-gas from scrap recovery and solid waste treatment system	1.68E+8 (5.93E+6)	1.77E+8 (4.40E+6)	3.42E+7 (1.21E+6)	-	-	-	4.11E+3 (9.05E+3)	1.20E-3 (1.65E-3)	-	-	-	1.71E+1 (3.77E+1)	-	-	-	-	-
L	Gaseous	Process off-gas from scrap recovery and solid waste treatment system	1.69E+8 (5.97E+6)	1.77E+8 (4.40E+6)	3.42E+7 (1.21E+6)	-	-	-	4.79E+3 (1.06E+4)	6.00E-6 (1.29E-5)	-	-	-	1.71E+1 (3.77E+1)	-	-	-	-	-
M	Solid	Filter fines and discarded bed material	-	-	-	-	-	-	-	-	-	-	-	-	2.95E+2 (6.50E+2)	-	-	-	-
N	Liquid	Spent scrubber solution	-	-	-	1.01E+4 (2.67E+3)	-	-	9.91E+3 (2.18E+4)	4.0E+0 (7.41E+0)	-	6.71E+1 (1.48E+2)	-	-	-	2.95E+2 (6.50E+2)	7.58E+2 (1.67E+3)	-	-
N	Liquid	Spent scrubber solution	-	-	-	1.13E+4 (2.98E+3)	-	-	1.11E+4 (2.44E+4)	4.0E+0 (7.41E+0)	-	7.21E+1 (1.59E+2)	-	-	-	2.97E+2 (6.54E+2)	8.05E+2 (1.78E+3)	3.68E+1 (8.11E+1)	-
O	Liquid	Makeup KOH solution	-	-	-	2.21E+3 (5.84E+2)	-	-	2.18E+3 (4.81E+3)	-	-	7.37E+1 (1.62E+2)	-	-	-	-	1.69E+2 (3.73E+2)	-	-
O	Liquid	Makeup KOH solution	-	-	-	2.40E+3 (6.34E+2)	-	-	2.36E+3 (5.20E+3)	-	-	7.99E+1 (1.76E+2)	-	-	-	-	1.84E+2 (4.06E+2)	-	-
P	Liquid	Regenerated KOH scrubber solution	-	-	-	7.75E+3 (2.05E+3)	-	-	7.61E+3 (1.68E+4)	-	-	2.58E+2 (5.70E+2)	-	-	1.17E-1 (2.58E-1)	-	5.89E+2 (1.30E+3)	-	-
P	Liquid	Regenerated KOH scrubber solution	-	-	-	8.24E+3 (1.82E+3)	-	-	8.10E+3 (1.79E+4)	-	-	2.75E+2 (6.06E+2)	-	-	1.35E-1 (2.98E-1)	-	6.25E+2 (1.38E+3)	-	-
Q	Solid	Lime feed	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6.89E+2 (1.52E+3)
Q	Solid	Lime feed	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7.35E+2 (1.62E+3)

as scrubber solutions for the fluorine production, although they will be regenerated in a separate inactive system.

Table 4.5. Ventilation air flows for the model 1500-metric ton/year recycle uranium -- UF₆ plant
(Process streams are identified in Fig. 4.6)

Case No.	Stream		Gas flow [liters/day or (scf/day)]			U
	Code	Description	Total	N ₂	O ₂	[kg/day or (lb/day)]
1-3	A	Effluent from fluorination and decontamination areas	6.12E+8 (2.16E+7)	4.78E+8 (1.69E+7)	1.28E+8 (4.53E+6)	4.00E-3 (8.82E-3)
4-5	A	Effluent from fluorination and decontamination areas	6.12E+8 (2.16E+7)	4.78E+8 (1.69E+7)	1.28E+8 (4.53E+6)	4.00E-5 (8.82E-5)
1-4	B	Effluent from main process ventilation area	4.89E+9 (1.73E+8)	3.82E+9 (1.35E+8)	1.02E+9 (3.62E+7)	3.00E-2 (6.61E-2)
5	B	Effluent from main process ventilation area	4.89E+9 (1.73E+8)	3.82E+9 (1.35E+8)	1.02E+9 (3.62E+7)	3.00E-5 (6.61E-5)
1-5	C	Effluent from process support ventilation area	1.84E+9 (6.50E+7)	1.44E+9 (5.07E+7)	3.85E+8 (1.36E+7)	1.00E-4 (2.20E-4)
1-5	D	Effluent from UF ₆ cylinder charging section ventilation area	6.12E+8 (2.16E+7)	4.78E+8 (1.69E+7)	1.28E+8 (4.53E+6)	-
1-5	E	Effluent from cold trap area ventilation air	2.45E+8 (8.65E+6)	1.91E+8 (6.76E+6)	5.13E+7 (1.81E+6)	-
1-4	F	Combined effluent from main ventilation area	7.59E+9 (2.68E+8)	5.93E+9 (2.09E+8)	1.58E+9 (5.61E+7)	3.01E-2 (6.64E-2)
5	F	Combined effluent from main ventilation area	7.59E+9 (2.68E+8)	5.93E+9 (2.09E+8)	1.58E+9 (5.61E+7)	1.30E-4 (2.87E-4)
1-5	G	Effluent from fluorine production building	1.22E+9 (4.31E+7)	9.53E+8 (3.36E+7)	2.56E+8 (9.04E+6)	-
1-3	H	Combined effluent from all ventilation areas	8.20E+9 (2.90E+8)	6.41E+9 (2.26E+8)	1.71E+9 (6.03E+7)	3.41E-2 (7.52E-2)
4	H	Combined effluent from all ventilation areas	8.20E+9 (2.90E+8)	6.41E+9 (2.26E+8)	1.71E+9 (6.03E+7)	3.01E-2 (6.64E-2)
5	H	Combined effluent from all ventilation areas	8.20E+9 (2.90E+8)	6.41E+9 (2.26E+8)	1.71E+9 (6.03E+7)	1.70E-4 (3.75E-4)

Table 4.6. Characteristics of the radioactive materials in the feed to the model 1500-metric ton/year recycle uranium -- UF₆ plant

Nuclide	Half-life ^a	Principal type ^b of decay	Initial activity in feed ^c (Ci/metric ton)	Nuclide	Half-life ^a	Principal type ^b of decay	Initial activity in feed ^c (Ci/metric ton)
Sr-89	5.2E+1 d	β	7.0E-4	Nd-147	1.1E+1 d	β	2.3E-7
Sr-90 ^d	2.8E+1 y	β	7.2E-4	Pm-147	2.6E+0 y	β	8.9E-4
Y-90	6.4E+1 h	β	7.0E-4	Pm-148	5.4E+0 d	β	2.0E-6
Y-91	5.9E+1 d	β	1.2E-3	Sm-151	8.7E+1 y	β	1.2E-5
Zr-95 ^d	6.5E+1 d	β	2.0E-2	Eu-152	1.2E+1 y	EC	1.3E-7
Nb-95 ^d	3.5E+1 d	β	3.8E-2	Gd-153	2.4E+2 d	EC	2.2E-7
Tc-99 ^d	2.1E+5 y	β	5.7E-1	Eu-154 ^d	1.6E+1 y	β	6.6E-5
Ru-103 ^d	4.0E+0 d	β	5.6E-3	Eu-155	1.8E+0 y	β	6.0E-5
Rh-106 ^d	1.3E+2 m	β	3.7E-2	Eu-156	1.5E+0 d	β	1.2E-6
Ru-106 ^d	3.7E+2 d	β	3.7E-2	Tb-160	7.2E+1 d	β	2.5E-6
Ag-110m	2.5E+2 d	β	2.2E-5	Th-234 ^d	2.4E+1 d	β	8.1E-2
Cd-113m	1.4E+1 y	β	1.0E-7	U-232 ^d	7.2E+1 y	α	1.5E-2
Cd-115m	4.3E+1 d	β	3.6E-7	U-233 ^d	1.6E+5 y	α	6.1E-5
Sn-119m	2.5E+2 d	IT	9.3E-8	U-234 ^d	2.5E+5 y	α	9.7E-1
Sn-123	1.2E+2 d	β	3.2E-5	U-235 ^d	7.1E+8 y	α	1.6E-2
Sb-124	6.0E+1 d	β	6.0E-7	U-236 ^d	2.4E+7 y	α	3.7E-1
Sb-125	2.7E+0 y	β	7.4E-5	U-237 ^d	6.8E+0 d	β	9.3E-1
Te-125m	5.8E+0 d	IT	3.0E-5	U-238 ^d	4.5E+9 y	α	3.2E-1
Te-127m	1.1E+2 d	IT	5.0E-5	Np-237 ^d	2.1E+6 y	α	1.6E-3
Te-127	9.4E+0 h	β	5.0E-5	Np-239 ^d	2.4E+0 d	β	3.2E-3
Te-129m	3.4E+1 d	IT	1.9E-5	Pu-236	2.8E+0 y	α	4.6E-7
Te-129	6.9E+1 m	β	1.2E-5	Pu-238 ^d	8.6E+1 y	α	4.3E-3
Cs-134 ^d	2.0E+0 y	β	2.0E-3	Pu-239 ^d	2.4E+4 y	α	3.4E-4
Cs-137 ^d	3.0E+1 y	β	1.0E-3	Pu-240 ^d	6.6E+3 y	α	4.9E-4
Ba-140	1.3E+1 d	β	2.1E-6	Pu-241 ^d	1.3E+1 y	β	1.0E-1
La-140	4.0E+1 h	β	2.5E-6	Pu-242	3.8E+5 y	α	1.4E-6
Ce-141	3.3E+1 d	β	3.9E-4	Am-241	4.6E+2 y	α	1.7E-6
Pr-143	1.4E+1 d	β	3.5E-6	Am-243	7.9E+3 y	α	1.8E-7
Ce-144 ^d	2.8E+2 d	β	6.5E-3	Cm-242	1.6E+2 d	α	1.7E-4
Pr-144	1.7E+1 m	β	6.4E-3	Cm-244 ^d	1.8E+1 y	α	2.4E-5

^aValues are taken from: C. M. Lederer, J. M. Hollander, and I. Perlman, Table of Isotopes, Sixth Edition, John Wiley & Sons, New York, 1967.

Symbol definition: m-minute, h-hour, d-day, y-year.

^bSymbol definition: α-alpha, β-beta, IT-isomeric transition, EC-orbital electron capture.

^cFor assumptions concerning feed, see Sect. 4.2.

^dNuclides used in calculating source terms.

Table 4.7. Specific activities and relative inhalation hazards
of the major radioactive materials in the feed to the model
1500-metric ton/year recycle uranium -- UF₆ plant

Nuclide	Specific activity of pure isotope (Ci/g)	Contribution to the total relative inhalation hazard ^a (%)
Sr-90	1.4E+2	<0.01
Zr-95	2.1E+4	<0.01
Nb-95	3.9E+4	<0.01
Tc-99	1.7E-2	0.05
Ru-103	3.2E+5	<0.01
Ru-106	1.4E+7	0.03
Cs-134	1.3E+3	<0.01
Cs-137	8.7E+1	<0.01
Ce-144	3.2E+3	<0.01
Eu-154	1.4E+2	<0.01
Th-234	2.3E+4	0.01
U-232	2.1E+1	2.75
U-233	9.6E-3	<0.01
U-234	6.1E-3	41.2
U-235	2.1E-6	0.68
U-236	6.3E-5	15.6
U-237	8.1E+4	---
U-238	3.3E-7	18.3
Np-237	7.2E-4	2.70
Np-239	2.3E+5	<0.01
Pu-238	1.7E+1	10.4
Pu-239	6.2E-2	0.95
Pu-240	2.3E-1	1.39
Pu-241	1.1E+2	5.93
Cm-244	8.1E+1	0.01

^aRelative inhalation hazard = curies present in 1 metric ton of fuel
divided by the Radiation Concentration Guide value.

Table 4.8. Airborne radioactive waste treatment variables for the model 1500-metric ton/year recycle uranium -- UF₆ plant

Source	Principal contaminant removed	Case 1, base plant	Case 2	Case 3	Case 4	Case 5
Evaporation and denitration	HNO ₃ , H ₂ O	Condenser system	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1
Reduction	Particulates	Primary 10-μ porous stainless steel filter; secondary 10-μ porous stainless steel filter	Same as Case 1	Same as Case 1	Case 1 plus KOH high-energy venturi scrubber	Same as Case 4
	H ₂ , H ₂ S	Flame arrestor; H ₂ , H ₂ S burner	Same as Case 1	Same as Case 1	Case 1 plus KOH high-energy venturi scrubber	Same as Case 4
Hydrofluorination	Particulates	Primary porous metal filter; secondary porous metal filter	Same as Case 1	Same as Case 1	Case 1 plus KOH high-energy venturi scrubber	Same as Case 4
	HF	KOH packed tower	Same as Case 1	Same as Case 1	Case 1 plus KOH high-energy venturi scrubber	Same as Case 4
Fluorination	Particulates	Primary porous metal filter; secondary porous metal filter	Same as Case 1	Same as Case 1	Case 1 plus HF-resistant HEPA filter	Same as Case 4
	UF ₆ product	Cold traps, 0°F and -50°F	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1
	UF ₆ , F ₂ , HF	KOH spray tower and packed tower system	Same as Case 1	Case 1 plus KOH coke-packed tower	Same as Case 3	Same as Case 3
Vacuum cleaner and feed preparation	Particulates	Centrifugal separator; cleaner bag; bag filter	Case 1 plus secondary bag filter	Same as Case 2	Case 3 plus HF-resistant HEPA filter	Same as Case 4
Scrap recovery and ash handling system	Particulates	HEPA filter	Same as Case 1	Same as Case 1	Case 1 plus secondary HEPA filter	Same as Case 4
Main plant ventilation system	Particulates	No treatment	Same as Case 1	Same as Case 1	Same as Case 1	Bag filter
Fluorination and decontamination area ventilation system	Particulates	Primary HEPA filter; secondary HEPA filter	Same as Case 1	Same as Case 1	Case 1 plus bag filter	Same as Case 4
Fluorine cell hydrogen off-gas	HF, H ₂	Flame arrestor; burner, KOH high-energy venturi scrubber and packed tower system	Same as Case 1	Same as Case 1	Same as Case 1	Same as Case 1

Table 4.9. Source terms for the model 1500-metric ton/year recycle uranium -- UF₆ plant - calculated release of radioactive material in airborne effluents

Nuclide	Case 1		Case 2		Case 3		Case 4		Case 5	
	Concentration ($\mu\text{Ci/ml}$)	Amount (Ci/yr)								
Sr-90	1.1E-14	3.5E-5	4.3E-15	1.4E-5	2.9E-15	9.5E-6	2.0E-15	6.5E-6	1.6E-17	5.2E-8
Zr-95	2.9E-13	9.4E-4	1.2E-13	3.7E-4	8.4E-14	2.6E-4	5.5E-14	1.8E-4	4.4E-16	1.4E-6
Nb-95	5.7E-13	1.8E-3	2.2E-13	7.1E-4	1.5E-13	4.9E-4	1.1E-13	3.4E-4	8.5E-16	2.7E-6
Tc-99	8.6E-12	2.8E-2	3.4E-12	1.1E-2	2.4E-12	7.5E-3	1.6E-12	5.2E-3	1.3E-14	4.1E-5
Ru-103	8.4E-14	2.7E-4	3.3E-14	1.1E-4	2.3E-14	7.3E-5	1.6E-14	5.0E-5	1.3E-16	4.0E-7
Ru-106	5.6E-13	1.8E-3	2.2E-13	7.1E-4	1.5E-13	4.9E-4	1.1E-14	3.4E-4	8.5E-16	2.7E-6
Cs-134	2.9E-14	9.4E-5	1.2E-14	3.7E-5	8.0E-15	2.6E-5	5.5E-15	1.8E-5	4.4E-17	1.4E-7
Cs-137	1.5E-14	4.9E-5	6.1E-15	1.9E-5	4.2E-15	1.3E-5	2.9E-15	9.2E-6	2.3E-17	7.4E-8
Ce-144	9.7E-14	3.1E-4	3.8E-14	1.2E-4	2.7E-14	8.5E-5	1.8E-14	5.9E-5	1.5E-16	4.7E-7
Eu-154	1.0E-15	3.2E-6	3.9E-16	1.3E-6	2.7E-16	8.7E-7	1.9E-16	6.0E-7	1.5E-18	4.8E-9
Th-234	1.2E-12	3.9E-3	4.8E-13	1.5E-3	3.3E-13	1.1E-3	2.3E-13	7.4E-4	1.8E-15	5.9E-6
U-232	2.2E-13	7.0E-4	8.7E-14	2.8E-4	6.0E-14	1.9E-4	4.1E-14	1.3E-4	3.3E-16	1.1E-6
U-233	9.2E-16	2.9E-6	3.6E-16	1.2E-6	2.5E-16	8.0E-7	1.7E-16	5.5E-7	1.4E-18	4.4E-9
U-234	1.5E-11	4.7E-2	5.8E-12	1.8E-2	4.0E-12	1.3E-2	2.8E-12	8.8E-3	2.2E-14	7.0E-5
U-235	2.4E-13	7.7E-4	9.5E-14	3.0E-4	6.6E-14	2.1E-4	4.5E-14	1.5E-4	3.6E-16	1.2E-6
U-236	5.5E-12	1.8E-2	2.2E-12	7.0E-3	1.5E-12	4.8E-3	1.0E-12	3.3E-3	8.3E-15	2.6E-5
U-237	1.4E-11	4.5E-2	5.5E-12	1.8E-2	3.8E-12	1.2E-2	2.6E-12	8.4E-3	2.1E-14	6.7E-5
U-238	4.9E-12	1.6E-2	1.9E-12	6.2E-3	1.3E-12	4.3E-3	9.2E-13	2.9E-3	7.3E-15	2.3E-5
Np-237	2.4E-14	7.6E-5	9.5E-15	3.0E-5	6.5E-15	2.1E-5	4.5E-15	1.4E-5	3.6E-17	1.1E-7
Np-239	4.9E-14	1.6E-4	1.9E-14	6.1E-5	1.3E-14	4.2E-5	9.2E-15	2.9E-5	7.3E-17	2.3E-7
Pu-238	6.5E-14	2.1E-4	2.6E-14	8.2E-5	1.8E-14	5.6E-5	1.2E-14	3.9E-5	9.7E-17	3.1E-7
Pu-239	5.1E-15	1.6E-5	2.0E-15	6.4E-6	1.4E-15	4.4E-6	9.5E-16	3.0E-6	7.6E-18	2.4E-8
Pu-240	7.4E-15	2.4E-5	2.9E-15	9.3E-6	2.0E-15	6.5E-6	1.4E-15	4.5E-6	1.1E-17	3.5E-8
Pu-241	1.6E-12	5.0E-3	6.3E-13	2.0E-3	4.3E-13	1.4E-3	3.0E-13	9.5E-4	2.4E-15	7.6E-6
Cm-244	3.7E-16	1.2E-6	1.5E-16	4.7E-7	1.0E-16	3.2E-7	7.0E-17	2.2E-7	5.5E-19	1.8E-9

Table 6.1. Estimated capital and annual costs and contribution to reprocessing and power costs for the model 1500-metric ton/year recycle uranium -- UF₆ plant

Radwaste treatment case	Capital cost ^a (\$1000)	Annual fixed charges (\$1000)	Annual operating cost ^b (\$1000)	Total annual cost (\$1000)	Conversion cost ^c (\$/kg U)	Contribution to power cost ^d (mills/kWhr)
<u>Total cost - base plant</u>						
1 ^e	20,000	5,200	2,080	7,280	4.85	0.02
<u>Additional cost for radwaste treatment systems</u>						
2	341 (20,341)	89 (5,289)	7 (2,087)	96 (7,376)	0.06 (4.91)	0.00026 (0.02026)
3	540 (20,540)	140 (5,340)	11 (2,091)	151 (7,431)	0.10 (4.95)	0.00041 (0.02041)
4	1,135 (21,135)	295 (5,495)	27 (2,103)	322 (7,598)	0.21 (5.06)	0.00086 (0.02086)
5a	3,322 (23,322)	864 (6,064)	71 (2,151)	935 (8,215)	0.62 (5.47)	0.0025 (0.0225)
5b	3,586 (23,586)	932 (6,132)	209 (2,298)	1,141 (8,421)	0.76 (5.61)	0.0031 (0.0231)

^aSystem and structure capital cost consists of direct and indirect costs. The interest during construction is included as an indirect cost.

^bAnnual operating costs are estimated at 40% of annual fixed charges, except for the venturi scrubbers and bag filters which are based on published information and on experience at ORNL for the HEPA filters. The annual costs of drums (\$73,600) and cement (\$47,300) for Case 5b are included as additional annual operating costs. The annual cost of storing the drums onsite, burial onsite, or shipping offsite for storage or burial is not included.

^cThe contribution to the conversion cost equals the annual cost divided by the 1.5×10^6 kg of uranium per year charged to the reactors.

^dThe contribution to power cost is computed on the basis of a 1500-metric ton/year recycle uranium UF₆ conversion plant servicing a nuclear economy of 32 1000-MW(e) PWRs (irradiation level, 33,000 MWd/metric ton; load factor, 80%; thermal efficiency, 32.5%) and 18 1000-MW(e) BWRs (irradiation level, 27,500 MWd/metric ton; load factor, 80%; thermal efficiency, 35%). The costs include the direct charges but do not include the effect of carrying charges on fuel working capital.

^eCase 1, the base case, represents a complete model recycle uranium conversion plant that produces UF₆ that is shipped to the enrichment plant. The 1973 capital cost of the plant is estimated at \$20,000,000. Radwaste treatment Cases 2-5b are additions to the base case; consequently, the total capital cost for Cases 2-5b would be \$20,000,000 plus the capital cost of the radwaste treatment case. The numbers in parentheses are total cost (i.e., base case plus added radwaste treatment cost).

Table 6.2. Installed cost^a of equipment for model 1500-metric ton/year recycle uranium -- UF₆ plant radwaste treatment: Cases 2-5b

Radwaste treatment case		Costs without structures (\$1000)	
		Direct ^b	Capital ^c
2	Pulse jet bag filter, 5300 scfm	89.3	214
	Pulse jet bag filter, 1800 scfm	<u>46.3</u>	<u>111</u>
		135.6	325
3	Pulse jet bag filter, 5300 scfm	89.3	214
	Pulse jet bag filter, 1800 scfm	46.3	111
	HEPA filters, 5300 scfm	40.9	98
	Coke-packed tower, 8 scfm	<u>36.0</u>	<u>86</u>
		212.5	509
4	Pulse jet bag filter, 5300 scfm	89.3	214
	Pulse jet bag filter, 1800 scfm	46.3	111
	Pulse jet bag filter, 15,000 scfm	166.0	398
	Coke-packed tower, 8 scfm	36.0	86
	HEPA filters, 5300 scfm	40.9	98
	HEPA filters, 1808 scfm	22.7	54
	HEPA filters, 4000 scfm	34.4	83
	High-energy venturi scrubber condenser, 128 scfm	4.5	11
High-energy venturi scrubber condenser, 68 scfm	<u>3.1</u>	<u>7</u>	
		443.2	1062
5a	Pulse jet bag filter, 5300 scfm	89.3	214
	Pulse jet bag filter, 1800 scfm	46.3	111
	Pulse jet bag filter, 15,000 scfm	166.0	398
	Pulse jet bag filter, 60,000 scfm (3)	911.0	2186
	Coke-packed tower, 8 scfm	36.0	86
	HEPA filters, 5300 scfm	40.9	98
	HEPA filters, 1808 scfm	22.7	54
	HEPA filters, 4000 scfm	34.4	83
High-energy venturi scrubber condenser, 128 scfm	4.5	11	
High-energy venturi scrubber condenser, 68 scfm	<u>3.1</u>	<u>7</u>	
		1354.2	3248
5b	Pulse jet bag filter, 5300 scfm	89.3	214
	Pulse jet bag filter, 1800 scfm	46.3	111
	Pulse jet bag filter, 15,000 scfm	166.0	398
	Pulse jet bag filter, 60,000 scfm (3)	911.0	2186
	Coke-packed tower, 8 scfm	36.0	86
	HEPA filters, 5300 scfm	40.9	98
	HEPA filters, 1808 scfm	22.7	54
	HEPA filters, 4000 scfm	34.4	83
High-energy venturi scrubber condenser, 128 scfm	4.5	11	
High-energy venturi scrubber condenser, 68 scfm	3.1	7	
Cement plant	<u>66.3</u>	<u>159</u>	
		1420.5	3407

^aDetails of the cost estimates are presented in Appendix A.

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

^cCapital cost is calculated by multiplying the direct cost by 2.4. Capital cost includes direct cost and indirect cost.

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

Site	Latitude (N)	Longitude (W)
Midwestern	35° 52' 50"	97° 35' 00"
	38° 12' 18"	90° 28' 28"
	41° 22' 43"	88° 16' 36"
Coastal	33° 15' 00"	81° 29' 20"
	33° 53' 13"	80° 55' 58"
	34° 19' 19"	77° 56' 12"

^aPopulation distributions are the average of population distributions around two fuel fabrication plants and one reprocessing plant.

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)		←————— 95 —————→					96	←————— 126 —————→		←————— 440 —————→		

^aStandard deviation of the mean (total).

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

Sector	Radial distance (miles)											
	0-0.5	0.5-1	1-2	2-3	3-4	4-5	5-10	10-15	15-25	25-35	35-45	45-55
N	0	0	0	151	0	46	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	124,804	169,238	305,647	429,036	552,990
Density (ind./mile ²)		←—————55—————→					289	←—————61—————→		←—————51—————→		

^aStandard deviation of the mean (total).

Table 7.4. Maximum dose^a to individuals^{b,c} from airborne effluents from the model
1500-metric ton/year recycle uranium -- UF₆ plant

Radwaste treatment case	Maximum total-body dose (millirem)	Maximum adult organ dose (millirem)									
		GI tract	Bone	Thyroid	Lungs	Muscle	Kidney	Liver	Spleen	Testes	Ovaries
<u>Midwestern site</u>											
1	6.1E-2	9.1E-2	5.4E-1	6.1E-2	2.8E-1	5.8E-2	1.3E-1	6.3E-2	4.9E-2	5.6E-2	4.8E-2
2	2.5E-2	3.7E-2	2.2E-1	2.5E-2	1.2E-1	2.4E-2	5.4E-2	2.6E-2	2.0E-2	2.3E-2	2.0E-2
3	1.8E-2	2.6E-2	1.6E-1	1.8E-2	8.2E-2	1.7E-2	3.8E-2	1.8E-2	1.4E-2	1.6E-2	1.4E-2
4	1.2E-2	1.8E-2	1.1E-1	1.2E-2	5.7E-2	1.2E-2	2.6E-2	1.3E-2	9.8E-3	1.1E-2	9.7E-3
5	9.6E-5	1.4E-4	8.6E-4	9.7E-5	4.5E-4	9.2E-5	2.1E-4	1.0E-4	7.7E-5	8.8E-5	7.6E-5
<u>Coastal site</u>											
1	5.5E-2	8.4E-2	4.7E-1	5.5E-2	2.4E-1	5.3E-2	1.2E-1	5.6E-2	4.4E-2	5.0E-2	4.3E-2
2	2.2E-2	3.3E-2	1.9E-1	2.2E-2	9.4E-2	2.1E-2	4.6E-2	2.2E-2	1.7E-2	2.0E-2	1.7E-2
3	1.5E-2	2.3E-2	1.3E-1	1.5E-2	6.5E-2	1.5E-2	3.2E-2	1.5E-2	1.2E-2	1.4E-2	1.2E-2
4	1.0E-2	1.6E-2	8.8E-2	1.0E-2	4.4E-2	9.8E-3	2.2E-2	1.0E-2	8.2E-3	9.4E-3	8.0E-3
5	8.4E-5	1.3E-4	7.3E-4	8.5E-5	3.7E-4	8.1E-5	1.8E-4	8.6E-5	6.7E-5	7.7E-5	6.6E-5

^a50-year dose commitment from exposure to effluents from 1 year's operation of the model plant.

^bMaximum dose to individuals at 1.5 miles and downwind of the prevailing wind direction; maximum doses at 0.5 mile and at 1.0 mile are 2.3 and 1.5 times higher.

^cAll food is produced and consumed at the location of the dose calculation. Daily intakes are 1 liter of milk, 0.25 kg of vegetables, and 0.3 kg of beef.

Table 7.5. Summary of annual doses^a to the population^b from airborne effluents from the model
1500-metric ton/year recycle uranium -- UF₆ plant

Radwaste treatment case	Total-body dose (person-rem)	Population organ doses (person-organ-rem)									
		GI tract	Bone	Thyroid	Lungs	Muscle	Kidney	Liver	Spleen	Testes	Ovaries
<u>Midwestern site</u>											
1	1.39E00	2.03E00	1.14E+1	1.40E00	5.72E00	1.33E00	2.83E00	1.39E00	1.10E00	1.27E00	1.08E00
2	5.51E-1	8.04E-1	4.52E00	5.54E-1	2.27E00	5.27E-1	1.12E00	5.50E-1	4.35E-1	5.02E-1	4.28E-1
3	3.81E-1	5.56E-1	3.13E00	3.84E-1	1.57E00	3.65E-1	7.76E-1	3.81E-1	3.01E-1	3.48E-1	2.96E-1
4	2.65E-1	3.86E-1	2.17E00	2.66E-1	1.09E00	2.53E-1	5.39E-1	2.64E-1	2.09E-1	2.41E-1	2.06E-1
5	2.09E-3	3.04E-3	1.71E-2	2.10E-3	8.59E-3	2.00E-3	4.25E-3	2.08E-3	1.65E-3	1.90E-3	1.62E-3
<u>Coastal site</u>											
1	7.53E-1	1.08E00	6.38E00	7.57E-1	3.34E00	7.20E-1	1.56E00	7.67E-1	5.97E-1	6.87E-1	5.87E-1
2	2.97E-1	4.26E-1	2.51E00	2.98E-1	1.31E00	2.84E-1	6.12E-1	3.01E-1	2.35E-1	2.71E-1	2.31E-1
3	2.04E-1	2.94E-1	1.72E00	2.06E-1	8.95E-1	1.96E-1	4.22E-1	2.07E-1	1.62E-1	1.86E-1	1.59E-1
4	1.40E-1	2.02E-1	1.18E00	1.41E-1	6.07E-1	1.34E-1	2.88E-1	1.42E-1	1.11E-1	1.28E-1	1.09E-1
5	1.13E-3	1.62E-3	9.51E-3	1.13E-3	4.96E-3	1.08E-3	2.32E-3	1.14E-3	8.92E-4	1.03E-3	8.77E-4

^a50-year dose commitment from exposure to effluents from 1 year's operation of the model plant.

^bTo the entire population within 55 miles of the model plant; daily intake assumed to be 0.25 kg of vegetables, 0.3 kg of beef, and 300 ml of milk. It is assumed that 100% of the food consumed is produced or grown at the location of dose calculation.

Table 7.6. Contribution of exposure modes to total-body dose from the airborne effluents of a model 1500-metric ton/year recycle uranium -- UF_6 plant^a

Exposure mode	Annual dose (millirem)	Percent of total dose
Immersion in air	4.9E-7	<0.1
Contaminated ground	3.5E-2	56.8
Inhalation ^b	8.9E-3	14.7
Ingestion ^c	1.7E-2	28.6

^aRadwaste treatment Case 1 at 1.5 miles from the plant in the prevailing wind direction; midwestern site.

^bDaily intake assumed to be 20 m³ of air.

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

Table 7.7. Contribution of major radionuclides^a to total-body and organ doses^b of individuals at 1.5 miles from the model 1500-metric ton/year recycle uranium -- UF₆ plant

Radionuclide	Percent of total-body and organ dose				
	Total body	GI tract	Bone	Lung	Kidney
Sr-90	0.05	0.01	0.31	0.01	0.02
Zr-95	0.21	0.24	0.03	0.05	0.09
Nb-95	0.11	0.44	0.01	0.03	0.05
Tc-99	0.20	25.8	0.06	0.07	4.26
Ru-103	0.01	0.17	0.00	0.00	0.00
Ru-106	0.35	19.0	0.08	0.11	0.45
Cs-134	0.49	0.22	0.05	0.01	0.18
Cs-137	0.58	0.30	0.08	0.11	0.24
Ce-144	0.01	0.25	0.01	0.01	0.01
Eu-154	0.05	0.03	0.01	0.01	0.02
Th-234	0.01	0.98	0.01	0.01	0.03
U-232	25.3	13.0	5.81	8.19	10.0
U-234	27.4	15.2	40.4	51.5	39.9
U-235	9.81	3.65	2.28	2.56	3.76
U-236	7.83	4.45	12.4	18.5	12.1
U-237	0.19	0.07	0.04	0.04	0.07
U-238	21.2	15.5	15.1	17.6	16.3
Np-237	1.82	0.40	2.74	0.34	3.56
Pu-238	2.61	0.06	11.6	0.74	5.12
Pu-239	0.22	0.00	1.05	0.05	0.45
Pu-240	0.33	0.01	1.53	0.08	0.65
Pu-241	1.14	0.08	6.24	0.02	2.53
Cm-244	0.05	0.07	0.10	0.01	0.12

^aRadionuclides contributing <0.01% are not included.

^bRadwaste treatment Case 1; midwestern site.

Table 7.8. Contribution of major radionuclides^a to total-body and organ doses^b of the population out to 55 miles from the model 1500-metric ton/year recycle uranium -- UF₆ plant, midwestern site

Radionuclide	Percent of total-body and organ dose (population)				
	Total body	GI tract	Bone	Lung	Kidney
Sr-90	0.04	0.01	0.27	0.01	0.02
Zr-95	0.23	0.26	0.03	0.05	0.10
Nb-95	0.12	0.43	0.02	0.03	0.06
Tc-99	0.16	22.2	0.05	0.06	3.76
Ru-103	0.01	0.19	0.00	0.00	0.01
Ru-106	0.37	20.7	0.09	0.12	0.50
Cs-134	0.40	0.19	0.05	0.08	0.17
Cs-137	0.58	0.30	0.09	0.13	0.25
Ce-144	0.01	0.27	0.01	0.01	0.01
Eu-154	0.05	0.03	0.01	0.01	0.02
Th-234	0.00	1.05	0.01	0.01	0.03
U-232	26.5	14.1	6.26	8.92	11.1
U-234	26.2	15.2	40.9	48.2	39.4
U-235	10.4	3.96	2.53	2.85	4.14
U-236	7.78	4.46	13.2	21.2	12.7
U-237	0.20	0.07	0.04	0.05	0.08
U-238	21.6	15.90	15.7	17.1	16.8
Np-237	1.70	0.43	2.49	0.38	3.19
Pu-238	2.15	0.06	10.3	0.68	4.45
Pu-239	0.19	0.00	0.93	0.05	0.39
Pu-240	0.27	0.01	1.36	0.07	0.57
Pu-241	0.94	0.08	5.57	0.02	2.21
Cm-244	0.06	0.07	0.11	0.01	0.13

^aRadionuclides contributing <0.01% to dose are not included.

^bRadwaste treatment Case 1.

Table 7.9. Contribution of major radionuclides^a to total-body and organ doses^b of the population out to 55 miles from the model 1500-metric ton/year recycle uranium -- UF₆ plant, southeastern coastal site

Radionuclide	Percent of total-body and organ dose (population)				
	Total body	GI tract	Bone	Lung	Kidney
Sr-90	0.04	0.01	0.25	0.01	0.02
Zr-95	0.22	0.26	0.03	0.05	0.10
Nb-95	0.12	0.43	0.02	0.03	0.05
Tc-99	0.16	22:1	0.05	0.06	3.63
Ru-103	0.01	0.19	0.00	0.00	0.01
Ru-106	0.36	20.7	0.09	0.12	0.48
Cs-134	0.40	0.19	0.05	0.07	0.16
Cs-137	0.57	0.29	0.08	0.12	0.24
Ce-144	0.01	0.27	0.01	0.01	0.01
Eu-154	0.05	0.03	0.01	0.01	0.02
Th-234	0.01	1.06	0.01	0.01	0.03
U-232	26.1	14.1	6.04	8.48	10.8
U-234	26.4	15.2	40.1	49.6	39.2
U-235	10.2	3.95	2.42	2.68	4.02
U-236	7.90	4.57	13.0	20.2	12.6
U-237	0.20	0.07	0.04	0.04	0.08
U-238	21.4	15.9	15.3	17.3	16.5
Np-237	1.78	0.43	2.68	0.36	3.47
Pu-238	2.42	0.06	11.3	0.71	4.92
Pu-239	0.21	0.00	1.01	0.05	0.43
Pu-240	0.31	0.01	1.48	0.08	0.63
Pu-241	1.05	0.08	6.05	0.02	2.44
Cm-244	0.05	0.07	0.11	0.01	0.12

^aRadionuclides contributing <0.01% to dose are not included.

^bRadwaste treatment Case 1.

Table 7.10. Percent of contribution of radionuclides^a to total-body dose^b by pathway from the airborne effluents of a model 1500-metric ton/year recycle uranium -- UF₆ plant

Radionuclide	Percent of total-body dose by pathway			
	Contaminated ground	Ingestion	Inhalation	Submersion in air
Sr-90	<0.1	0.1	<0.1	<0.1
Zr-95	0.2	<0.1	<0.1	<0.1
Nb-95	0.1	<0.1	<0.1	<0.1
Tc-99	<0.1	0.2	<0.1	<0.1
Ru-106	0.3	<0.1	<0.1	<0.1
Cs-134	0.3	0.3	<0.1	<0.1
Cs-137	0.5	0.1	<0.1	<0.1
Ce-144	<0.1	<0.1	<0.1	<0.1
Eu-154	0.1	<0.1	<0.1	<0.1
U-232	23.4	1.4	0.5	<0.1
U-234	5.4	17.0	5.4	<0.1
U-235	9.5	0.3	0.1	<0.1
U-236	1.1	4.8	1.9	<0.1
U-237	0.2	<0.1	<0.1	<0.1
U-238	15.0	4.9	1.6	<0.1
Np-237	0.9	<0.1	0.9	<0.1
Pu-238	<0.1	<0.1	2.6	<0.1
Pu-239	<0.1	<0.1	0.2	<0.1
Pu-240	<0.1	<0.1	0.3	<0.1
Pu-241	<0.1	<0.1	1.1	<0.1

^aRadionuclides contributing <0.1% are not included.

^bRadwaste treatment Case 1 at 1.5 miles from midwestern site plant.

Table 7.11. Percent contribution to organ dose^a of inhaled and ingested radionuclides^b from airborne effluents of a model 1500-metric ton/year recycle uranium -- UF₆ plant

Radionuclide	GI tract		Bone		Lung		Kidney	
	Inhaled ^c	Ingested ^d						
Sr-90	<0.1	<0.1	<0.1	0.3	<0.1	<0.1	<0.1	<0.1
Zr-95	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Nb-95	<0.1	0.4	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Tc-99	<0.1	25.8	<0.1	0.1	0.1	<0.1	<0.1	4.3
Ru-103	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Ru-106	<0.1	18.9	<0.1	<0.1	<0.1	<0.1	<0.1	0.3
Cs-134	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1
Cs-137	<0.1	0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1
Ce-144	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Th-234	<0.1	1.0	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
U-232	<0.1	0.2	0.7	2.2	3.0	0.3	0.3	1.0
U-234	0.1	16.1	9.7	30.1	47.4	3.6	9.5	29.6
U-235	<0.1	0.2	0.2	0.5	0.7	0.1	0.2	0.5
U-236	<0.1	4.2	3.5	8.7	17.4	1.0	3.5	8.6
U-238	<0.1	10.5	3.0	9.2	13.9	1.1	2.8	8.7
Np-237	<0.1	<0.1	2.5	0.1	0.1	<0.1	3.2	0.1
Pu-238	<0.1	0.1	11.5	0.1	0.7	<0.1	5.1	<0.1
Pu-239	<0.1	<0.1	1.0	<0.1	0.1	<0.1	0.4	<0.1
Pu-240	<0.1	<0.1	1.5	<0.1	0.1	<0.1	0.7	<0.1
Pu-241	<0.1	0.1	6.1	0.1	<0.1	<0.1	2.5	<0.1
Cm-244	<0.1	0.1	<0.1	0.1	<0.1	<0.1	<0.1	0.1

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^aRadwaste treatment Case 1; 1.5 miles from effluents of midwestern site plant.

^bRadionuclides contributing <0.1% are not included.

^cDaily intake of 20 m³ of air is assumed.

^dDaily intake of 0.25 kg of vegetables, 0.3 kg of beef, and 1 liter of milk is assumed. It is also assumed that 100% of the food consumed is produced or grown at the reference location.

Table 7.12. Curies and concentrations on the ground of long-lived radionuclides released during the 30-year life of the model 1500-metric ton/year recycle uranium -- UF₆ plant

Radionuclide	Release during 30-year life of plant ^a (Ci)	Concentration on the earth ^b (Ci/m ²)
Tc-99	8.3E-1	3.4E-11
U-232	2.1E-2	8.5E-13
U-234	1.4E00	5.7E-11
U-235	2.3E-2	9.3E-13
U-236	5.3E-1	2.2E-11
U-238	4.7E-1	1.9E-11
Np-237	2.3E-3	9.3E-14
Pu-238	6.2E-3	2.5E-13
Pu-239	4.8E-4	2.0E-14
Pu-240	7.1E-4	2.9E-14

^aRadwaste treatment Case 1, midwestern site. These values are divided by area within 55-mile radius ($2.46 \times 10^{10} \text{ m}^2$) of plant to give assumed deposition rate.

^bDeposition is assumed to occur uniformly out to a distance of 55 miles.

Table 7.13. Contribution of radionuclides and exposure modes from contaminated ground to the annual total-body dose^a to individuals from the time of cessation of the model 1500-metric ton/year recycle uranium -- UF₆ plant operation^b until significant decay of all radionuclides occurs

Radionuclide ^a	Total-body dose (millirem) per exposure mode			
	Contaminated ground	Inhalation	Ingestion	Total
Tc-99	0	1.2E-11	1.7E-7	1.7E-7
U-232	2.5E-6	4.5E-8	3.4E-7	2.9E-6
U-234	1.5E-4	5.5E-7	4.1E-6	1.5E-4
U-235	3.3E-5	8.2E-9	6.2E-8	3.3E-5
U-236	5.3E-5	2.0E-7	1.5E-6	5.5E-5
U-238	4.0E-7	1.6E-7	1.2E-6	1.8E-6
Np-237	1.5E-6	9.4E-8	7.2E-9	1.6E-6
Pu-238	6.5E-7	2.6E-7	2.0E-9	9.1E-7
Pu-239	2.0E-8	2.3E-8	1.8E-10	4.3E-8
Pu-240	6.5E-8	3.4E-8	2.7E-10	9.9E-8
Total	2.4E-4	1.4E-6	7.4E-6	2.5E-4

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

^bA 30-year lifetime for the plant is assumed.

Table 7.14. Annual dose^a to organs of individuals (from long-lived radionuclides deposited on the ground during the operating life^b of the model 1500-metric ton/year recycle uranium -- UF₆ plant) from cessation of plant operation until significant decay of all radionuclides occurs

Radionuclide	Organ dose (millirem) per exposure mode					
	GI tract		Bone		Kidney	
	Inhalation	Ingestion	Inhalation	Ingestion	Inhalation	Ingestion
Tc-99	3.8E-12	3.3E-5	3.1E-11	4.2E-7	5.7E-10	7.8E-6
U-232	2.6E-10	7.7E-8	6.5E-7	4.7E-6	7.0E-8	5.2E-7
U-234	1.5E-8	5.2E-6	8.8E-6	6.6E-5	2.1E-6	1.5E-5
U-235	2.9E-10	8.4E-8	1.5E-7	1.0E-6	3.2E-8	2.4E-7
U-236	5.7E-9	1.9E-6	3.3E-6	1.8E-5	7.8E-7	5.8E-6
U-238	4.9E-9	1.3E-6	2.7E-6	2.0E-5	6.1E-7	4.5E-6
Np-237	2.9E-11	8.4E-9	2.3E-6	1.8E-7	7.0E-7	5.4E-8
Pu-238	7.8E-11	7.7E-9	1.0E-5	8.2E-8	1.1E-6	8.7E-9
Pu-239	6.2E-12	6.2E-10	9.6E-7	7.6E-9	9.9E-8	7.7E-10
Pu-240	9.1E-12	9.0E-10	1.4E-6	1.1E-8	1.4E-7	1.1E-9
Total	2.6E-8	4.2E-5	3.0E-5	1.1E-4	5.6E-6	3.4E-5

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^aThe dose is the average individual dose out to a distance of 55 miles from the plant.

^bAn operating lifetime of 30 years is assumed.

Table 7.15. Annual dose to the population^a (resulting from long-lived radionuclides deposited on the ground during the lifetime^b of a model 1500-metric ton/year recycle uranium -- UF₆ plant) from the time of cessation of plant operation until significant decay of all radionuclides occurs

Radionuclide	Dose (person-rem or person-organ-rem per 3.6 x 10 ⁶ persons ^c)			
	Total body	GI tract	Bone	Kidney
Tc-99	6.1E-4	1.2E-1	1.5E-3	2.8E-2
U-232	1.0E-2	2.8E-4	1.9E-2	2.1E-3
U-234	5.4E-1	1.9E-2	2.7E-1	6.2E-2
U-235	1.2E-1	3.0E-4	4.1E-3	9.8E-4
U-236	2.0E-1	6.9E-3	7.8E-2	2.4E-2
U-238	6.5E-3	4.7E-3	8.2E-2	1.8E-2
Np-237	5.8E-3	3.0E-5	8.9E-3	2.7E-3
Pu-238	3.3E-3	2.8E-5	3.6E-2	4.0E-3
Pu-239	1.5E-4	2.2E-8	3.5E-3	3.6E-4
Pu-240	3.6E-4	3.3E-6	5.1E-3	5.1E-4
Total	8.9E-1	1.5E-1	5.1E-1	1.4E-1

^aDose to the population is the sum of the individual doses out to a distance of 55 miles from the plant.

^bA lifetime of 30 years is assumed for plant operation.

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

Table 8.1. Annual cost for reduction of the radiological dose of the model
1500-metric ton/year recycle uranium -- UF₆ plant

	Case 1	Case 2	Case 3	Case 4	Case 5a
Annual cost ^a (\$)	Base	9.60E+4	1.51E+5	3.18E+5	9.35E+5 ^b
<u>Midwestern Site</u>					
Maximum annual individual dose at 1.5 miles from airborne effluents, mrem					
Total body	6.1E-2	2.5E-2	1.8E-2	1.2E-2	9.6E-5
Bone	5.4E-1	2.2E-1	1.6E-1	1.1E-1	8.6E-4
Lung	2.8E-1	1.2E-1	8.2E-2	5.7E-2	4.5E-4
Kidney	1.3E-1	5.4E-2	3.8E-2	2.6E-2	2.1E-4
Annual total population dose out to 55 miles from airborne effluents, person-rem					
Total body	1.39E00	5.51E-1	3.81E-1	2.65E-1	2.09E-3
Bone	1.14E+1	4.52E00	3.13E00	2.17E00	1.71E-2
Lung	5.72E00	2.27E00	1.57E00	1.09E00	8.59E-3
Kidney	2.83E00	1.12E00	7.76E-1	5.39E-1	4.25E-3
<u>Coastal Site</u>					
Maximum annual individual dose at 1.5 miles from airborne effluents, mrem					
Total body	5.5E-2	2.2E-2	1.5E-2	1.0E-2	8.4E-5
Bone	4.7E-1	1.9E-1	1.3E-1	8.8E-2	7.3E-4
Lung	2.4E-1	9.4E-2	6.5E-2	4.4E-2	3.7E-4
Kidney	1.2E-1	4.6E-2	3.2E-2	2.2E-2	1.8E-4
Annual total population dose out to 55 miles from airborne effluents, person-rem					
Total body	7.53E-1	2.97E-1	2.04E-1	1.40E-1	1.13E-3
Bone	6.38E00	2.51E00	1.72E00	1.18E00	9.51E-3
Lung	3.34E00	1.31E00	8.95E-1	6.07E-1	4.96E-3
Kidney	1.56E00	6.12E-1	4.22E-1	2.88E-1	2.32E-3

^aMid-1973 dollars; annual cost for radwaste treatment for each case with reference to Case 1.

^bAdditional cost of \$2.05E+5 to incorporate radioactive solid waste in cement (Case 5b).

Table 8.2. Annual cost increments, dose decrements, and cost/benefits between case studies at the model 1500-metric ton/year recycle uranium -- UF₆ plant

Case increment	Increase in annual cost (\$1,000) ^a	Decrease in maximum annual individual dose at 1.5 miles (mrem)		Decrease in annual dose to population out to 55 miles (person-rem)		Cost/benefit				
		Total body	Bone	Total body	Bone	Individual at 1.5 miles (\$1,000/mrem)		Total population within 55 miles (\$1,000/person-rem)		
						Total body	Bone	Total body	Bone	
<u>Midwestern site</u>										
1/2	96	3.6E-2	3.2E-1	8.4E-1	6.9E00	2.7E+3	3.0E+2	1.1E+2	1.4E+1	
2/3	55	7.0E-3	6.0E-2	1.7E-1	1.4E00	7.8E+3	9.2E+2	3.2E+2	3.9E+1	
3/4	167 _b	6.0E-3	5.0E-2	1.2E-1	9.6E-1	2.8E+4	3.3E+3	1.4E+3	1.7E+2	
4/5a	617 ^b	1.2E-2	1.1E-1	2.6E-1	2.1E00	5.1E+4	5.6E+3	2.4E+3	2.9E+2	
<u>Coastal site</u>										
1/2	96	3.3E-2	2.8E-1	4.6E-1	3.9E00	2.9E+3	3.4E+2	2.1E+2	2.5E+1	
2/3	55	7.0E-3	6.0E-2	9.3E-2	7.9E-1	7.8E+3	9.2E+2	5.9E+2	6.9E+1	
3/4	167 _b	5.0E-3	4.2E-2	6.4E-2	5.4E-1	3.3E+4	4.0E+3	2.6E+3	3.1E+2	
4/5a	617 ^b	1.0E-2	8.7E-2	1.4E-1	1.1E00	6.2E+4	7.1E+3	4.4E+3	5.6E+2	

^aMid-1973 dollars.

^bAdditional cost of \$2.05E+5 to incorporate radioactive solid waste in cement (Case 5b).

Table 8.3. Annual cost for reduction of dose from airborne effluents at the model 1500-metric ton/year recycle uranium -- UF₆ plant -- dust control system^a

Case No.	Total annual cost increase over base (\$1000) ^b	Maximum annual individual dose at 1.5 miles (mrem)				Annual total population dose out to 55 miles (person-rem)	
		Total body	Bone	Lung	Kidney	Total body	Bone
<u>Midwestern site</u>							
1	Base	4.3E-2	3.8E-1	2.0E-1	9.1E-2	9.8E-1	8.0E00
2	96.0	6.2E-3	5.5E-2	3.0E-2	1.3E-2	1.4E-1	1.1E00
3	125.6	9.0E-4	8.0E-3	4.1E-3	1.9E-3	1.9E-2	1.6E-1
4	141.9	3.0E-6	2.7E-5	1.4E-5	6.5E-6	6.5E-5	5.4E-4
5a	141.9	3.0E-6	2.7E-5	1.4E-5	6.5E-6	6.5E-5	5.4E-4
<u>Coastal site</u>							
1	Base	3.9E-2	3.3E-1	1.7E-1	8.4E-2	5.3E-1	4.5E00
2	96.0	5.5E-3	4.7E-2	2.3E-2	1.1E-2	7.4E-2	6.2E-1
3	125.6	7.5E-4	6.5E-3	3.3E-3	1.6E-3	1.0E-2	8.6E-2
4	141.9	2.6E-6	2.3E-5	1.1E-5	5.5E-6	3.4E-5	2.9E-4
5a	141.9	2.6E-6	2.3E-5	1.1E-5	5.5E-6	3.4E-5	2.9E-4

^aDust control system exclusive of other systems.

^bMid-1973 dollars.

Table 8.4. Annual cost for reduction of dose from airborne effluents at the model 1500-metric ton/year recycle uranium -- UF₆ plant -- process off-gas^a

Case No.	Total annual cost increase over base (\$1000) ^b	Maximum annual individual dose at 1.5 miles (mrem)				Annual total population dose out to 55 miles (person-rem)	
		Total body	Bone	Lung	Kidney	Total body	Bone
<u>Midwestern site</u>							
1	Base	5.2E-3	4.6E-2	2.5E-2	1.1E-2	1.2E-1	9.6E-1
2	Base	5.2E-3	4.6E-2	2.5E-2	1.1E-2	1.2E-1	9.6E-1
3	25.4	3.1E-3	2.7E-2	1.4E-2	6.5E-3	6.5E-2	5.3E-1
4	62.1	2.5E-5	2.3E-4	1.2E-4	5.4E-5	5.4E-4	4.5E-3
5a	62.1	2.5E-5	2.3E-4	1.2E-4	5.4E-5	5.4E-4	4.5E-3
<u>Coastal site</u>							
1	Base	4.6E-3	3.9E-2	2.0E-2	9.9E-3	6.3E-2	5.4E-1
2	Base	4.6E-3	3.9E-2	2.0E-2	9.9E-3	6.3E-2	5.4E-1
3	25.4	2.6E-3	2.2E-2	1.1E-2	5.5E-3	3.5E-2	2.9E-1
4	62.1	2.1E-5	1.9E-4	9.3E-5	4.6E-5	2.9E-4	2.5E-3
5a	62.1	2.1E-5	1.9E-4	9.3E-5	4.6E-5	2.9E-4	2.5E-3

^aProcess off-gas system exclusive of other systems.

^bMid-1973 dollars.

Table 8.5. Annual cost for reduction of dose from airborne effluents at the model 1500-metric ton/year recycle uranium -- UF₆ plant -- building ventilation effluent^a

Case No.	Total annual cost increase over base (\$1000) ^b	Maximum annual individual dose at 1.5 miles (mrem)				Annual total population dose out to 55 miles (person-rem)	
		Total body	Bone	Lung	Kidney	Total body	Bone
<u>Midwestern site</u>							
1	Base	1.3E-2	1.2E-1	6.3E-2	2.9E-2	3.0E-1	2.4E00
2	Base	1.3E-2	1.2E-1	6.3E-2	2.9E-2	3.0E-1	2.4E00
3	Base	1.3E-2	1.2E-1	6.3E-2	2.9E-2	3.0E-1	2.4E00
4	114	1.2E-2	1.1E-1	5.7E-2	2.6E-2	2.6E-1	2.1E00
5a	731	6.8E-5	6.1E-4	3.2E-4	1.5E-4	1.5E-3	1.2E-2
<u>Coastal site</u>							
1	Base	1.2E-2	1.0E-1	5.1E-2	2.5E-2	1.6E-1	1.4E00
2	Base	1.2E-2	1.0E-1	5.1E-2	2.5E-2	1.6E-1	1.4E00
3	Base	1.2E-2	1.0E-1	5.1E-2	2.5E-2	1.6E-1	1.4E00
4	114	1.0E-2	8.8E-2	4.4E-2	2.2E-2	1.4E-1	1.1E00
5a	731	5.9E-5	5.2E-4	2.6E-4	1.3E-4	8.0E-4	6.7E-3

^aBuilding ventilation effluent exclusive of other systems.

^bMid-1973 dollars.

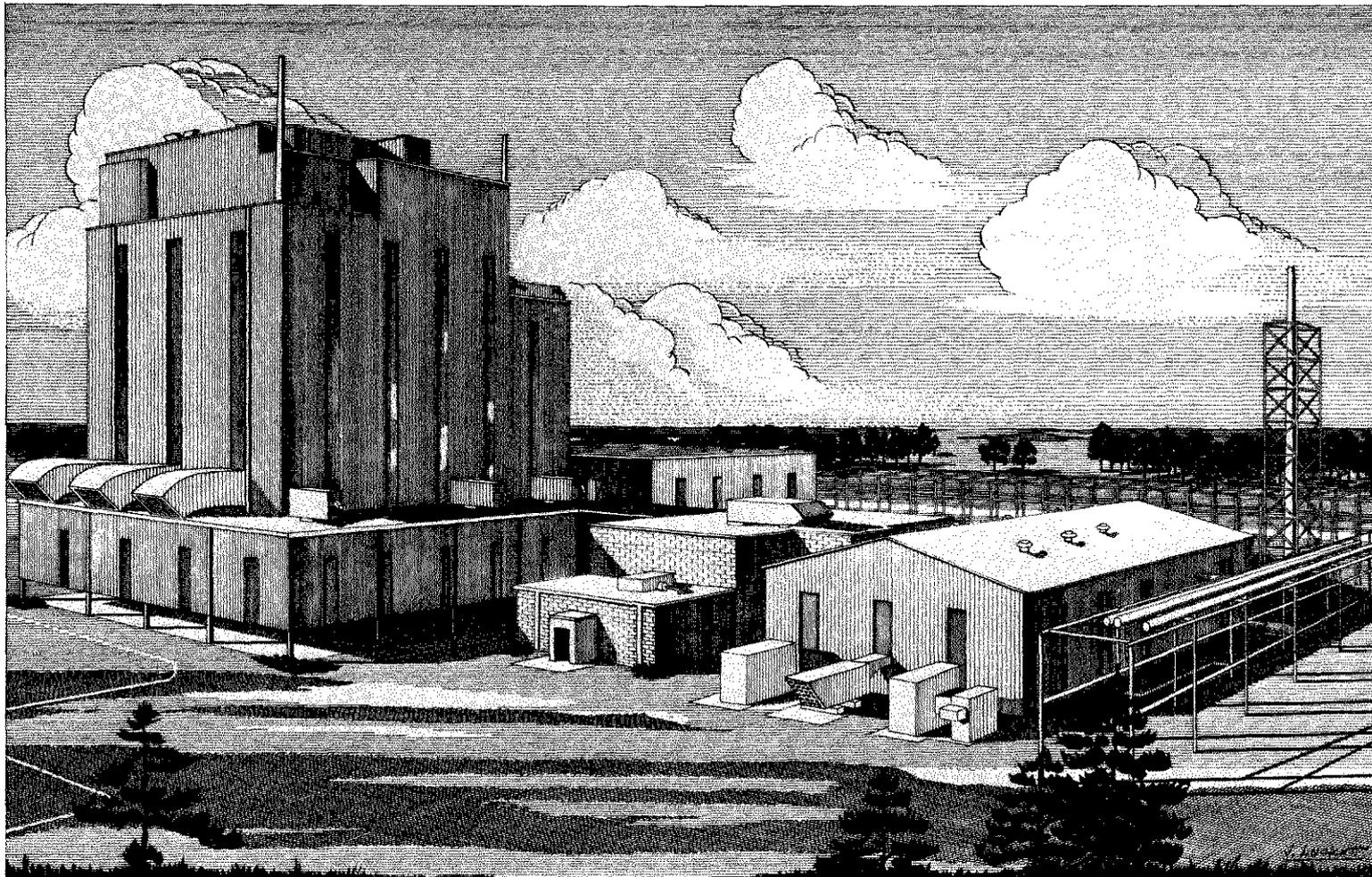


Fig. 3.1. Artist's conception of the UF_6 facility constructed by Allied-General Nuclear Services near Barnwell, South Carolina.

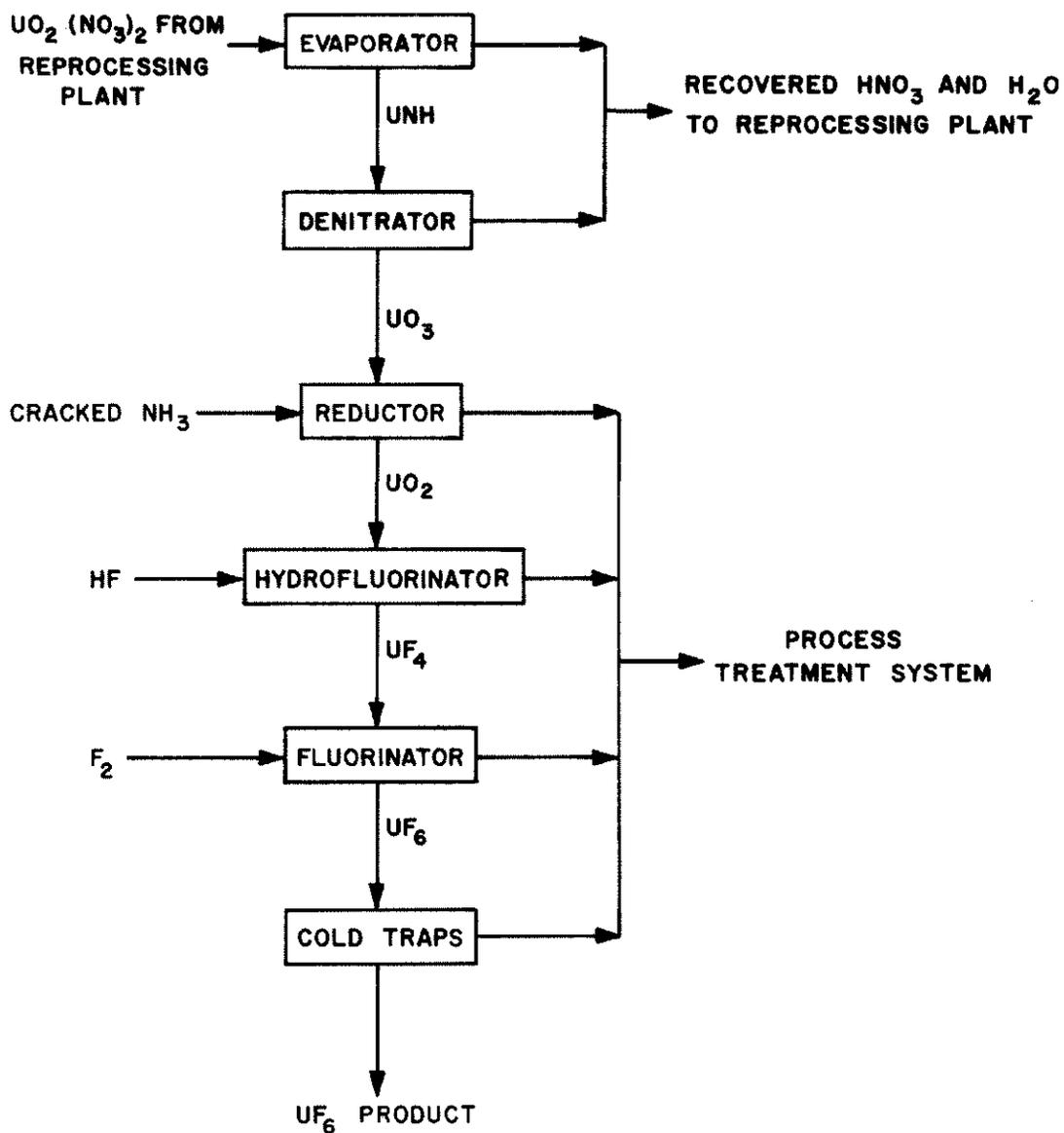
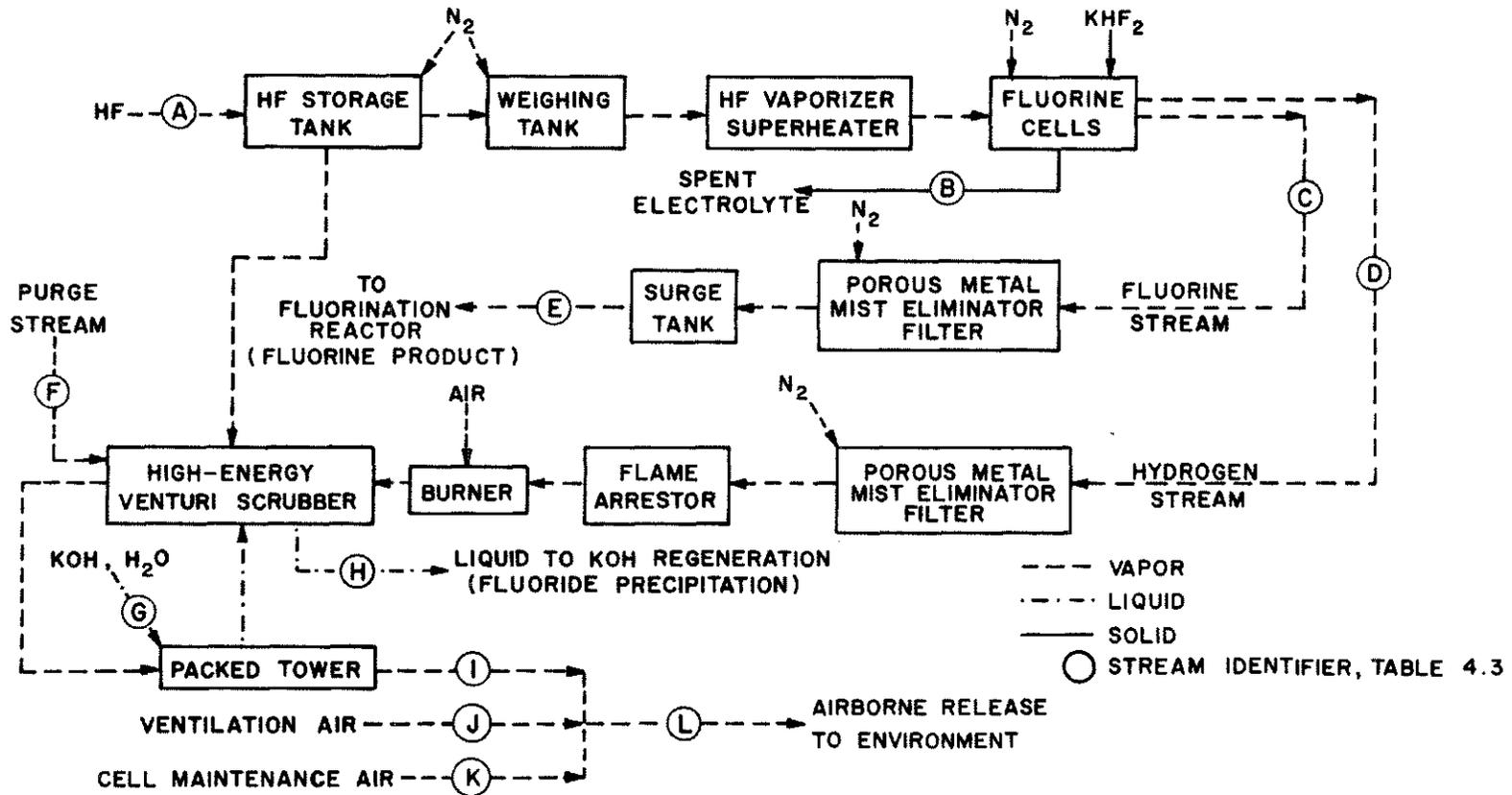


Fig. 3.2. Simplified flow diagram for the uranium hexafluoride process.



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Fig. 4.3. Process and waste treatment system for the production of fluorine.

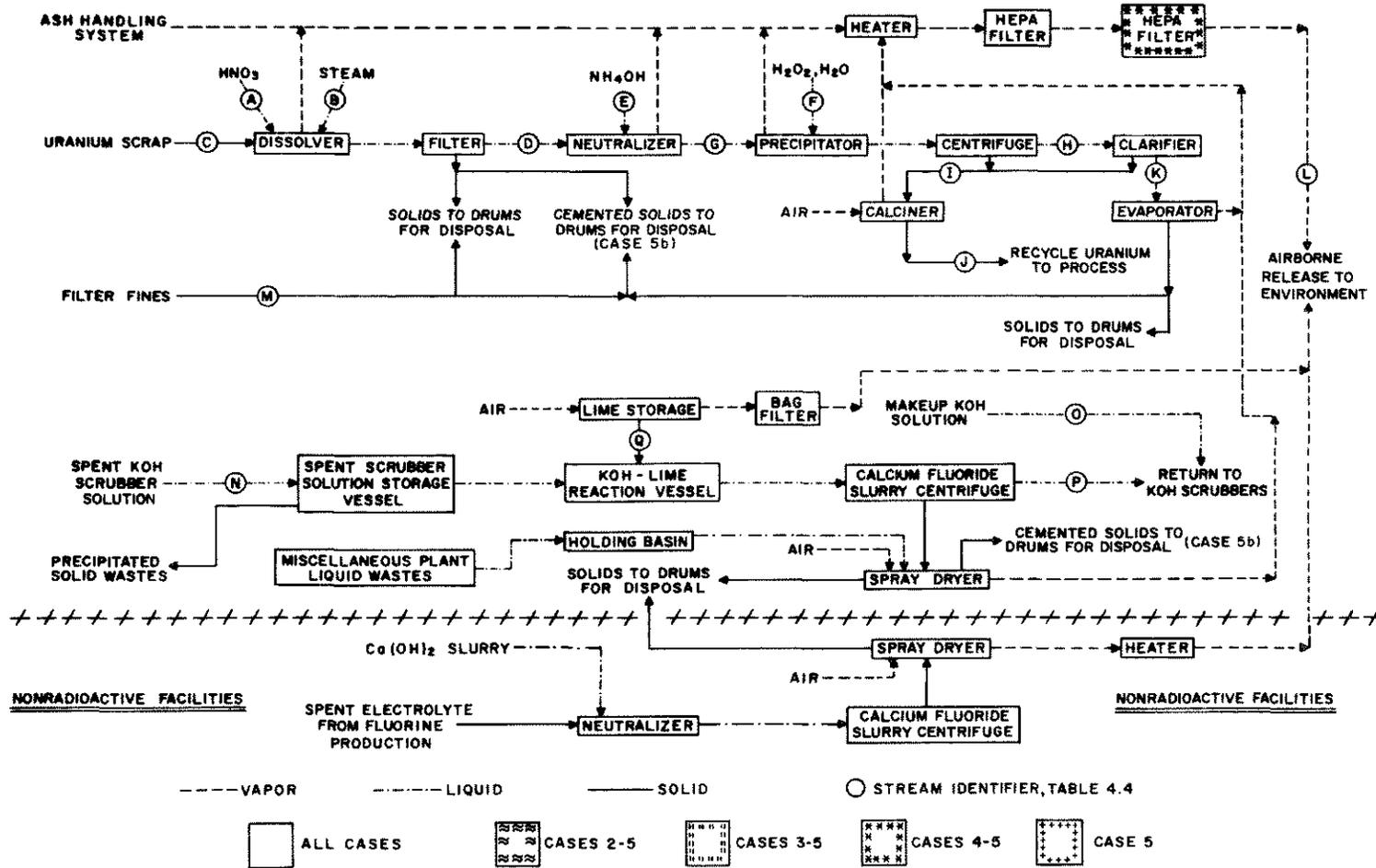


Fig. 4.4. Process and waste treatment system for the scrap recovery process.

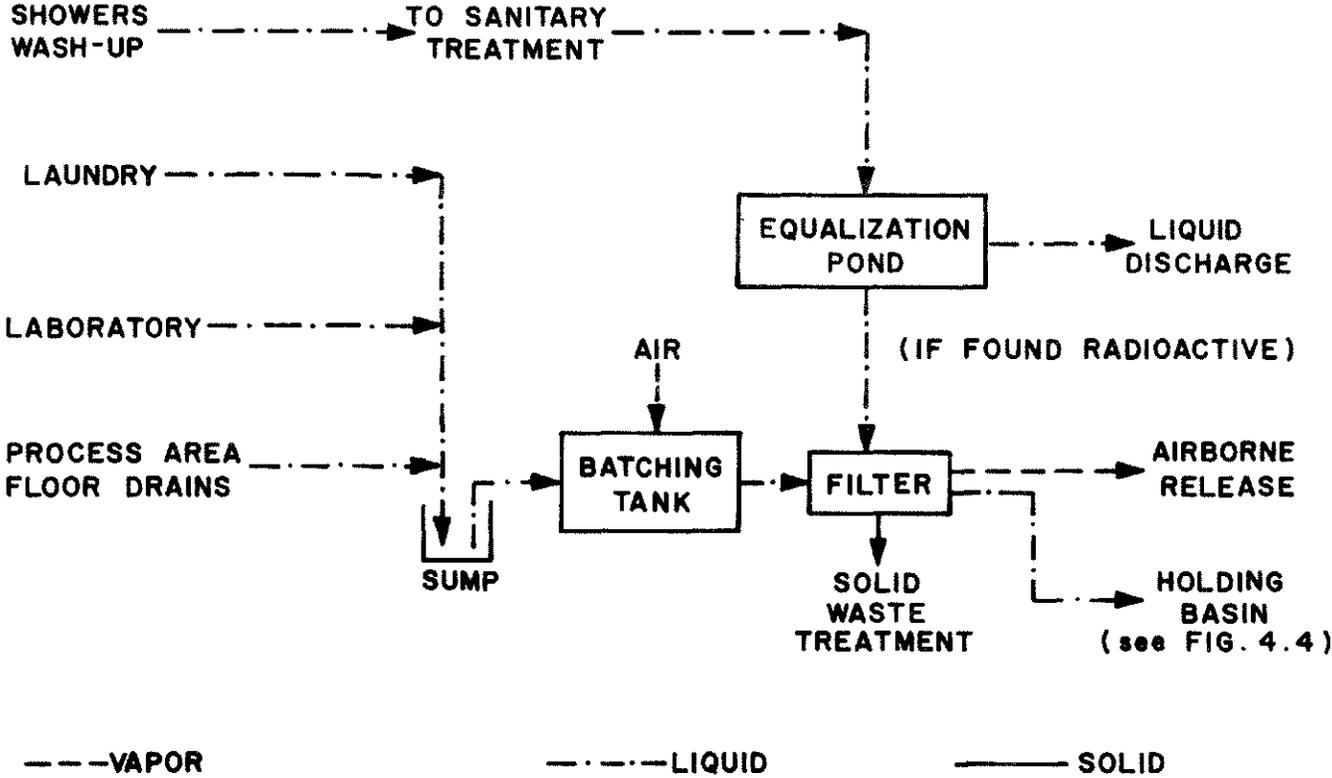


Fig. 4.5. Miscellaneous liquid waste treatment system.

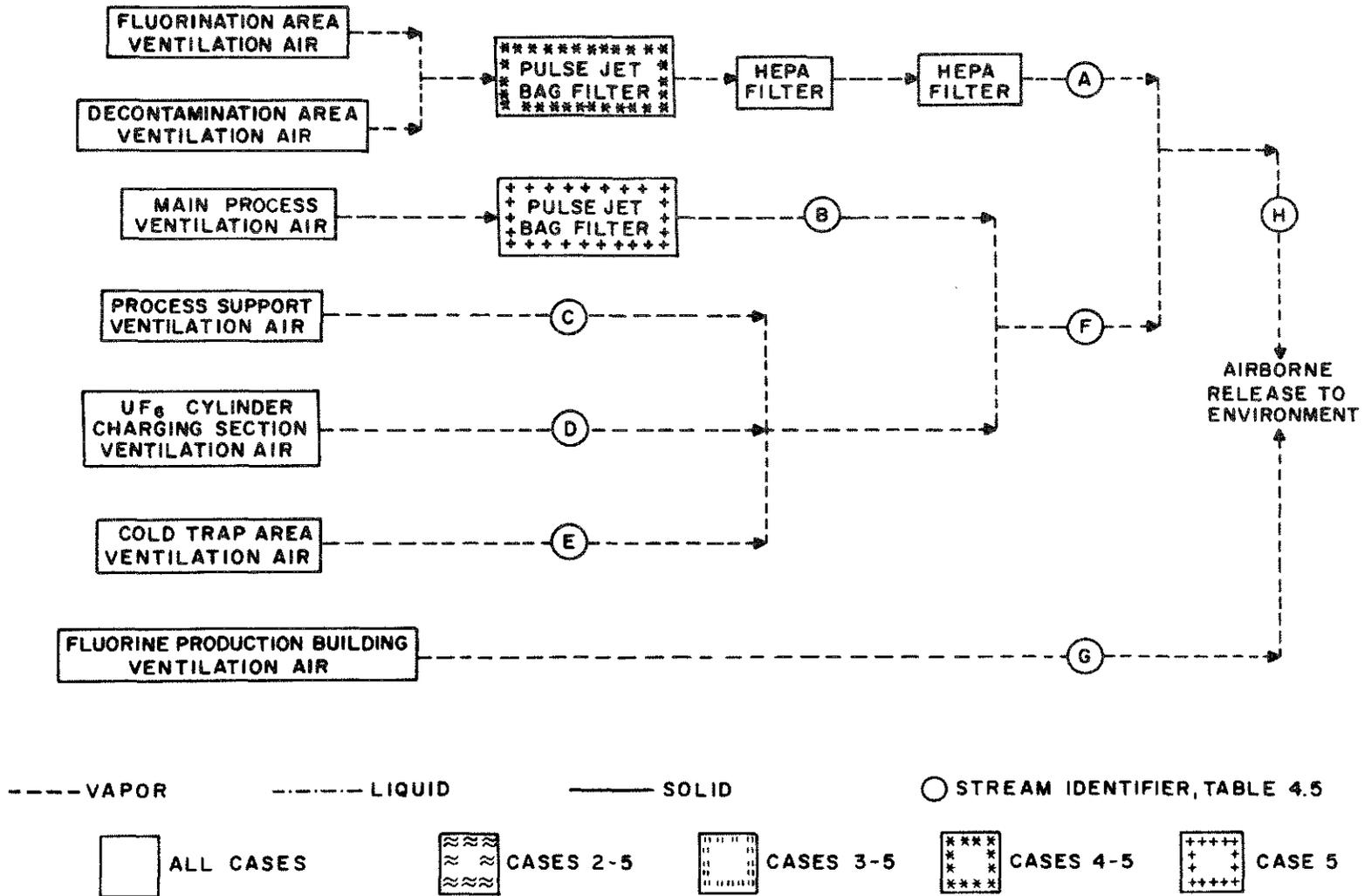


Fig. 4.6. Plant ventilation gaseous treatment system.

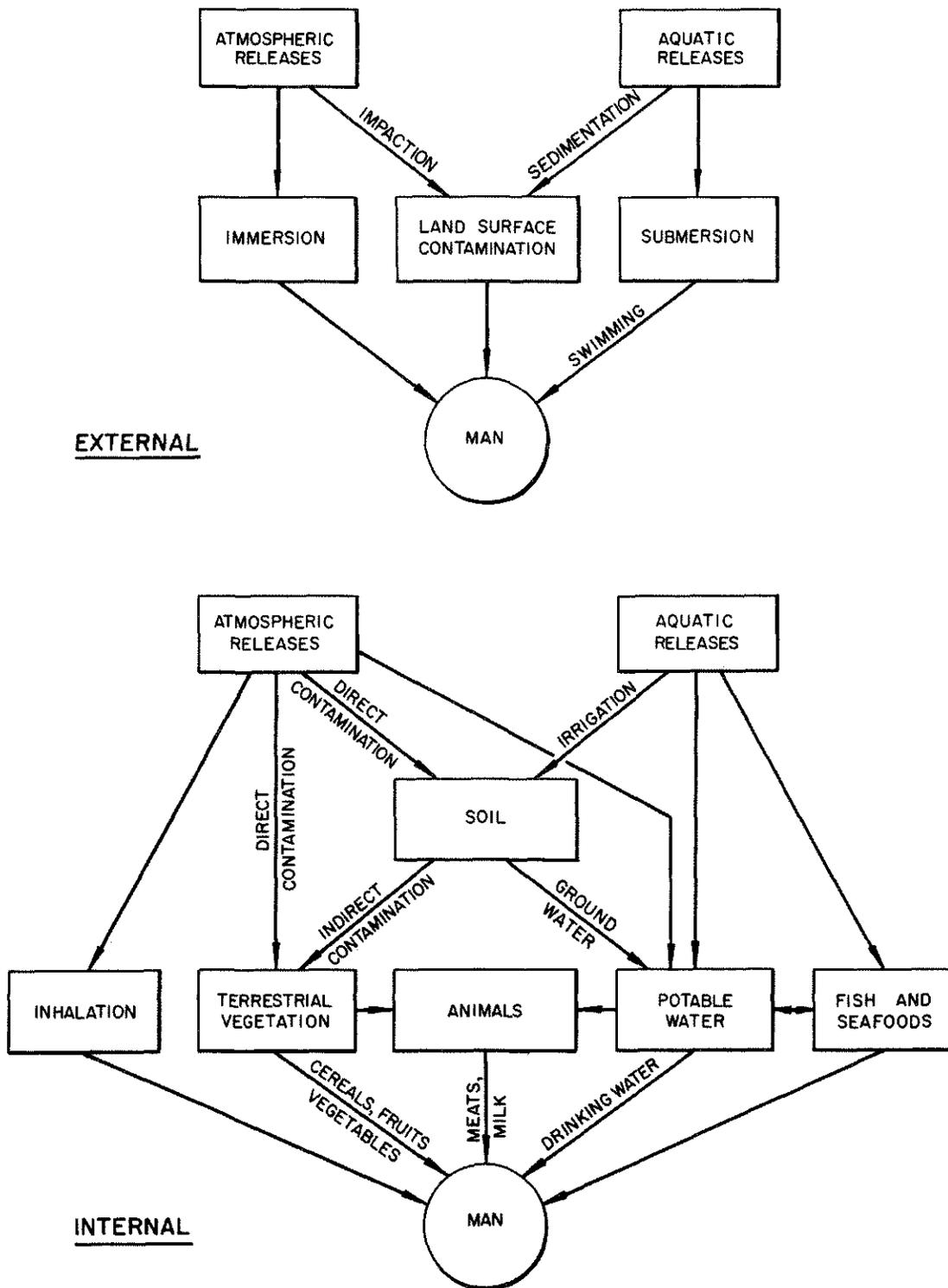


Fig. 7.1. Pathways for external and internal exposure of man.

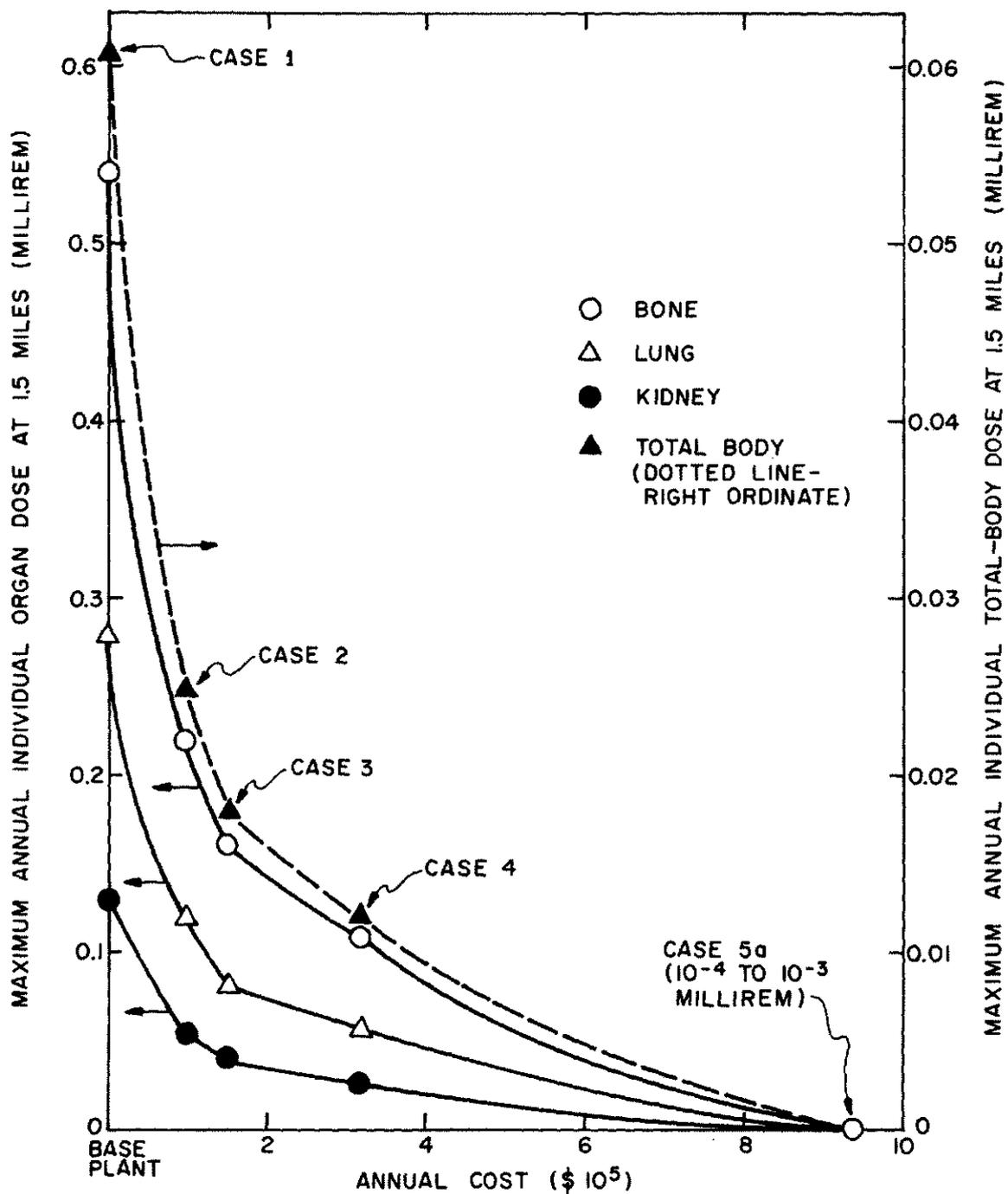


Fig. 8.1. Annual cost for reduction of maximum annual individual organ and total-body doses from airborne effluents at 1.5 miles from the model recycle uranium - UF_6 plant. (Doses are for the midwestern location.)

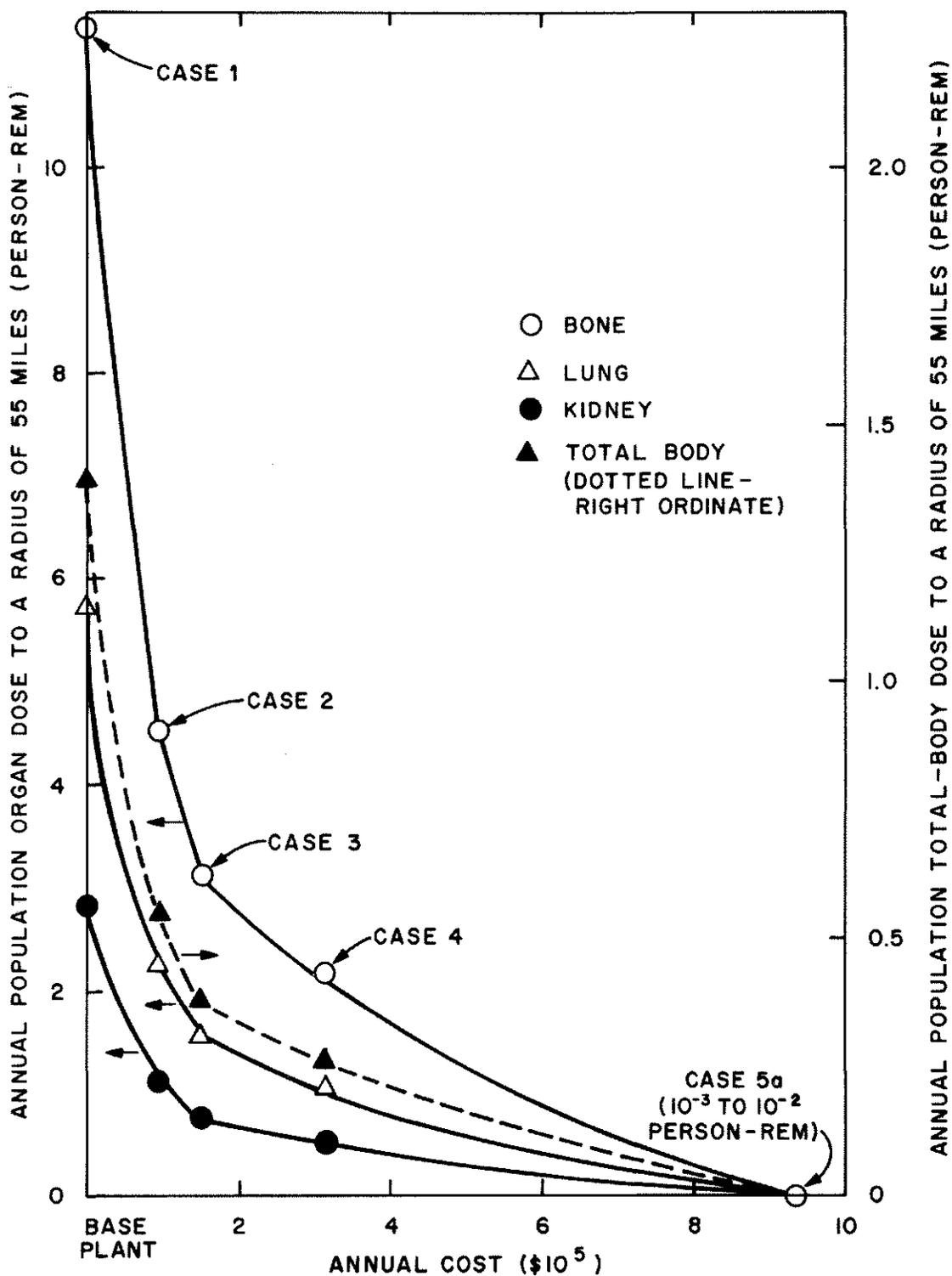


Fig. 8.2. Annual cost for reduction of annual population individual organ and total-body doses out to a radius of 55 miles from the model recycle uranium - UF₆ plant. (Doses are for the midwestern location).

APPENDIX A. PREPARATION OF COST ESTIMATES

1.0 INTRODUCTION

This appendix presents the details of the methods used to estimate the capital and annual costs of the radioactive waste treatment cases for the model 1500-metric ton/year recycle UF₆ plant. The details of the methods used for estimating the annual fixed charges, annual operating costs, total annual costs, and contribution to reprocessing and power cost are presented in Sect. 6.0 of the survey report. In summary, the capital cost is the sum of the direct cost (complete installation cost of the equipment and additional structure required) and the indirect cost, and the annual cost is the sum of the annual fixed charge (26% of the capital cost) and the annual operating and maintenance cost.

All costs are based on new construction costs where all of the equipment that is added for each case study is included in an integrated plant. Backfitting costs for existing plants are not considered. The costs of storing drums of solid waste onsite or shipping offsite for storage or burial are not included. The costs for radioactive waste treatment Cases 2 through 5b are presented in Table A-1.

1.1 Capital Costs

The capital cost of each radioactive waste treatment case 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 major equipment components were sized and a base cost estimated. The base cost for the conventional chemical equipment, such as packed towers, tankage, pumps, etc., is estimated based on general methods for costing equipment for conceptual designs. Appropriate factors are applied to the equipment cost to estimate the cost of installation, piping, instruments and controls, and electrical.¹⁻³ The base cost for the particulate removal equipment, venturi scrubbers, and bag filters is the complete installed cost, and it is estimated using published information.⁴⁻⁷ The cost for the HEPA filters is based on experience at ORNL.⁸⁻¹⁰

Structural requirements are estimated using equipment size and allowing for auxiliary equipment for Cases 2, 3, and 4; however, it is assumed that the building ventilation bag filters in Case 5a are installed exterior to the main structure in a self-contained housing and the cost of an additional structure is not required. The cost of a warehouse and related facilities is not included. The total direct cost for each treatment case is the sum of the installed equipment (material and labor) cost and the cost of the structure where applicable.

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	35
Total	140

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

1.1.3 Method of estimating costs

Radioactive Waste Treatment Case 2. Case 2 consists of installing a 5300-scfm pulse jet bag filter in the UO_3 feed preparation off-gas system (Fig. 4.1) and a 1800-scfm pulse jet bag filter in the UF_4 feed preparation off-gas system (Fig. 4.2).

The installed cost of the pulse jet bag filters is estimated based on the method used in ref. 6, assuming that the cost of a pulse jet bag filter is 1.1 times the cost of a reverse jet bag filter.

5300 scfm is equivalent to 7800 cfm at 70°F.

The 1965 estimated installed cost of a 60,000-cfm reverse jet bag filter was £73,000 which, at \$2.80/£, is equivalent to \$204,000 (Table IX, ref. 4).

The escalation factor from 1965 to March 1973 = $(141.0 - 104.2)/104.2 = 36.8/104.2 = 35.3\%$

The estimated installed cost of a 7800-cfm unit =
 $1.1 \times (7800/60,000)^{0.6} \times \$204,000 \times 1.353 = \$89,300$

It is estimated, based on the equipment size,¹¹ that a structural area of 180 ft² costing \$22/ft² is required, resulting in a structure cost of \$4000.²

The annual operating and maintenance (O&M) cost is estimated based on information presented in ref. 7, p. 1147, for 1974.

The calculations are as follows:

The annual O&M cost for a bag filter handling 70,000 scfm at 250°F is \$15,750 (ref. 7).

The annual O&M cost for a 7800-cfm bag filter is as follows:

$$70,000 \text{ scfm at } 250^{\circ}\text{F} = 52,300 \text{ cfm at } 70^{\circ}\text{F}$$

$$(7800/52,300)^{0.6} \times \$15,750 \times 0.94 = \$4700 \text{ (1973 dollars)}$$

$$\text{Building: Assume } 0.05 \times \$4000 = \$200$$

$$\text{Total O\&M} = \$4900$$

The installed cost and annual O&M cost for the 1800-scfm bag filter is estimated in a similar manner.

$$1800 \text{ scfm} = 2637 \text{ cfm at } 70^{\circ}\text{F} \text{ (Use } 2600 \text{ cfm)}$$

$$\text{Installed cost: } 1.1 \times (2600/60,000)^{0.6} \times \$20,400 \times 1.353 = \$46,300$$

$$\text{Structure cost: } 100 \text{ ft}^2 \text{ at } \$22/\text{ft}^2 = \$2200$$

$$\text{Total} = \$48,500$$

$$\text{Annual O\&M: } (2799/52,300)^{0.6} \times \$15,750 \times 0.94 = \$2500$$

The complete costs for Case 2 are as follows:

Direct Cost:

$$\text{Installed equipment} = \$135,600$$

$$\text{Structure} = \$6,200$$

$$\text{Total} = \$141,800 \text{ (Use } \$142,000)$$

Indirect Cost:

$$\$142,000 \times 1.4 = \$198,800 \text{ (Use } \$199,000)$$

Capital Cost:

$$\$142,000 + \$199,000 = \$341,000$$

Annual Fixed Charge:

$$\$341,000 \times 0.26 = \$88,660 \text{ (Use } \$89,000)$$

Annual O&M:

$$\$4900 + \$2500 = \$7400$$

Total Annual Cost:

$$\$89,000 + \$7400 = \$96,400 \text{ (Use } \$96,000)$$

Radioactive waste treatment Case 3. Case 3 includes Case 2 with the addition of a 5300-scfm-capacity HEPA filter installation in the UO_3 feed preparation off-gas system (Fig. 4.1) and an 8-scfm-capacity coke-packed tower in the UF_4 fluidized-bed fluorinator off-gas system (Fig. 4.2).

The cost estimate for the HEPA filter installation is based on the cost of a 16,000-cfm system installed at ORNL in April 1973.⁸⁻¹⁰

$$\begin{aligned} 5300 \text{ scfm with a 1.36 safety factor} &= 5300 \times 530/492 \times 1.36 \\ &= 7764 \text{ cfm at } 70^{\circ}\text{F} \end{aligned}$$

A 8000-cfm system is costed. The installed cost of the ORNL system including filter housing, SST ductwork, fans, filters, dampers, instrumentation, and electrical was \$62,000.

$$\begin{aligned} \text{Estimated cost of a 8000-cfm system} &= \$62,000 (8000/16,000)^{0.6} = \$40,900 \\ \text{Building: } 140 \text{ ft}^2 \text{ at } \$22/\text{ft}^2 &= \$3100 \\ \text{Total} &= \$44,000 \end{aligned}$$

Annual O&M:

$$\begin{aligned} \text{Fan power: } 20 \text{ hp} \times \$40/\text{yr-hp} \times 0.85 &= \$680 \\ \text{Filter testing twice per year: } \$30 \times 2 &= \$60 \\ \text{Filter replacement every 2 years: } \$700/2 &= \$350 \\ \text{Maintenance: Estimated at 3\% of equipment and building cost} & \\ = 0.03 \times \$44,000 &= \$1320 \\ \text{Total} &= \$2410 \text{ (Use } \$2400) \end{aligned}$$

The cost of the coke-packed tower is estimated as follows:

Assume that the tower is a 6-ft-diam x 20-ft-high rubber-lined mild-steel tank with 15 ft of activated charcoal as packing. The 1968 purchase price of the tower based on information presented in ref. 2, a field installation factor of 1.9, and an escalation factor of 6% per year for 5 years results in an installed cost of the tower as follows:

$$\begin{aligned} \$8000 \times 1.9 \times 1.06^5 &= \$20,300 \\ \text{Area of tower} &= [(0.7854 \times 36) + (\pi \times 6 \times 20)] = 434 \text{ ft}^2 \\ \text{Cost of lining} &= 434 \text{ ft}^2 \times \$4/\text{ft}^2 = \$1736 \text{ (use } \$1700) \\ \text{Cost of charcoal} &= (0.7854 \times 6^2 \times 15)(24 \text{ lb/ft}^3)(\$1.10/\text{lb}) = \$11,200 \\ \text{Total installed cost of tower} &= \$33,200 \end{aligned}$$

The cost of two 5-gpm centrifugal pumps based on information in ref. 2 is \$860. Using an installation factor of 2.4 and escalation of 6% for 5 years, the total direct cost is as follows:

$$\begin{aligned} \$860 \times 2.4 \times 1.06^5 &= \$2762 \text{ (Use } \$2800) \\ \text{Building: } 144 \text{ ft}^2 \text{ at } \$22/\text{ft}^2 &= \$3200 \\ \text{Total direct cost} &= \$39,200 \end{aligned}$$

The annual O&M cost is estimated at 3% of direct cost: $0.03 \times \$39,200 = \1200
The complete costs for Case 3 are as follows:

Direct Cost:

Installed equipment = \$212,500
 Structure = \$12,500
 Total = \$225,000

Indirect Cost:
 $\$225,000 \times 1.4 = \$315,000$

Capital Cost:
 $\$225,000 + \$315,000 = \$540,000$

Annual Fixed Charge:
 $\$540,000 \times 0.26 = \$140,400$ (Use \$140,000)

Annual O&M:
 $\$4900 + \$2500 + \$2400 + \$1200 = \$11,000$

Total Annual Cost:
 $\$140,000 + \$11,000 = \$151,000$

Radioactive Waste Treatment Case 4. Case 4 includes Case 3 with the addition of the following equipment:

1. 128-scfm high-energy venturi scrubber-condenser in the first-stage fluidized-bed hydrofluorinator off-gas (Fig. 4.2),
2. 1808-scfm HEPA filter system in the combined UF₄ feed preparation and UF₄ fluidized-bed fluorinator off-gas system (Fig. 4.2),
3. 68-scfm high-energy venturi scrubber-condenser in the UO₃ reductor off-gas system (Fig. 4.1),
4. 15,000-scfm pulse jet bag filter in the combined fluorination area and decontamination area ventilation systems (Fig. 4.6), and
5. 4000-scfm HEPA filter system in the combined ash handling calciner and spray dryer off-gas systems (Fig. 4.4).

The installed and annual O&M costs for the 128-scfm high-energy venturi is estimated using the method listed in ref. 6, which is based on information presented in ref. 5:

$128 \text{ scfm with safety factor of } 1.36 = 128 \times 530/492 \times 1.36 = 188 \text{ cfm at } 70^{\circ}\text{F}$

Cost with a 35.3% escalation factor =
 $(188/60,000)^{0.6} \times \$104,000 \times 1.353 = \$4400$
 Cost of demister at \$0.65/cfm = $188 \times 0.65 = \$122$
 Total = \$4522 (Use \$4500)
 Structure: Estimated 100 ft² at \$22/ft² = \$2200
 Total = \$6700

The annual O&M cost is estimated according to the method used in ref. 6, p. 80:

Power: $(188/60,000)^{0.6} \times \$41,600 \times 1.128 = \$1500$
 Water: $0.031 \times \$3390 \times 1.128 = \118

Maintenance Labor: $0.031 \times \$1005 \times 0.60 \times 1.258 \times 1.05 = \25

Material: $0.031 \times \$1005 \times 0.40 \times 1.145 \times 1.03 = \15

Total annual O&M = \$1700

The method used for estimating the installed and annual O&M cost of the 1808-scfm HEPA filter system is the same as that used for Case 3:

$1808 \text{ scfm} \times 530/492 \times 1.36 = 2648 \text{ cfm at } 70^{\circ}\text{F}$ (Use three 1000-cfm HEPA filters)

Installed equipment cost: $(3000/16,000)^{0.6} \times \$62,000 = \$22,700$

Structure: $(3000/16,000)^{0.6} \times \$3100 = \$1700$

Total = \$24,400

Annual O&M:

Maintenance: $0.03 \times \$24,400 = \732

Power: $10 \text{ hp} \times \$40/\text{hp-yr} \times 0.85 = \340

Filter Testing: twice per year, $\$30/\text{yr} \times 2 = \60

Filter Replacement: every 2 years, $\$300/2 = \150

Total = \$1282 (Use \$1300)

The estimated installed and annual O&M cost for the 68-scfm high-energy venturi is estimated as follows:

$68 \text{ scfm} \times 530/490 \times 1.36 \cong 100 \text{ cfm at } 70^{\circ}\text{F}$

Installed equipment cost: $(100/6000)^{0.6} \times \$104,000 \times 1.353 = \$3029$

Cost of demister: $100 \text{ cfm} \times \$0.65/\text{cfm} = \65

Total = \$3094 (Use \$3100)

Structure: $100 \text{ ft}^2 \times \$22/\text{ft}^2 = \$2200$

Total = \$5300

Annual O&M

$(128/188)^{0.6} \times \$1700 = \1349 (Use \$1400)

The estimated installed and annual O&M cost for the 15,000-scfm pulse jet bag filter is estimated as follows:

$15,000 \text{ scfm} \times 530/492 \times 1.36 = 22,000 \text{ cfm at } 70^{\circ}\text{F}$

Installed equipment cost:

$(22,000/60,000)^{0.6} \times \$204,000 \times 1.353 \times 1.1 = \$166,000$

Structure: ref. 11, p. 396

Assume: $7 \text{ cfm}/\text{ft}^2$ filter area = $22,000/7 = 3142 \text{ ft}^2$ filter area

360 ft^2 required at $\$22/\text{ft}^2 = \7900

Total = \$173,900 (Use \$174,000)

Annual O&M cost: ref. 7

Equipment: $(22,000/52,300)^{0.6} \times \$15,750 \times 0.94 = \$8800$

Structure: $0.05 \times \$7910 = \400

Total annual O&M = \$9200

The estimated installed and annual O&M cost for the 4000-scfm HEPA filter system is estimated as follows:

4000 scfm x 530/492 x 1.36 = 5860 cfm at 70°F (Use six 1000-cfm filters)

Installed equipment cost: $(6000/16,000)^{0.6} \times \$62,000 = \$34,400$

Structure: $140 \text{ ft}^2 \times \$22/\text{ft}^2 = \$3100$

Total = \$37,500

Annual O&M

Maintenance: $0.03 \times \$37,500 = \1125

Power: $15 \text{ hp} \times \$40/\text{hp-yr} \times 0.85 = \510

Filter Testing: twice per year, $\$30 \times 2 = \60

Filter Replacement: every 2 years, $\$500/2 = \250

Total = \$1945 (Use \$1900)

The complete costs for Case 4 are as follows:

Direct Cost:

Installed equipment = \$443,000

Structure = \$29,600

Total = \$472,600 (Use \$473,000)

Indirect Cost:

$\$473,000 \times 1.4 = \$662,200$ (Use \$662,000)

Capital Cost:

$\$473,000 + \$662,000 = \$1,135,000$

Annual Fixed Charge:

$\$1,135,000 \times 0.26 = \$295,100$ (Use \$295,000)

Annual O&M cost:

$\$11,000$ (Case 3) + \$1700 + \$1400 + \$1300 + \$9200 + \$1900 = \$26,500 (Use \$27,000)

Total Annual Cost:

$\$295,000 + \$27,000 = \$322,000$

Radioactive waste treatment Case 5a. Case 5a includes Case 4 and, in addition, the 120,000 scfm of main process ventilation air is passed through pulse jet bag filters (Fig. 4.6).

The installed and annual O&M costs are estimated as follows:

The volumetric flow at 70°F with a safety factor of 36% is:

$120,000 \times 530/492 \times 1.36 = 176,000 \text{ cfm}$

It is assumed that three 60,000-cfm pulse jet bag filters will be installed outside the main process building in a self-contained housing and that, consequently, an additional structure cost is not required.

Installed equipment cost: $3 \times \$204,000 \times 1.353 \times 1.1 = \$910,839$ (Use \$911,000)

Annual O&M cost:

$3 \times (60,000/52,300)^{0.6} \times \$15,730 \times 0.94 = \$48,000$

The complete costs for Case 5a are as follows:

Direct Cost:

Installed equipment = \$1,354,000

Structure = \$29,600

Total = \$1,383,600 (Use \$1,384,000)

Indirect Cost:

\$1,384,000 x 1.4 = \$1,937,600 (Use \$1,938,000)

Capital Cost:

\$1,384,000 + \$1,938,000 = \$3,322,000

Annual Fixed Charge:

\$3,322,000 x 0.26 = \$863,720 (Use \$864,000)

Annual O&M cost:

\$22,500 (Case 4) + \$48,000 = \$70,500 (Use \$71,000)

Total Annual Cost:

\$864,000 + \$71,000 = \$935,000

Radioactive waste treatment Case 5b. Case 5b includes Case 5a plus a cement plant, which is included for incorporating the filter fines bed material (Fig. 4.4) in cement and drumming the product. The costs of shipping the drums offsite for storage or burial are not included.

The installed equipment cost is estimated based on information presented in ref. 6, p. 190, and using a field installation factor of 1.8. The installed cost of the equipment comprising the cement plant is estimated as follows:

Solids to be handled:

	MT/year	Tons/year
Filter fines CaF ₂	67.5	74.3
Bed material CaF ₂	21	23.1
CaF ₂	165	181.5
Ca(OH) ₂	33.5	36.9
KOH	<u>107</u>	<u>117.7</u>
Total	394.0	433.5

It is assumed that the cement plant operates the equivalent of 150 days per year.

433.5 tons/year x 1 year/ 150 days = 2.89 (Use 3 tons/day)

It is assumed that the cemented solids have the following composition:

Cement	45%	9 tons/day
Solids	15%	3 tons/day
H ₂ O	40%	<u>8 tons/day</u>
Total		20 tons/day

Installed Equipment Cost:

Pneumatic Cement Unloader:

$$\$40,000 \times (9/50)^{0.6} \times 1.8 = \$12,900$$

Cement Storage Silo (75 tons):

$$\$34,774 \times (75/350)^{0.6} \times 1.8 = \$24,900$$

Drum Dumper: Assumed = \$6,000

Gravimetric Feeder:

$$\$6040 \times (75/350)^{0.6} \times 1.8 = \$4,300$$

Mixing Tank Rubber Lined:

$$\$11,704 \times (75/350)^{0.6} \times 1.8 = \$8,400$$

Slurry Pump:

$$\$4100 \times 2.4 = \$9,800$$

$$\text{Total} = \$66,300$$

Structure: Assume 100 ft² required

$$100 [(4.09 \times 1.3) + 1.75 + 1.5 + 1.7 + 1.1] \times 1.06^4 = \$14,400$$

Annual cost for drums:

$$20 \text{ tons/day} \times 150 \text{ days/year} \times 2000 \text{ lb/ton} = 6 \times 10^6 \text{ lb/year}$$

Assume density of cemented solids = 100 lb/ft³

$$(6 \times 10^6) / 100 = 60,000 \text{ ft}^3/\text{year}$$

A 55-gal drum is equivalent to 7.5 ft³

Assume: drums 90% filled - 7.5 x 0.9 = 6.75 ft³/drum

$$60,000 / 6.75 = 8900 \text{ drums/year at } \$10/\text{drum} = \$89,000$$

Allowance for Case 1 drums = \$15,400

Additional expense for Case 5b drums = \$73,600

Annual cost for cement: Assume \$35/ton

$$9 \text{ tons/day} \times 150 \text{ days/year} \times \$35/\text{ton} = \$47,250 \text{ (Use } \$47,300)$$

The complete costs for Case 5b are as follows:

Direct Cost:

$$\text{Installed equipment} = \$1,450,000$$

Structure = \$44,000
 Total = \$1,494,000

Indirect Cost:
 $\$1,494,000 \times 1.4 = \$2,091,600$ (Use \$2,092,000)

Capital Cost:
 $\$1,494,000 + \$2,092,000 = \$3,586,000$

Annual Fixed Charge:
 $\$3,586,000 \times 0.26 = \$932,360$ (Use \$932,000)

Annual O&M cost:
 Case 5a = \$71,000
 Cement Plant Annual Fixed Charge $\times 0.40 = \$16,600$
 Drums = \$73,600
 Cement = \$47,300
 Total = \$208,500 (Use \$209,000)

Total Annual Cost:
 $\$932,000 + \$209,000 = \$1,141,000$

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Table A-1. Summary of costs (dollars) for the model recycle uranium
 UF₆ plant - radwaste treatment Cases 2-5b

	Case 2	Case 3	Case 4	Case 5a	Case 5b
	5300-scfm pulse jet bag filters; 1800-scfm pulse jet bag filters	Case 2 plus 5300-scfm HEPA filters, 8-scfm coke-packed tower	Case 3 plus 128-scfm high-energy venturi, 68-scfm high-energy venturi, 15,000-scfm pulse jet bag filters, 1808-scfm HEPA filters, 4000-scfm HEPA filters	Case 4 plus three 60,000-scfm pulse jet bag filters	Case 5a plus cement plant
<u>Direct cost</u>					
Equipment	135,600	212,500	443,000	1,354,000	1,450,000
Structure	6,200	12,500	29,600	29,600	44,000
Total	142,000	225,000	473,000	1,384,000	1,494,000
<u>Indirect cost</u>					
Direct cost x 1.4	199,000	315,000	662,000	1,938,000	2,092,000
<u>Capital cost</u>					
Direct and indirect cost	341,000	540,000	1,135,000	3,322,000	3,586,000
<u>Annual fixed charges</u>					
Capital cost x 0.26	89,000	140,000	295,000	864,000	932,000
<u>Annual O&M</u>					
Calculated O&M	7,400	11,000	23,000	71,000	71,000
Annual fixed charge x 0.40					16,600
Drums					73,600
Cement					47,300
Total	7,400	11,000	23,000	71,000	209,000
<u>Total annual cost</u>					
Annual fixed charge and annual O&M	96,000	151,000	318,000	935,000	1,141,000

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196. G. G. Eichholz, Georgia Institute of Technology, School of Nuclear Engineering, Atlanta, Ga. 30332
197. B. Kahn, Environmental Resources Center, Georgia Institute of Technology, Atlanta, Ga. 30332
198. A. Schneider, Georgia Institute of Technology, School of Nuclear Engineering, Atlanta, Ga. 30332
199. M. Eisenbud, New York University Medical Center, Institute of Environmental Median, 550 1st Ave., New York, N. Y. 10016
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201. B. I. Spinrad, Radiation Center, Oregon State University, Corvallis, Oregon 97331
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204. B. L. Cohen, Department of Physics, University of Pittsburgh, Pittsburgh, Pa. 15261
205. K. G. Schiager, Department of Radiation Health, Graduate School of Public Health, University of Pittsburgh, Pittsburgh, Pa. 15261

206. F. L. Parker, Socio-Engineering, Vanderbilt University, Nashville, Tenn. 37235
207. T. R. Lash, National Resources Defense Council, Inc., 664 Hamilton Avenue, Palo Alto, Calif. 94301
208. W. R. Ney, Executive Director, National Council on Radiation Protection and Measurements, 7910 Woodmont Avenue, Suite 1016, Bethesda, Md. 20014
209. L. S. Taylor, National Council on Radiation Protection and Measurements, 7910 Woodmont Avenue, Suite 1016, Bethesda, Md. 20014
210. R. F. Foster, Pacific Northwest Laboratory, Battelle Memorial Institute, Box 999, Richland, Wash. 99352
211. D. A. Baker, Radiological Health Research, 3717 Bldg., 300 Area, Pacific Northwest Laboratories, P. O. Box 999, Richland, Wash. 99352
212. A. M. Platt, Pacific Northwest Laboratory, Battelle Memorial Institute, Box 999, Richland, Wash. 99352
213. K. J. Schneider, Pacific Northwest Laboratory, Battelle Memorial Institute, Box 999, Richland, Wash. 99352
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216. G. L. Simmons, Science Applications, Inc., 1200 Prospect St., LaJolla, Calif. 92037
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