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**Correlation of Radioactive Waste
Treatment Costs and the Environmental
Impact of Waste Effluents in the Nuclear
Fuel Cycle—Conversion of Yellow Cake
to Uranium Hexafluoride. (Part I.)
The Fluorination-Fractionation
Process**

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Prepared for the U.S. Nuclear Regulatory Commission
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CORRELATION OF RADIOACTIVE WASTE TREATMENT COSTS AND THE ENVIRONMENTAL
IMPACT OF WASTE EFFLUENTS IN THE NUCLEAR FUEL CYCLE - CONVERSION
OF YELLOW CAKE TO URANIUM HEXAFLUORIDE. PART I. THE
FLUORINATION-FRACTIONATION PROCESS

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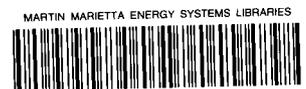
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CORRELATION OF RADIOACTIVE WASTE TREATMENT COSTS AND
THE ENVIRONMENTAL IMPACT OF WASTE EFFLUENTS IN THE
NUCLEAR FUEL CYCLE - CONVERSION OF YELLOW CAKE TO
URANIUM HEXAFLUORIDE. PART I. THE
FLUORINATION-FRACTIONATION PROCESS

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ABSTRACT

A cost/benefit study was made to determine the cost and effectiveness of radioactive waste (radwaste) treatment systems for decreasing the release of radioactive materials and chemicals from a model uranium hexafluoride (UF_6) production plant using the fluorination-fractionation (dry hydrofluor) process, and to evaluate the radiological impact (dose commitment) of the released materials on the environment. This study is designed to assist in defining the term "as low as is reasonably achievable" (ALARA) in relation to limiting the release of radioactive materials from nuclear facilities. The model plant processes 10,000 metric tons of uranium per year. Base-case waste treatment is the minimum necessary to operate the process. Effluents meet the radiological requirements listed in the Code of Federal Regulations, Title 10, Part 20 (10 CFR 20), Appendix B, Table II, but may not be acceptable chemically at all sites. Additional radwaste treatment techniques are applied 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 costs for the added waste treatment operations and the corresponding dose commitment are calculated for each case. In the final analysis, radiological dose is plotted vs the annual cost for treatment of the radwastes. The status of the radwaste treatment methods used in the case studies is discussed. Much of the technology used in the advanced cases will require development and demonstration or else is proprietary and unavailable for immediate use. The methodology and assumptions for the radiological doses are found in ORNL-4992.

1.0 SUMMARY

A study was made to determine the dollar cost and effectiveness of radwaste-chemwaste treatment systems for decreasing the amounts of radioactive materials and chemicals released from a model uranium hexafluoride (UF_6) production plant using the fluorination-fractionation (dry hydrofluor) process. A second objective was to estimate the radiological impact (50-year dose commitment) of the released radioactive materials on the environment.^a A UF_6 production facility purifies the semirefined uranium ore concentrate, called yellow cake, produced by the mills and converts it to UF_6 suitable for feed to the enrichment plants.

1.1 Model Plant

The model UF_6 plant processes 10,000 metric tons of uranium per year operating on a 300-day-per-year basis. Eighty-five percent of the plant feed is produced by the model acid leach mills and 15% by the model alkaline leach mills described in ORNL-4903. About 14,000 Ci of radioactivity enter the plant each year, most of which is natural uranium or the short-lived daughters ^{234}Th and ^{234m}Pa . Essentially all the uranium leaves the plant as UF_6 product. The ^{234}Th and ^{234m}Pa decay on-site. In the fluorination-fractionation process, most of the other radioactive impurities in the plant feed leave the plant as fluorides in a highly insoluble calcium fluoride waste, which is shipped off-site to an approved repository (burial ground). Liquid treatment systems in the advanced cases generate large quantities of solids containing very low levels (only slightly above background) of radioactive materials. The radionuclides of interest are ^{238}U , ^{235}U , ^{234}U , ^{230}Th , ^{226}Ra , ^{234}Th , ^{234m}Pa , and ^{222}Rn .

Off-site releases of radioactive materials consist of airborne dusts, radon gas, and both dissolved and suspended solids carried by liquid effluents to surface streams. In the most advanced case, there is no release of liquid bearing radioactive materials. Settling basins are lined with an impervious, synthetic material to minimize seepage or leaching of stored solids by natural waters.

^aThese are hypothetical studies and are not intended to be an environmental assessment of any existing UF_6 plant where the capacity, plant feed, waste treatment efficiencies, and environmental parameters may differ from the model.

1.2 Case Studies and Assumptions

Waste treatment. Four conceptual case studies and their corresponding flowsheets are presented for treating the effluents from the model UF₆ production plant (Sect. 4.0). The waste treatment systems consist of methods which (1) reduce the amount of airborne radioactive dusts released, (2) reduce the amount of noxious gases released, (3) reduce the amount of radioactive materials released in liquid effluents, (4) reduce the amount of chemicals released in liquid effluents, (5) treat liquid streams for recycle to the process, and (6) provide additional isolation of solid wastes from the environment. No treatment is provided for radon. The general plan is shown in Table S-1. A more detailed summary is presented in Table 1.1 (page 159). Case 1 represents the minimum treatment necessary to operate the process. Effluents meet the radiological requirements listed in 10 CFR 20, Appendix B, Table II, but may not meet the 40 CFR 190 environmental standards or be acceptable chemically at all sites. Waste treatment is principally for uranium recovery and reduction of noxious fumes. Case 1 serves as the base for the cost/benefit analysis; it does not necessarily describe current industrial practice. Case 2 treatment includes secondary bag filters on dust control streams, secondary or tertiary scrubbers on process off-gas streams, and chemical treatment of liquid wastes. In general, Case 2 represents the practical limits of technology which is readily available today. Cases 3 and 4 add treatments to the building ventilation effluent and use methods on the process off-gas which are either proprietary or in an early stage of development so that the systems are not available for immediate use. Case 4 also includes an evaporator so that there is no release of liquids bearing radioactive materials, and incorporates the solid wastes, containing the bulk of the ²²⁶Ra and ²³⁰Th, in cement to provide additional isolation in the event of drum failure.

The amounts of radioactive materials (the source terms) and chemicals released as well as the solid wastes generated are calculated for each case (Sect. 4.0). The various assumptions made in estimating the makeup of the feed to the plant, selecting the flows to the waste treatment systems, and determining the treatment efficiency ratings are realistically

Table S-1. Conceptual waste treatment case studies

	Case 1	Case 2	Case 3	Case 4
Level of waste treatment	Minimum, marginally licensable	Practical limit of technology today	Limit of technology in the public domain; may not be fully developed	Not available for immediate use; proprietary or in an early stage of development
Airborne effluents	Primary and sometimes secondary treatment of process off-gas for particulates and noxious chemicals	Primary and secondary treatment of all process off-gas; tertiary treatment of HF-bearing streams	Case 2 plus treatment of building ventilation effluent for particulates	Case 2 plus better treatment of building ventilation effluent, HEPA filters on process off-gas, and more efficient chemical usage in process
Liquid effluents	Uranium recovery	Case 1 plus fluoride treatment, recycle of KOH and Na ₂ CO ₃ streams	Case 2 plus radium treatment, new specifications on plant feed to eliminate some waste streams	Case 3 plus evaporator, more efficient chemical usage in process
Solid radwaste	Dry and drum (to burial ground)	Dry and drum (to burial ground)	Dry and drum (to burial ground)	Incorporate in cement and drum (to burial ground)
Solid chemwaste	Not applicable	Impound on-site	Impound on-site	Impound on-site

conservative. That is, source terms are based on operating data if available. When such data are not available, assumptions are chosen which tend to make the source terms or costs slightly high.

Doses. The radiological impact (50-year dose commitment, Sect. 7.0) for each case is assessed at a midwestern site characteristic of contemporary nuclear facilities including UF₆ production, and at a New Mexico site to illustrate the effects of siting a plant near the uranium mills. Doses are estimated for total body, bone, lung, kidney, GI tract, thyroid, muscle, liver, spleen, testes, and ovaries. Meteorologic data are derived from nearby first-order weather stations, and the population distribution is obtained from census tapes for the regions around several midwestern nuclear facilities or western uranium mills, respectively. Conservative (i.e., maximizing) assumptions are used in defining the movement of radio-nuclides in the environment and in selecting food and liquid consumption patterns. Estimates are presented of the maximum dose an adult living 0.5 mile (800 m) downwind from the model UF₆ plant might receive as a result of exposure to airborne plant effluents for one year and consuming food produced 0.5 mile downwind of the plant. A 16-ft (5-m) release height is assumed, which maximizes the doses. Dose reduction factors which may be applied for other release heights, food production and consumption pathways, and distances from the plant are presented (Tables 7.9-7.11). The dose to the total population (person-rem) within a 55-mile radius of the model plant is estimated. The airborne radioactive effluents are predominantly particulates. Since most particulates are deposited on the ground within 55 miles, there is little, if any radiological impact to the population beyond the 55-mile radius.

Annual dose commitments to individuals from liquid effluents are presented on two bases - after dilution in a 15-cfs stream and after the 15-cfs stream flows into a 1300-cfs river. Population dose is not estimated for liquid effluents since in a generic report it is not practical to predict a population distribution along a river or dilution by tributary streams.

Costs. The total annual costs for reduction of the radiological dose commitment and chemical exposure to the population surrounding the model UF_6 plant are summarized in Sect. 6.0. The total annual costs include costs for radwaste and chemwaste treatment of airborne and liquid effluents plus the cost of storing solids on-site or packaging solid wastes ready for shipment off-site. These costs do not include the costs of shipping, permanent disposal of solid wastes, decommissioning the plant, process changes at the uranium mills to meet new specifications on the chemical composition of the UF_6 plant feed, or development costs for the advanced treatment methods. Costs are estimated in mid-1973 dollars for the construction of a new plant to be consistent with other reports in this series. The costs do not include redundant (parallel) treatment units to ensure continued operation of complex systems in case one of the units should become inoperable.

1.3 Radiological Impact and Cost/Benefit Analysis for Feed Containing "High" Levels of ^{230}Th and ^{226}Ra Impurities^a

The annual cost of treatments which reduce releases from the model plant is correlated with the radiological impact (50-year dose commitment), the quantity of radioactive material released, or the quantity of chemicals released in Sect. 8.0. Assumptions tend to maximize the doses and, in some cases, to minimize the costs. Treatment of the various effluent streams is assessed separately before they are combined in the summary cases. Cost/benefit correlations of the combined treatment methods reveal only gross comparisons and mask many components of the cases where comparisons can be made regarding the relative cost/benefit of alternative procedures. There is some uncertainty in the source terms for ^{226}Ra and ^{230}Th , which is reflected in the dose estimates and cost/benefit analysis. However, this uncertainty does not affect the relative importance of the treatment methods.

Airborne effluents. The maximum annual individual doses at 0.5 mile from the model plant processing the "high-impurity" feed and the doses to the population out to 55 miles from airborne effluents are presented in

^aPlant feed contains 14,200 pCi of ^{230}Th and 1600 pCi of ^{226}Ra per gram of U_{nat} .

Tables S-2 and 8.1 for the midwestern site. The individual total-body dose is reduced from 9.9 mrem in Case 1 to 3.8 mrem in Case 2, and the bone dose from 130 mrem to 51 mrem respectively. The population total-body dose is reduced from 9.3 person-rem in Case 1 to 3.6 person-rem in Case 2. For airborne Cases 1/2, the incremental cost/benefit is \$51,000/person-rem total body and \$4,100/person-rem bone (Table 8.4). At the New Mexico site, individual doses are slightly higher than at the midwestern site, but population doses are much lower because the area is sparsely settled (Table 8.2). Further airborne dose reductions beyond Case 2 are possible but more expensive. Two-thirds of the releases in Case 2 are in the building ventilation effluent, which is expensive to treat because of the large volume of air that must be handled (\$180,000/person-rem total body and \$15,000/person-rem bone at the midwestern site). Most of the remaining releases in Case 2 are in the dust control effluent. The process off-gas is a minor contributor to the radiological dose. The amount of gaseous HF released is reduced from 88 lb/day in Case 1 to 1 lb/day in Case 2 (Table 8.1). Although further reduction in HF release is possible, the technology is both expensive and proprietary. Other gaseous chemical releases are discussed in Sects. 4.0 and 8.0.

The estimated doses to the individual receiving the maximum exposure represent the probable upper limit and are based on a number of maximizing assumptions about both the source terms and the environmental pathways. It is unlikely that all these maximizing assumptions would apply collectively to any one plant. Doses from a specific plant might be significantly lower than the doses estimated for the generic model. For example, the use of a 100-ft (30-m) release height instead of a 16-ft (5-m) height would reduce the maximum dose to an individual by a factor of 3 (Table 7.10). Removing the land in the immediate vicinity of the plant from food production would reduce the dose to the total body and to the bone (the critical organ) by nearly a factor of 2 (Table 7.9). Using a yellow cake feed which contains less ^{226}Ra and ^{230}Th than the model feed would also reduce the doses, since these impurities contribute half the total-body dose and 70% of the bone dose (Table 7.7). The estimated ^{226}Ra and ^{230}Th source terms used in the model may be high (Sect. 4.2.1 and Addendum).

Table S-2. Annual costs and total-body doses for the model UF₆ plant chemwaste-radwaste treatment case studies--feed containing "high" levels of ²³⁰Th and ²²⁶Ra impurities^a

	Case 1	Case 2	Case 3	Case 4
Annual cost increase over base, \$ (mid-1973 dollars)	Base	6.85E+5	1.14E+6	2.91E+6
Airborne effluents				
Maximum annual dose to individual at 0.5 mile, mrem	9.9 ^b	3.8 ^b	1.2	0.02
Annual dose to population out to 55 miles, person-rem	9.3	3.6	1.2	0.12
Liquid effluents				
Annual dose to individuals after dilution in:				
15-cfs stream, mrem	5.6 ^c	5.4 ^c	0.1	-
1300-cfs river, mrem	0.1	0.1	<0.1	-

^a10,000 metric tons of uranium/yr; fluorination-fractionation process; midwestern site; feed contains 14,200 pCi of ²³⁰Th and 600 pCi of ²²⁶Ra per gram of U_{nat}.

^bEstimates represent probable upper limit. It is unlikely that all the maximizing assumptions used in the model would apply collectively to any one plant.

^cIndividual is unlikely to use the 15-cfs stream because of the high salt content and small size.

Liquid effluents. Annual individual doses from untreated liquid effluents after dilution by a 1300-cfs river are 0.07 mrem total body and 0.7 mrem bone. Doses from using the waters of the 15-cfs stream are 80 times higher. It is unlikely that an individual would routinely use the 15-cfs stream as a source of drinking water or fish, or a locale for swimming because of its small size and the high chemical content of the releases (44,000 lb/day in Case 1). The Case 2 liquid treatment at an annual cost of \$393,000 reduces chemical releases (fluoride from 5100 lb/day to 21 lb/day; carbonate from 2600 lb/day to 150 lb/day, potassium from 7000 lb/day to 170 lb/day, and sulfide from 720 lb/day to approximately 0) but has very little effect on the doses. The Case 3 treatment to remove radium is effective in lowering the individual total-body dose from using the 1300-cfs river to 0.001 mrem and the bone dose to 0.02 mrem. The advanced Case 4 has an evaporator-dryer system in addition to chemical treatments for recycle of all liquids bearing radioactive materials. It is of marginal value radiologically. The benefit of retaining additional chemicals on-site in Case 4 will depend upon the characteristics of the receiving stream. The costs of liquid treatment for Case 3 and Case 4 are \$429,000 and \$461,000 respectively. The liquid case studies are not directly comparable because the feed to the treatment system is a variable which affects both costs and doses. Therefore, no incremental assessment is drawn for the liquid case studies. However, some incremental relationships for individual waste streams are presented in Sect. 8.4.

Isolation of solid waste from the environment. In Cases 1-3, a low-level CaF_2 ash from the fluid-bed fluorination is drummed and shipped off-site to a licensed waste disposal facility (burial ground). This waste contains traces of unrecovered uranium as well as small quantities of ^{226}Ra and ^{230}Th which are present in the yellow cake feed to the plant. It is a potential long-term source of ^{222}Rn gas from the decay of ^{226}Ra . The waste is nearly insoluble so that the leach rate will be low if it should happen to contact water in the environment. In Case 4, the fluorination ash is incorporated in cement at an annual cost of \$514,000. This dose not include the additional costs for shipping and burial of the cemented wastes. Cementing reduces the potential long-term radon release

as well as the already low potential for leaching by natural waters. The potential benefit of cementing the fluorination ash must be evaluated in terms of a specific waste disposal site, which is beyond the scope of this study.

In Cases 2-4, the liquid waste treatment systems generate large quantities of solid chemwaste, principally CaF_2 , from lime treatment of fluoride scrub liquors. Most of these wastes are nearly insoluble and contain levels of radioactive materials which are barely distinguishable from natural background. They are impounded on-site in settling basins lined with an impervious, synthetic material. Costs for the impoundment basins are considered as part of the liquid waste treatment. Other chemwastes are discussed in Sect. 4.0.

1.4 Radiological Impact and Cost/Benefit Analysis for Feed Containing "Low" Levels of ^{230}Th and ^{226}Ra Impurities^a

After completion of the original report, new data became available which indicate that the ^{230}Th and ^{226}Ra values used for the feed to the model plant in Sects. 1.3 and 4-8 are high. This development has a significant effect on the 50-year dose commitment from airborne effluents and the cost/benefit analysis. A brief assessment of the model plant for a feed containing "low" levels of ^{230}Th and ^{226}Ra impurities is attached in the Addendum to this report. Other parameters may be estimated from the factors given in Sects. 4-8.

The maximum annual individual doses at 0.5 mile from the model plant processing the "low-impurity" feed and the doses to the population out to 55 miles from airborne effluents are presented in Tables S-3 and A-12 for the midwestern site. The individual total-body dose is reduced from 4.9 mrem in Case 1 to 1.8 mrem in Case 2, and the bone dose from 47 mrem to 18 mrem respectively. The population total-body dose is reduced from 5.0 person-rem in Case 1 to 1.9 person-rem in Case 2. These values are about half the doses from the plant processing the "high-impurity" feed (Table S-2). For airborne Case 1/2, the incremental cost/benefit is \$94,000/person-rem total body and \$10,000/person-rem bone (Table A-15). At the New

^aPlant feed contains 2800 pCi of ^{230}Th and 200 pCi of ^{226}Ra per gram of U_{nat} .

Table S-3. Annual costs and total-body doses for the model UF_6 plant chemwaste-radwaste treatment case studies--feed containing "low" levels of ^{230}Th and ^{226}Ra impurities^a

	Case 1	Case 2	Case 3	Case 4
Annual cost increase over base, \$ (mid-1973 dollars)	Base	6.85E+5	1.14E+6	2.91E+6
Airborne effluents				
Maximum annual dose to individual at 0.5 mile, mrem	4.9	1.8	0.6	< 0.01
Annual dose to population out to 55 miles, person-rem	5.0	1.9	0.6	0.01
Liquid effluents				
Annual dose to individual after dilution in:				
15-cfs stream, mrem	5.6 ^b	5.4 ^b	0.1	-
1300-cfs river, mrem	0.1	0.1	<0.1	-

^a10,000 metric tons of uranium/yr; fluorination-fractionation process; midwestern site; feed contains 2800 pCi of ^{230}Th and 200 pCi of ^{226}Ra per gram of U_{nat} .

^bIndividual is unlikely to use the 15-cfs stream because of the high salt content and small size.

Mexico site, individual doses are slightly higher than at the midwestern site; however, population doses are much lower because the area is sparsely settled (Table A-13). Further airborne dose reductions beyond Case 2 are possible but more expensive. The relative importance of treating the different airborne streams is the same as discussed in Sect. 1.3, although the absolute cost/benefit ratio is less favorable (i.e., a smaller dose reduction per \$1000 spent on waste treatment).

The estimated doses to the individual receiving the maximum exposure represent the probable upper limit for the "low-impurity" feed and are based on a number of maximizing assumptions. It is unlikely that all of these assumptions would apply collectively to any one plant. Doses from a specific plant might be significantly lower than the doses estimated for the generic model. For example, the use of a 100-ft (30-m) release height instead of a 16-ft (5-m) height would reduce the maximum dose to an individual by a factor of 3 (Table 7.10). Removing the land in the immediate vicinity of the plant from food production would reduce the dose to the bone (the critical organ) by nearly a factor of 2 (Table A-7).

The relationships for treating liquid effluents from the model plant processing the "low-impurity" feed will be similar to those for the "high-impurity" feed (Sect. 1.3, Table S-2). This is because the major liquid source terms are estimated from solubility data rather than the plant feed.

Solid wastes are similar to those described in Sect. 1.3, except that they will contain smaller quantities of ^{230}Th , ^{226}Ra , and associated daughter products.

1.5 Contribution of the Cost of Radwaste Treatment to UF₆ Conversion and Total Nuclear Power Costs

The estimated 1973 capital cost of the base plant is \$35 million, including the Case 1 off-gas treatment system. Capital costs for the radwaste treatment systems in Cases 2-4 range from \$2.02 million to \$7.35 million, or 6 to 21% of the cost of the base plant. The annual cost increases over the base case for radwaste-chemwaste treatment range from \$683,000 to \$2,908,000 and are equivalent to a contribution to power of 0.0013 to 0.0054 mill/kWhr. Thus, while absolute dollar costs are high, the contribution to total power generation costs is low.

2.0 INTRODUCTION

This study was performed to determine the cost and effectiveness of additional or alternative radwaste-chemwaste treatment systems and internal process changes that are used, or could be used, at UF_6 conversion plants to decrease the amount of radioactive materials and chemicals released to the environment. A second objective is to estimate the radiological impact (50-year dose commitment) of these releases on the environment. The effectiveness of the alternate treatment systems under consideration is measured by comparing the quantities of radioactive materials released (the "source terms") by the various systems. The radiological impact on the environment is compared with the radwaste treatment costs as the basis for a cost/benefit analysis.

The function of a uranium conversion and UF_6 production facility is to purify semirefined uranium ore concentrate, called yellow cake, produced by the mills and to convert it to UF_6 suitable for feed to the enrichment plants. The radioactive materials are natural uranium in secular equilibrium with ^{234m}Th and ^{234m}Pa , and containing small amounts of ^{230}Th , ^{226}Ra , and other uranium daughters. All of the radioactivity is of natural origin in the earth's crust. The radioactive wastes are either prepared for shipment off-site or are impounded in on-site storage basins. Only small fractions of the radioactive materials and noxious chemicals are released as airborne particulates and gases. Liquid effluents contain varying quantities of radioactive materials and chemicals. In the most advanced case, all liquid streams bearing radioactive materials are treated and the water is recycled to the process.

This report presents a general overview of the UF_6 conversion industry and a detailed assessment of a model fluorination-fractionation (F-F) plant. The assessment of a model solvent extraction-fluorination (SX-F) plant is also in progress. Model flowsheets which serve to illustrate the waste treatment methods have been developed from the best available information, but are not necessarily representative of either existing or future plants. The radiological impact is considered at two sites, i.e., the model midwestern site and the model New Mexico site.

Case 1, which serves as the base for the cost/benefit analysis, contains the minimum treatment necessary for economically operating the process, including uranium recovery and 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; however, 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 advanced cases are contingent on technology which ranges from that currently in use to the foreseeable limits of available technology on the basis of expected typical operations over the next 30 years. Several of the advanced treatment methods are not presently available for industrial application and will require considerable development work and/or access to proprietary or classified information before the technology can be "reduced to practice." However, it is necessary to use such technology to predict cost/benefit relationships over the next few decades.

This report is one in a series of studies on the nuclear fuel cycle. Other reports in the series are concerned with reprocessing LWR fuels,¹ fabricating LWR fuels containing enriched uranium,² milling uranium ores,^{3,4} fabricating LWR fuels containing plutonium,⁵ fabricating HTGR fuels containing ^{233}U and thorium,⁶ and reprocessing HTGR fuels.⁷

2.1 References

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3.0 OBJECTIVES AND ASSUMPTIONS

3.1 Objectives

The objectives of this study are: (1) to determine the cost in dollars that would be required to reduce the amount of radioactive materials and chemicals released to the environment from conceptual UF₆ conversion plants, and (2) to evaluate the radiological impact (50-year dose commitment) of these releases. The definition of the incremental value of additional radioactive waste treatment equipment is an important part of the basic objective and is emphasized in the study. Generally, these values will not change significantly with the size of the plant. For example, the volume of waste effluent to be treated generally increases with the plant size, and larger treatment systems are required; however, essentially the same fraction is released for large and small systems. Thus, a larger total amount of radioactive material is released for the larger unit 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 the plant size and with the ²²⁶Ra and ²³⁰Th contents of the plant feed. The volumes and composition of radioactive wastes are based on model flowsheets developed from the available information.

Estimates are made of the average radioactive and nonradioactive releases and the cost of radioactive waste treatment. In a similar study for nuclear power reactors,¹ primary emphasis was placed on maintaining continuous operation of the power plant. Consequently, the more complex radioactive waste treatment systems contained redundant (parallel) treatment units to ensure continued operation in case one of the units should become inoperable. In the UF₆ 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, including anticipated operational occurrences, have been considered in this study.

3.2 Selection of the Model UF₆ Plants

There are two types of UF₆ plants - solvent extraction-fluorination (SX-F; five out of six refineries in the western world) (Sect. 4.1) and fluorination-fractionation (F-F). The primary difference is whether the uranium is purified by solvent extraction before conversion to UF₆ or by fractional distillation of the UF₆ after conversion. Both types of plants produce high-purity UF₆ suitable as feed to the enrichment plants. A model fluorination-fractionation plant (Part I) and a model solvent extraction-fluorination plant (Part II) are considered because they generate different wastes with regard to liquid and solid volumes, bulk chemicals, and radioactive element concentration. Even similar processes such as reduction, hydrofluorination, and fluorination require different flowsheets at the two model plants. Insofar as possible, the internal plant flowsheets are designed to be representative of the industry today and for the foreseeable future. The UF₆ industry is highly competitive both domestically and internationally. Because some technology is proprietary, the study team did not have access to detailed flowsheets giving the compositions and flow rates of the various effluent streams. The models serve to illustrate the various waste treatment methods, but they do not necessarily correspond to existing or future plants.

Each model UF₆ plant has an annual capacity of 10,000 metric tons of uranium. The processes are assumed to operate 24 hr/day for 300 days a year with the exception of uranium recycle operations, which operate 8 hr/day. It is assumed that the plant has sufficient surge capacity to continue operation when one section is down. Costs are amortized over 15 years. The assessment of long-term environmental impact is based on a 30-year operating life.

Descriptions of the model flowsheets are deferred to Sect. 4.4, where they are discussed in relation to the waste treatment systems.

3.3 Management of Radioactive Wastes

The most complex flowsheets in this study illustrate very low, but not zero, releases of radionuclides (Sect. 4.0).

Airborne effluents. Airborne effluents consist of radioactive particulates which are released through the dust control systems on dry materials handling operations, the process off-gas systems, and the building ventilation systems; noxious fumes such as HF, NO_x, H₂S, SO₂, and NH₃; and radon gas. Gaseous effluents are treated with filters and wet scrubbers to retain increasingly large fractions of the radioactive particulates, as well as noxious fumes. The case studies also include changes in internal processes and the plant feed which reduce the load to the waste treatment systems. Radon is a minor contributor to the dose; therefore, no radon treatment is provided.

Liquid effluents. Liquid effluents consist of a nitrate waste from the solvent extraction plant which contains significant quantities of radioactive materials, an ammonium sulfate-sodium sulfate waste and a sodium carbonate waste from the fluorination-fractionation plant, and scrub liquors from both plants which have high chemical contents (principally fluoride) but low concentrations of radioactive materials. The base plants release essentially untreated liquid wastes with only the minimum treatment required to meet 10 CFR 20 requirements. Both radwaste and chemwaste releases are reduced in subsequent case studies by impoundment, chemical treatment before liquid release, chemical treatment with liquid recycle, biological treatment before liquid release, evaporators with airborne water release, and evaporators with water recycle or nitric acid recovery. The case studies also include changes in internal processes in the plant feed to reduce or eliminate certain waste streams. All settling basins and impoundment lagoons are lined with an essentially impervious synthetic material to minimize seepage of radioactive materials and chemicals or potential leaching of stored solids by natural waters.² The most advanced case study has no release of liquid waste bearing radioactive materials to surface streams, but does have a release of a nonradioactive waste from the fluorine cells after treatment to remove fluorides.

Solid waste. The principal solid wastes are the solids generated by the liquid waste treatment systems and the leached fluorination ash which is generated by the fluorination-fractionation model plant and contains significant quantities of radioactive materials. Solids from treating scrub liquors, which have low solubilities in water and contain

only small concentrations of radioactive materials, are stored on-site in lined basins or pits. Solids which contain appreciable concentrations of radioactive materials and/or soluble chemicals are dried and drummed ready for shipment to a licensed waste disposal facility (burial ground). In the most advanced case, the solids containing most of the radium and thorium are incorporated in cement to isolate them from the environment, and are drummed for shipment to a burial ground. Still residues are stored at the fluorination-fractionation plant for possible future recovery. Dust collected on primary filters is automatically returned to the process. Vacuum cleaner systems are used for housekeeping, and the dust collected is processed through the scrap recovery system. Small amounts of miscellaneous wastes such as rags, clothing, sludges from the uranium settling basin, spent filters, spent filter bags, and old drums are generated. Combustible wastes are incinerated. All miscellaneous wastes containing uranium are processed through scrap recovery. Materials such as old drums or spent filters are buried. The case studies do not address the cost of final disposal such as shipping and burial or of decommissioning the plant since these costs will vary with the location of the plant.

3.4 Cost Parameters

Capital and annual costs are estimated for the waste treatment systems that are added to the base plant 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 for new model plants, and no attempt has been made to estimate backfitting costs for present plants. The capital cost of the base 10,000-metric ton/year UF_6 conversion plants is estimated as \$35 million in 1973. Costs are estimated in terms of 1973 dollars to make this report consistent with other reports in this series.³⁻⁹ Details of the cost estimating procedure are listed in Sect. 6.0 and Appendix A.

3.5 Equipment Operation

It is assumed that all radioactive wastes will be treated, i.e., wastes will not bypass treatment systems and be discharged even though the radioactive content of the untreated waste is lower than "permissible" licensing levels. The equipment is adequately sized to ensure high operating flexibility and efficiency factors. This type of design provides extra assurance that radioactive releases will not exceed the calculated design levels.

3.6 Plant Siting

The model UF_6 conversion plants are located at each of two sites - a midwestern site and a New Mexico site. The midwestern site is characteristic of contemporary commercial and ERDA nuclear facilities. The New Mexico site was selected for the alternate site to illustrate the environmental impact of locating a UF_6 plant near the mills that provide the plant feed. An arid climate would have advantages over a midwestern climate for the solvent extraction plant. The western site has certain disadvantages because of limited water supplies and poor north-south transportation from the Wyoming, Colorado, and Utah mills. In addition, the highly sophisticated chemical technology used in these plants must be serviced by readily accessible major-parts suppliers, which are generally not available in western locations.

Site 1 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 are derived from the first-order weather station at St. Louis, Missouri. The population distribution was determined by averaging the distribution around several nuclear installations in the Midwest. Distributions for sites near St. Louis, Missouri, were included in the averaging. Site 2 is located in a sparsely populated western area. The population distribution is determined by averaging the distributions around several uranium mills in New Mexico and Wyoming. Meteorological data are derived from the first-order weather station at Albuquerque, New Mexico. Site 2 is also located adjacent to a continuously flowing stream which empties into a large river. Site selection is described in detail in Sect. 7.0.

3.7 Radiological Impact

Radiation doses to the population and biota surrounding the model plants are estimated using the procedures currently being applied in the preparation of environmental impact statements for light-water-cooled, nuclear power stations by the U.S. Nuclear Regulatory Commission.¹ Pathways both for external radiation dose from sources outside the body and for internal dose from sources within the body are considered. Immersion in the airborne particulates and radon gas as they are diluted and dispersed leads to external exposure, and inhalation causes internal exposure. The deposition of radioactive particulates on the land surface leads to direct external exposure and to internal exposure by the ingestion of food products through various food chains. Similarly, swimming in waters containing radionuclides can lead to external exposure, whereas the harvest of fish or drinking from the waters can lead to internal exposures.

The estimated radiation doses to individuals, the human population, and the biota are calculated for annular distances out to 55 miles in 22.5° sectors using the site parameters listed in Sect. 7.1. Doses to individuals are calculated for the total body and individual organs. Population doses (person-rem) are the sum of the doses to all individuals in the population considered. Details of dose models, assumptions, and methods are given in Sect. 7.0.

3.8 References

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4.0 SOURCE TERMS FOR RELEASE OF RADIOACTIVE MATERIALS FOR FEED CONTAINING "HIGH" LEVELS OF ^{230}Th AND ^{226}Ra ^a IMPURITIES

The function of a yellow cake conversion and UF_6 production facility is to purify the semirefined uranium ore concentrate produced by the mills and to convert it to UF_6 suitable for feed to the enrichment plants. This is the third step (mining, milling, conversion) in the preparation of natural uranium for use as nuclear fuels. The only radioactivity handled by the plant is from naturally occurring sources (i.e., there are no fission products). Off-site releases of radioactive materials consist of airborne dusts, both dissolved and suspended compounds in liquid wastes, and small quantities of radon gas. Impoundment basins at the model plants are lined with a synthetic material to minimize the underground migration of radioactive materials that may occur as the result of seepage of liquid effluents or water leaching of stored solids.

A series of increasingly efficient (and increasingly expensive) radwaste treatment cases is presented for the model fluorination-fractionation UF_6 production plant (Table 1.1). There are four conceptual case studies which have been subdivided into airborne, liquid, and solid radwaste according to the type of plant effluent streams that must be treated. Uranium is a valuable commodity, and industry today uses sophisticated technology to minimize losses. Waste streams have a high chemical content because excess reagents are used, but are contaminated with only small amounts of radioactive materials. The removal of nonradioactive chemicals is also considered since (1) the advanced radwaste treatment methods must be designed on the basis of the chemical flowsheets, and (2) chemical releases are also of concern. These are hypothetical case studies and are not intended to be an assessment of any particular plant, which must be evaluated in terms of the specific parameters which apply at that site.

Generally, the release of radioactive materials decreases and the cost increases with increasing case number. Case 1, the base case,

^aSee Addendum for an assessment of a model plant processing a more realistic "low-impurity" feed.

represents the minimum treatment and lowest cost. Plant effluents meet the requirements of 10 CFR 20, Appendix B, Table II, but may not be acceptable chemically at all sites. Most Case 1 treatments are essential to the economical operation of the process and are, therefore, considered to be a part of the cost of the base plant, rather than an environmental protection cost. Case 1 does not necessarily represent current industrial practice. Case 2 treatment of process effluents generally represents the practical limit of existing technology in the public domain. Many of the Case 2 treatment methods are currently in use. Cases 3 and 4 include treatment of the building ventilation effluent; internal process changes at both the uranium mill to change the feed to the UF₆ plant, and at the UF₆ plant to reduce the load to the waste treatment systems; and advanced technology which is not ready for immediate use either because it is in an early stage of development or because it is proprietary. Airborne uranium releases are estimated from a straight-line extrapolation of data supplied by the industry and conservative assumptions in selecting treatment efficiency ratings which tend to maximize the amounts released. Uranium releases in liquids are, in part, extrapolated from data supplied by the industry and, in part, estimated from similar systems in uranium mill circuits. Releases of radionuclides other than uranium are estimated on the basis of general chemical principles assuming that the feed to the model UF₆ plant is the product of the model mills described in a previous report (ORNL/TM-4903). There is a great deal of uncertainty in the amounts of radium and thorium entering the plant, which introduces a similar uncertainty in the calculation of the amounts released from the plant (the source terms) and in the estimation of the radiological doses. For example, at the fluorination-fractionation model plant, ²²⁶Ra and ²³⁰Th combined contribute about 70% of the dose to the bone from airborne effluents, while ²²⁶Ra alone contributes about 90% of the dose from liquid effluents (Sect. 7.0). Technical descriptions of the systems and the calculated amounts of radioactive materials that would be released are given in Sect. 4.4.

4.1 The Uranium Conversion and UF₆ Production Industry

In 1974 six uranium refining facilities were operating in the western world to purify uranium ore concentrate (yellow cake): the Kerr-McGee Sequoyah plant (eastern Oklahoma),¹ the Allied Chemical plant (Metropolis, Illinois),² the ERDA-Fernald refinery (Ohio),^{3,4} the Eldorado Port Hope refinery (Canada),⁵ the Springfields refinery (Great Britain),⁶⁻⁸ and the Malvesi plant (France)^{9,10} (Table 4.1). Four of these plants - Kerr-McGee, Allied Chemical, Eldorado, and Springfields - produce UF₆ suitable for feed to the enrichment plants. Uranium hexafluoride is also made at the ERDA gaseous diffusion plants at Paducah, Kentucky,¹¹ and Portsmouth, Ohio,¹² using purified feed from a refinery or fuel reprocessing plant. Other products of a uranium refinery may include "nuclear-grade" uranium dioxide (UO₂), uranium metal, and uranium tetrafluoride (UF₄), but most uranium is converted to UF₆. The ERDA Weldon Spring refinery and the UF₆ production facilities at the Oak Ridge Gaseous Diffusion Plant have been closed. The Australians have no refinery.¹³

The processes used in the central refineries and UF₆ production facilities require high levels of supporting and operating technology plus relatively expensive raw materials (H₂, HF, and F₂). Since the technology and raw materials are not generally available at remote mill sites, UF₆ production facilities are not located near mills. In the fall of 1974, the Allied Chemical plant¹⁴ had a capacity of about 13,000 metric tons of uranium per year and Kerr-McGee¹⁵ of about 5000 metric tons of uranium per year compared with the annual yellow cake production by all U.S. mills of 10,000 to 11,000 metric tons of uranium for the period 1968-1972.¹⁶ The solvent extraction system at the Kerr-McGee plant has a capacity of 10,000 tons of uranium per year, and the company expects to expand the UF₆ conversion capacity in the near future.¹⁵ On a world basis, refineries usually have an annual capacity of at least 2500 to 5000 tons of uranium.¹³ The domestic commercial plants provide conversion services to foreign countries.

The ERDA facilities primarily handle special materials, although Fernald is still processing some ore concentrate from the ERDA stockpile.¹⁷ Fernald processes a variety of uranium scrap materials from off-site ERDA

programs, recycle UO_3 , and uranyl nitrate from irradiated fuel reprocessing.⁴ The principal product at Fernald is UO_2 , although it has the capability of making UF_4 and uranium metal.¹⁸ Portsmouth is a small (20-metric ton/year) facility designed specifically for enriched uranium.¹²

4.2 Composition and Amount of Radioactive Material Processed by the Model UF_6 Production Plant

4.2.1 Feed to the model UF_6 production plant

The model UF_6 plant processes 10,000 metric tons of natural uranium per year in the form of ore concentrate (yellow cake) produced by domestic uranium mills. The feed to the model UF_6 plant is assumed to be a composite product of the model uranium mills (85% acidleached--amine solvent extracted and 15% alkaline leached),¹⁹ which has aged at least 6 months in sealed drums after milling. Impurities other than radionuclides, ammonium ion, and sodium are based on the average current feeds to the Allied Chemical UF_6 plant, the Kerr-McGee UF_6 plant, and the ERDA-Fernald Refinery. The major chemical and radionuclide constituents for Cases 1 and 2 are listed in Table 4.2 and the assumptions in Table 4.3. The model does not consider radionuclides introduced as impurities in the chemical or water feed to the plant.

The radionuclides of primary concern are $U_{(nat)}$,^a ^{226}Ra , ^{230}Th , ^{234}Th , ^{234m}Pa , and ^{222}Rn . The daughter products of radon are not listed individually

^aThe "old" (prior to July 10, 1974) definition of a curie of natural uranium (U_{nat}) is used throughout this report to be consistent with the earlier report in this series on uranium mills.¹⁹ One curie of U_{nat} is the sum of 3.7×10^{10} dis/sec from ^{238}U , 3.7×10^{10} dis/sec from ^{234}U , and 9×10^8 dis/sec from ^{235}U ; it is also equivalent to 3000 kg of natural uranium. Under this definition, 1 kg of U_{nat} is equivalent to 333.3 μCi of U_{nat} or the sum of 333.3 μCi of ^{238}U , 333.3 μCi of ^{234}U , and 8.1 μCi of ^{235}U . Under the "new" (July 10, 1974) definition, 1 kg of U_{nat} is equivalent to 677 μCi of U_{nat} , or the sum of 330.9 μCi of ^{238}U , 330.9 μCi of ^{234}U , and 15.4 μCi of ^{235}U . In calculating source terms, there is about a 1% difference between the "old" and the "new" curie, except for ^{235}U , which is only a minor contributor to the dose (Sect. 7.0).

as source terms either because they have half-lives of less than 2 hr and do not accumulate in the bioenvironment (^{218}Po , ^{214}Pb , ^{214}Bi , and ^{214}Po) or because they individually contribute less than 0.02% of the total relative hazard (^{210}Pb , ^{210}Bi , ^{210}Po). However, the daughter products are included when the dose from radon is calculated. The relative hazard is estimated by dividing the curies present by the Radiation Concentration Guide for that nuclide (presented in 10 CFR 20, Appendix B, Table 2, Column 1, soluble nuclide).

In Cases 1 and 2, a simplified feed consisting of a mixture of $(\text{NH}_4)_2\text{U}_2\text{O}_7$, UO_3 , and $\text{Na}_2\text{U}_2\text{O}_7$ is used to illustrate the waste treatment methods. Uranium hexafluoride plants also process some U_3O_8 and MgU_2O_7 . For the most part, their behavior is similar to that of the model feed. When U_3O_8 is processed in an SX-F plant, NO_x is produced during the dissolution of the U_3O_8 in nitric acid and a slightly higher amount of uranium is lost as insoluble material (Part II). When MgU_2O_7 is processed in an SX-F plant, more sludge is deposited in the lagoons (Part II); when processed in an F-F plant, a little more fluorination ash is formed, but it is easier to handle than $\text{Na}_2\text{U}_2\text{O}_7$ in the F-F plant since it does not require the aqueous $(\text{NH}_4)_2\text{SO}_4$ wash (Part I, Sect. 4.4.11).

Sodium and ammonium ions are excluded from the feed in Cases 3 and 4 because they create difficulties in the advanced waste treatment systems (Part I, Sects. 4.4.5, 4.4.11, and Part II). It is simpler to change the mill processes to eliminate these ions from the yellow cake, for example, by precipitating UO_4 with peroxide, than to design advanced waste treatment systems to handle them at the UF_6 plant. There is no change in the amount of radioactive materials handled in Cases 3 and 4.

This study does not address the conversion of recycle material from fuel reprocessing plants to UF_6 . The model plant is not designed to handle enriched uranium. In addition, the product of a fuel reprocessing plant is already highly purified so that there is no need for the purification steps, which are a major source of radioactive effluents at a yellow cake conversion plant.

This study does not address the processing of foreign ore concentrates. Processing "high" thorium concentrates from Canada or "high" radium concentrates from pitchblend ores would have a greater impact on the environment.

Airborne uranium source terms are, for the most part, based on a straight-line extrapolation of data supplied by the industry, but source terms for radionuclides other than uranium are estimated. The amounts of trace radioactive materials entering the plant in the yellow cake, their movement in the plant, and the amounts released in the plant effluents are not reported in the literature. The ^{226}Ra and ^{230}Th feed to the plant are estimated from data for yellow cake processed by obsolete mill circuits and may be high (see discussion in ref. 19, pp. 32-33 and 122-23). This uncertainty is relatively unimportant in assessing uranium mills since the yellow cake contributes only a small part of the total dose; however, at the model UF_6 plant this uncertainty could have an appreciable effect on the dose. This is particularly true at the model fluorination-fractionation plant where ^{226}Ra and ^{230}Th together contribute about 70% of the dose to the bone from airborne effluents, while ^{226}Ra alone contributes about 90% of the dose from liquid effluents (Sect. 7.0, Tables 7.7 and 7.13). Based on general chemical principles, it is assumed that the radioactive impurities other than radon, which is a gas, accompany the uranium in the same ratio as that present in the feed as far as solvent extraction at the SX-F plant or fluorination at the F-F plant. At the F-F plant, most of the radioactive impurities leave the plant as slightly soluble solids in the fluorination ash. At the SX-F plant most of the radioactive impurities leave the plant as soluble species in the liquid nitrate waste from solvent extraction. Concentrations of radioactive materials in liquid effluents are either estimated from the uranium content or determined by analogy to uranium mill circuits (Sect. 4.4). The industry has made a few scouting tests for radium in liquid streams, but results are preliminary and no quantitative data are available.

4.2.2 Growth and decay of radionuclides within the model UF_6 production plant

In the estimation of source terms for a facility processing radioactive materials, one can often ignore the quantity of nuclides being

formed from precursors or decaying within the plant. This is because the majority of the nuclides either have a long half-life (i.e., ^{238}U , ^{230}Th , ^{226}Ra , and ^{210}Pb), so that the amount of nuclide produced or decaying while the material is being processed is negligible, or because the mixture has essentially reached secular equilibrium where the rate of formation of the nuclide is equal to the rate of decay so that the quantity of the nuclide is constant. However, if a short-lived nuclide such as ^{234}Th or ^{222}Rn is separated from a long-lived parent during processing, the production or decay of the nuclide in different fractions may appreciably affect the source terms.

Thorium-234 (half-life, 24 days) is chemically separated from ^{238}U during processing. Holdup of thorium- or uranium-rich streams within the plant area, for example, storing the fluorination ash before scrap recovery or holding liquid effluents in settling basins prior to release, affects the source terms. Protactinium-234m has a half-life of only 1.18 min and is in secular equilibrium with ^{234}Th at all times. The next members of the series, ^{230}Th and ^{226}Ra , have long half-lives - 83,000 years and 1620 years respectively; thus their production and decay during processing may be ignored. Radon-222 (half-life, 3.8 days) is a gas and may be continuously removed from its nonvolatile ^{226}Ra precursor by the air or gas sparges used in dry materials handling, in fluidizing beds, and in controlling the gas-solid reactions during conversion. The radon diffusion properties of the solids are not known, although some radon holdup which permits decay within the particles is expected. Relatively little holdup of radon in piping and wet scrubbers is expected once radon has entered the gas stream. This study estimates the potential radon release if all radon that is present when sealed drums are opened and is produced during the processing of dry solids is released to the atmosphere. Water is an excellent radon diffusion barrier; therefore, most of the radon generated in the settling basins will decay within the stored solids. The short-lived radon daughters are included with radon in the dose calculations and are not listed individually as source terms. Radon and short-lived radon daughters are assumed to be in secular equilibrium with ^{226}Ra in all particulates released. The decay of radon gas as it is dispersed

in the environment is included in the dose calculations (Sect. 7.0). Lead-210 has a 22-year half-life and is not present in significant amounts in the UF₆ plant. However, on a long-term basis, ²¹⁰Pb and its daughters will grow into the stored waste.

4.3 Waste Management Methods

A general description of waste treatment methods follows. Details of the specific applications are deferred to Part I, Sect. 4.4 and Part II. In some case studies, it is simpler technically to change the process or plant feed to avoid or reduce the formation of a waste rather than to treat the waste.

4.3.1 Airborne radwaste-chemwaste treatment methods

4.3.1.1 Dry dust collectors. Filters are the principal means by which uranium particulates are recovered from off-gas streams; however, the wet scrubbers used to remove noxious gases also collect some particulates (Sect. 4.3.1.2).

Pulse-jet bag filters. ²⁰⁻²³ The bag filter is quite efficient for removing fine dusts down to 1 micron from cool, dry streams. Dusty gas flows through a filter made of compressed felt and deposits particles in the voids. As the voids fill, a cake builds up on the fabric surface and the pressure drop increases to a point where the deposited dust must be removed by a reverse jet of air from the "clean" side. Cleaning may be effected either by pulsing a jet of compressed air through valves controlled by a timer or by employing a reverse jet through a blow ring which moves continuously up and down the bags. Very high dust concentrations can be handled because the maximum period between cleaning cycles is only a few seconds. High dust concentrations are usually an advantage since the deposited dust tends to be dislodged in "slabs" rather than being redispersed in the gas phase. The pulse-jet type has proved to be reliable in UF₆ plants, displaying a long bag life and requiring relatively little maintenance ²⁴⁻²⁶ in contrast to the mechanical problems associated with the blow ring mechanism. ²⁴ All UF₆ plants use bag filters to recover uranium dusts from materials handling operations. Primary bag filters are

designed to automatically return material to the process; dust from secondary bag filters is collected in drums and manually recycled.

Long-term plant and laboratory investigations by Stairmand have shown that the reverse-jet bag filter is 99.9% efficient under typical industrial conditions.^{20,21} Losses are primarily from leaks around seals or holes in the bag. Under optimum conditions (i.e., no leaks), the average efficiency of the blow ring type of bag filters at one uranium refinery was 99.986%.²⁴ Efficiencies remain close to 100% for particles down to 1 micron.²⁰

In this study, the primary bag filter is assumed to have an efficiency of 99.9% and the system of primary plus secondary bag filters an efficiency of 99.986%. The second unit, which receives any dust that has leaked through the first unit, ordinarily collects relatively little material.

Sintered-metal filters. Porous metal filters with up to 50% of their volume interconnecting voids or pores are made by sintering prealloyed metal powders of selected particle sizes in a controlled-atmosphere furnace. The powdered metal particles fuse at their points of contact, resulting in a bond with a homogeneous crystalline structure. Because dust particles may impinge on surfaces as the gas passes through the filter, the removal rating is higher than the mean pore size. For example, a 1/8-in.-thick filter with a mean pore size of 10 μ will remove 98% of the 0.7- μ -diameter particles.²⁷

Uranium hexafluoride plants use sintered stainless steel filters with a nominal pore size of 10 microns on the reduction off-gas and either Monel or nickel 10- μ sintered metal filters on the fluorination off-gas to recover uranium. Primary filters are equipped with automatic blowback devices which return material directly to the process. Secondary filters, which serve as a receiver of particles that leak through the primary filters, ordinarily collect little material. Parallel trains of filters are installed, with one train in use while the other is being cleaned. The quantity of uranium passing the reduction filters is estimated from data provided by the industry on scrubber liquors and the stack effluent downstream from the metal filters. Particulates passing the fluorination

filters are estimated from the reduction data. The average particle size of material passing the filters is assumed to be 2 microns when estimating efficiencies of downstream wet scrubbers (Sect. 4.3.1.3).

Porous carbon filters. Uranium hexafluoride plants use porous carbon filters on the hydrofluorination off-gas to recover uranium. These are very efficient filters. For example, a 3/4-in.-thick filter is 99.9995% efficient on uranium refinery dusts.²⁸ The carbon filter system is arranged like the sintered-metal filters, that is, in parallel trains with one train in use while the other is being cleaned. Automatic blowback devices return the material collected on the primary filters to the process. The secondary filters collect particles which leak through the primary filters and ordinarily collect little material. In this assessment, the amount of material passing the filter system was estimated from data on downstream scrub liquors and condensed off-gases provided by the industry.

Vacuum cleaner bag. The plant vacuum cleaner system contains a bag (and possibly also a cyclone) for collecting coarse dust and debris. This is a necessary part of the vacuum cleaner system. It has a low efficiency on <10-micron particles, and the air must be cleaned further with a high-efficiency pulse-jet bag filter.

HEPA filters.^{29,30} High Efficiency Particulate Air (HEPA) filters have been used for many years in the nuclear industry to effectively remove radioactive particulates from air streams. A modular HEPA filter has a cross section of 2 ft by 2 ft, a depth of 1 ft, and a capacity of about 1000 cfm. The modules are formed into banks to achieve the required capacity for filtering air. The filter medium is a pleated mat of woven fiberglass. By definition, a HEPA filter is an expendable (single-use), extended-medium, dry filter having (1) a minimum particle removal efficiency of no less than 99.97% for 0.3-micron particles; (2) a resistance of 1.0 in. H₂O when clean, and up to 6 to 10 in. H₂O when in service and operated at the rated air flow capacity; and (3) a rigid casing extending the full depth of the medium.²⁹ Based on experimental data and known characteristics of filter systems, it is assumed that the efficiency of the system is 99.95% (tested with 0.3-micron smoke).²⁹

The following items apply to the design and operation of HEPA installations:

1. A high efficiency for the filters can be ensured by installing them in such a manner that all of the gas to be treated passes through the filters. The filters should be tested, before and after installation and also periodically while in service, by a method such as the dioctylphthalate smoke (DOP) test. Continuous pressure drop measurements can indicate whether the filters are plugging or have been ruptured.
2. HEPA filters are strictly backup units and must be preceded by high-efficiency dust collectors. If one assumes an average particulate capacity of 4 lb/unit, HEPA filters on the drum dumping off-gas, for example, would need to be replaced every 3 months using a primary bag filter compared with replacement every 2 years with both a primary and a secondary bag filter.
3. Excessive moisture can impair the efficiency of the filter. It is mandatory to remove all entrained moisture or to heat the air to above the dew point.
4. Fires can seriously damage a filter as the result of overheating the fiber mat or burning the wooden frame.
5. The type of operating data that can be extrapolated for design purposes is limited.³⁰

HF-resistant HEPA filters.^{31,32} HF-resistant HEPA filters are under development and are expected to be commercially available within the next five years, i.e., by 1982. Experimental filter assemblies have been made which have a resistance of about 1.3 in. H₂O and an efficiency of about 99.9%.³¹ These filters 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.³² In this study, it is assumed that the objective of a 99.95% efficient HEPA filter which is resistant to a HF concentration of 40 µg/liter will be achieved.^a

^aStreams bearing HF which would require HF-resistant HEPAs carry such a small fraction of the total radioactive dusts that the difference between 99.9 and 99.95% efficiency has a negligible effect on the overall assessment.

The HEPA filters are preceded by condensers and KOH scrubbing systems to lower the HF concentration in the gas stream to 40 µg/liter or less.

4.3.1.2 Wet scrubbers for absorbing noxious gases. Both physical and chemical processes are involved in the wet scrubbing of gases.³³ Physical processes include gas-liquid contact, diffusion in the gas phase, diffusion in the liquid phase, and mist removal from the effluent gas stream. Chemical absorption may be an equilibrium reaction, such as the absorption of HF in water where the vapor pressure of HF above the solution limits the efficiency of the scrubber, or it may be an irreversible reaction, such as the neutralization of HF in a KOH scrubber where physical processes limit the scrubber efficiency. The heat of reaction from the chemical absorption must be considered in the scrubber design since it may affect the efficiency if the vapor pressure of the gas in equilibrium with the scrubber solution increases as a function of temperature. The design of the scrubber must also consider that the gas feed may be hot and/or contain water vapor which will condense in the scrubber. Scrubber tests with HCl - a reactive gas - and water are a good measure of the physical efficiency of the equipment and may be used to estimate efficiencies for other reactive systems (i.e., scrubbing HF with KOH). Efficiencies for less reactive systems such as HF and water or H₂S and caustic must be measured experimentally.

Scrubbing solutions and efficiencies are given in Table 4.4. Either water or caustic solution may be used to scrub HF and H₂S, although caustic is more effective. Water scrubbing of F₂ is not practiced because of the potential explosion hazard.³⁴ A caustic solution is effective; however, the concentration should be maintained above 2% KOH (or equivalent) to prevent the formation of poisonous OF₂.¹⁴ Water scrubbing of SO₂ is ineffective because of the low solubility, but caustic scrubbing may be used. Water or dilute acid may be used to scrub HNO₃ vapor. Simple water scrubbing systems are ineffective on the NO_x gases which are also present in the SX-F plant off-gas. The NO_x absorption tower is discussed separately in Sect. 4.3.1.4. In the case studies, all KOH scrubbers are recirculating systems which operate within the range 10 to 2 wt % KOH.

Water scrubbers may be either single-pass liquid flow (early cases) or recirculating systems to minimize liquid effluents.

Although the primary purpose of the wet scrubbers in a UF_6 plant is to absorb noxious gases, they will simultaneously collect small quantities of particulates (Sect. 4.3.1.3).

Baffle (orifice, self-induced spray deduster).²⁰⁻²² Air flows through a stationary baffle at high velocity, carrying the water in a heavy turbulent sheet. The centrifugal force exerted by rapid changes in direction of flow causes the dust particles to penetrate the water film. The mechanical action of the gas flow moving the water creates a spray which serves to scrub the gas. This is a simple device with no moving parts in contact with the liquid and is readily constructed of corrosion-resistant materials. Baffle scrubbers are especially suitable under corrosive conditions or in cases where airflows may fluctuate over a wide range. Ordinarily the baffle is thought of as a dust collector, but in SX-F Cases 1-3, the baffle together with a vertical fin tube cooler collect 70% of the nitric acid values in the off-gas. The separate condenser is necessary since there is no provision for cooling coils in the baffle. The advantage of this system is that 40 wt % nitric acid suitable for direct recycle to the process is recovered. The corrosion problems of recovering 40 wt % nitric acid in scrubbers with mechanical recirculating systems or in gas absorption towers are severe because the acid is contaminated with chloride.

Spray tower, spray scrubber.^{22,35} Liquid is sprayed into the top of the tower, and coarse droplets fall by gravity through a countercurrent flow of the gas being scrubbed. Dust particles are collected by inertial impaction and interception. The usual arrangement is spray, followed successively by a fan and a mist eliminator. Efficiencies and pressure drops are low. The scrubber is useful for a heavy loading of noxious gas or coarse particles or for absorption accompanied by solids removal. Spray towers are used at the F-F plant to scrub the reduction off-gas which contains free sulfur as well as H_2S gas. They are also used on the fluorination off-gas where the chemical reactions occurring in the

scrubber form precipitates which might clog the more efficient scrubbers. The SX-F plant off-gas is less likely to cause clogging, and the more efficient venturi scrubber is used. The efficiency of a water spray tower on the H₂S-S off-gas is 50% of the total sulfur.¹⁴ The efficiency of a KOH spray tower is 80% for UF₆,¹⁴ and is assumed to be 80% for F₂ and HF by analogy to UF₆¹⁴ and HCl.³⁵

Wetted packed tower.^{22,35} Wetted packing provides an impingement surface for good absorption of gases and prevents reentrainment of dusts. Packing may be fixed, or it may be a floating bed of low-density spheres. Gases to be removed must be below 1% by volume. Dust collection is secondary to direct-contact cooling and gas absorption. The usual countercurrent packed tower has almost no solids-handling capacity since solids tend to plug the packing and support plates, which can be cleaned only by removal. Crossflow scrubbers can handle dust loadings up to 5 grains/ft³ by washing the face of the packing with spray nozzles in parallel flow while the body of the packing is irrigated from the top. Advantages are low cost, simplicity, corrosion resistance, and no moving parts. The KOH packed tower has an efficiency of 99% for H₂S and UF₆,¹⁴ and is assumed to have an efficiency of 99% for HF and F₂ by analogy to UF₆¹⁴ and HCl.³⁵

Venturi scrubber.^{22,36} Liquid is introduced into the throat section and atomized by the high-velocity gas stream. The high relative velocity between the accelerating solid particle and the liquid droplet makes for high efficiency by impingement. Gases are removed by absorption or chemical reaction with the contacting liquid. The venturi must be followed by a mist eliminator (sold separately). Venturi scrubbing systems are capable of efficiently scrubbing a multiple-constituent fume containing vapors, aerosols, and particulates. The ejector venturi scrubber utilizes the velocity of the liquid as a pump so that there are no mechanical parts in contact with the gas stream - an advantage in handling corrosive gases.³⁶ Water containing up to 10% solids can be recirculated.³⁷ The efficiency depends upon the pressure drop. High efficiencies require a high power input. The medium-energy and high-energy water venturis have HF efficiencies of about 90%¹⁴ and 95%

respectively.³⁶ Efficiencies for the high-energy KOH venturi are 85% for H₂S,^{14,36} 98% for SO₂,³⁶ and assumed to be 99% for HF by analogy to HCl and Cl₂.³⁶

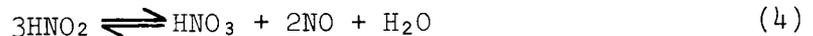
KOH coke box. The use of a KOH coke box as a tertiary scrubber to absorb the final traces of HF, UF₆, and F₂ from a gas stream is a proprietary development of the Allied Chemical Corporation.¹⁴ Presumably, it has some features in common with a packed tower; in addition, the carbon may enter into the reactions either as a catalyst or by sorbing the reactive gases. Since this is a generic study, the proprietary efficiency is downgraded to 90% because the fully developed technology is not in the public domain. Proprietary technology is avoided if possible in generic studies, but the coke box is the only presently developed system and appears to have technical advantages over the only known alternative which might be developed.^a

4.3.1.3 Wet scrubbers for collecting particulates.²⁰⁻²² The principal mechanism involved in wet collection of particulate matter is impingement of individual particles upon scrubbing liquid droplets. As the flowing gas approaches an individual droplet, it diverges to avoid the obstacle; however, the inertia of heavier entrained particles keeps them moving in a nearly straight path, forcing them to collide with the droplets. The droplets, being substantially larger and more massive, collect the particulates and then fall due to gravity. The wet scrubber recovers the dust as a slurry. In general, the efficiencies are directly proportional to the pressure drop and decrease with decreasing particle size (Table 4.5). The systems were previously described in Sect. 4.3.1.2. A wet baffle (orifice) scrubber is used as primary treatment on the

^aWet mineral wool filters will remove 90 to 95% of the HF from a gas stream containing 250 to 600 ppm of HF by reaction of the HF with SiO₂ to form SiF₄, which then hydrolyzes to silicic acids.³⁸ The filters are similar to HEPA filters, and are consumed during service. These filters probably could be used in place of the coke box, but the development problems associated with recovering the uranium from the silicic acid mixture, possible plugging of the filters with solids, and the expense and additional solid waste generated by frequent filter changes provide an incentive to develop the coke box rather than the mineralite wool filters.

denitrator off-gas at the SX-F model plant, and in Case 3 on the building ventilation effluent at each plant. Some dust also passes the sintered-metal or carbon filters on the process and is collected in the noxious gas scrubbers (Sect. 4.3.1.2). Venturi scrubbers are effective on particles as fine as 1 micron, but the dust collecting efficiency of the other wet scrubbers falls rapidly as the particle size of the dust drops below 5 microns (Table 4.5). For example, a spray tower which is 94% efficient on a 5-micron dust is only 55% efficient on a 1-micron dust. Therefore, it is important to consider the particle size in estimating efficiencies of multiple filters and scrubbers in a series. For purposes of this assessment, it is assumed that the average particle size of the dust passing the 10-micron sintered-metal filters is 2 microns.²⁷ The grade efficiency curves of Stairmand were used in estimating the particle size of material passing the wet scrubbers.^{20,39,a} The efficiencies estimated for multiple scrubbers in series are given in Table 4.8.

4.3.1.4 NO_x absorption tower.⁴⁰ Nitric acid is a valuable commodity which is recovered from NO_x off-gases for recycle to the SX-F process with a NO_x absorption tower. The reversible equilibrium reactions are:



^aThe graphs in refs. 39 and 20 are the same, but ref. 39 is a little easier to read than ref. 20.

Favorable absorption conditions are:

- (1) High partial pressure of nitrogen oxides.
- (2) High degree of oxidation of nitrogen oxides.
- (3) Low temperature.
- (4) Large gas-liquid interface.

Gases from the scrubber-condenser which still contain NO_x are passed through an oxidation chamber where NO is converted to NO_2 . The NO_2 is further oxidized and absorbed in a 20-plate absorption tower. The NO resulting from Eqs. (2) and (4) must be oxidized to NO_2 in the absorption tower so that tray spacing is not the same for all trays. Eight bars is the usual working pressure. Cooling coils must be installed on all lower and middle trays, although some of the trays in the tail section may be without cooling. Proper design with regard to cooling and tray spacing is critical to achieving optimum efficiency.

Precautions must be taken to avoid the buildup of chloride and fluoride, which are highly corrosive in the absorption tower.⁴¹⁻⁴³ In SX-F Cases 1-3, chloride is controlled by withdrawing 32 wt % nitric acid from the tower, even though this composition is lower than desired for recycle, because most of the chloride is removed from the tower with the 32% acid.¹⁵ Fluoride is no problem in SX-F Cases 1-3. An ozone sparge is used to remove chloride in SX-F Case 4 when producing >32% acid. The buildup of chloride in the tower is prevented by withdrawing acid from a high-chloride plate to a sparge tank where it is contacted with a 1% ozone-air mixture. The chloride is oxidized to chlorine according to:



and the chlorine is removed with the ozone-air sparge mixture. Sparged acid is returned to the next lower plate in the absorption tower. The ozone sparge was used successfully at the Fernald Refinery in the 1950s,⁴¹ and has been tested recently at the ERDA Y-12 Plant.⁴⁴ Fluoride is controlled in SX-F Case 4 by complexing with 5 parts of aluminum so that it does not volatilize with the NO_x .^{41,43}

4.3.1.5 HF condensers. HF condensers improve the HF efficiency of the plant, reduce the load to the HF off-gas scrubbers, reduce the load to the liquid fluoride treatment system, and decrease the amount of CaF_2 solid waste generated. The amount of HF removed by the condensers depends on the temperature of the coolant.

Aqueous HF condensers. The hydrofluorination off-gas is a mixture of water vapor (from the reaction) and excess HF. Condensation of the model SX-F plant off-gas yields a 25 wt % aqueous HF solution, which is low in radioactive materials and suitable for industrial use.^{15,a} In the F-F process, impurities such as silicon, boron, vanadium, molybdenum, and sulfur may be volatilized.⁴⁵ Because of the chemical impurities that are condensed, F-F plant hydrofluoric acid is of limited value. The base SX-F model plant (i.e., Case 1) includes a water-cooled condenser with an aqueous HF efficiency of 90%.⁴⁶ Both SX-F Case 4 and F-F Case 4 have a water-cooled condenser and a brine-cooled condenser with an HF efficiency for the system of 99%.⁴⁶

Anhydrous HF condensers. As generated, fluorine is contaminated with about 11 vol % HF, and the hydrogen off-gas from the fluorine cell contains about 9 vol % HF.⁴⁷ The base plants (i.e., Case 1) have inefficient brine-cooled condensers which decrease the HF contents of the fluorine and the hydrogen off-gas to 8 vol %¹¹ and 6.5 vol % respectively. (Recovered HF is returned to the process.) In Case 4, the brine-cooled condensers are replaced by -120°F condensers which reduce the HF content of the fluorine to 4 vol % and of the hydrogen to 3 vol %.⁴⁷ A lower limit of 2% HF is fixed by the polymerization properties of HF. Although the ERDA flowsheet for Case 4 has been described in general terms in the open literature,⁴⁷ the technology is still classified. Case 4 assumes that, at some future date, either private industry can develop this technology or the ERDA technology will be made available to industry.

^aTechnology is not available to break the HF-H₂O azeotrope so that anhydrous HF can be recovered from 25% aqueous HF for recycle within the UF₆ plant.

4.3.1.6 Hydrogen burner. In all case studies except F-F Case 1, a hydrogen burner is used on the reduction off-gas to convert the H_2S to SO_2 and to destroy the hydrogen.

4.3.1.7 Process changes. In addition to treatment methods applied directly to the off-gas, the case studies include several process changes which reduce the load to the waste treatment systems and thus reduce the quantity of chemwaste-radwaste released:

1. More efficient condensers on the fluorine cells (reduces HF release, Part I, Sects. 4.4.8.8, 4.4.9.6, and Part II).
2. Fluorine cleanup reactor or a more efficient fluorine cleanup reactor (reduces HF releases, Part I, Sect. 4.4.8.2 and Part II).
3. UF_6 cleanup reactor or a more efficient UF_6 cleanup reactor (reduces HF releases, Part I, Sect. 4.4.8.2 and Part II).
4. Elimination of ammonium and sodium ions from the plant feed via changes in the mill circuits (reduces F-F model releases of NH_3 , Part I, Sects. 4.4.5, 4.4.11.2, and 4.4.11.4).

4.3.2 Liquid and solid radwaste-chemwaste treatment methods

Liquid treatment methods ranging from simple settling ponds to complex recycle systems are included in the case studies. Waste streams vary widely in composition but usually have high concentrations of chemicals and low uranium contents. Consequently, the major objectives involve reducing the amounts of chemicals and uranium daughters (especially ^{226}Ra) which are released. The principal solid wastes are ash from the fluorination-fractionation plant and solids generated by the various liquid treatment systems. Solids are either impounded on-site or prepared for shipment to a burial ground. A general description of the waste treatment methods follows, with details of the specific applications deferred to Part I, Sect. 4.4 and Part II. In some case studies, it is simpler technically to change the process or the plant feed rather than to treat the waste.

4.3.2.1 Holding and settling before release. A basin is a simple, yet effective, method of clarifying liquid wastes before release. It allows time for achievement of complete precipitation (i.e., time to approach the equilibrium solubility of slightly soluble compounds), coalescence of colloidal particles, and gravity settling of solid particles, so that relatively clear supernate is released. The basin may also serve as the storage repository for solids generated by the liquid waste treatment systems and as an equalization system where streams are diluted with other plant wastes. The basin is lined with an impervious, synthetic material to minimize seepage of radioactive materials and chemicals.

The criteria for the construction of an acceptable liquid radioactive waste storage facility at a UF₆ plant are given in NRC (formerly referred to as AEC) Regulatory Guide 3.13, which enumerates minimum information requirements with regard to site, design of the embankment retention system, lining, stabilization of embankments and any loose radioactive material produced by evaporation, protection from water runoff from surrounding drainage areas, fencing, seepage assessment, maintenance, and stabilization when operations are terminated.⁴⁸ Additional information about the design of the embankment system, including stability analysis and minimum factors of safety, is contained in the Corps of Engineers Manual EM-110-1-1902.⁴⁹

4.3.2.2 Holding and decay before release. In Case 1, holding the SX raffinate permits decay of the relatively short-lived ²³⁴Th and ^{234m}Pa to permissible levels of release (Part II). (Note that for all other liquid wastes ²³⁴Th and ^{234m}Pa will grow toward secular equilibrium with ²³⁸U during holding.)

4.3.2.3 Impoundment with evaporation. In SX Case 2, nitrate-bearing SX raffinate waste is neutralized and impounded in a lined basin (Part II). A submerged combustion evaporator is used to dispose of water, primarily by raising the temperature and therefore the evaporation rate of the pond water, although some water is volatilized directly by

the evaporator. It is assumed that natural evaporation is sufficient to compensate for natural precipitation, but no credit is taken for natural evaporation of process wastes. In an arid environment, natural evaporation ponds could be used; however, this was not costed in the case studies. Neutralization is necessary to make the waste chemically compatible with the liner. Neutralization also precipitates radioactive materials, thus reducing the potential for accidental discharges of radioactive materials from the pond. Soluble nitrate waste bearing soluble radioactive materials concentrates in the retention basin along with the neutralization sludges. Impoundment is not a permanent solution to the problem of nitrate wastes. However, it is the only fully developed and immediately available alternative to releasing nitrate wastes. Criteria for the retention system are described in NRC (formerly AEC) Regulatory Guide 3.13.⁴⁸

4.3.2.4 Precipitation of chemicals and radioactive materials.

Many of the noxious chemicals and radioactive materials in the liquid wastes can be precipitated by the addition of suitable chemicals. After clarification, some streams can be recycled to the process, while others are released. Conventional mixer-settler, feed tanks, etc., are used in the cost estimates.

Lime treatment for fluoride. UF₆ plant off-gas scrubbers generate large volumes of waste scrub liquors which are high in fluoride but low in radioactive materials. Lime is used to precipitate the fluoride as CaF₂ and to neutralize the acid or regenerate the KOH. Water scrub liquors are separated from precipitated solids in a settling basin. Excess calcium (the lime-treated solution is slightly basic with a pH of about 10) is precipitated as CaSO₄ or CaCO₃ by the addition of H₂SO₄, and the solution is neutralized before release. The fluoride content of the clarified effluent from lime treatment is estimated as 25 ppm, assuming 20 ppm as soluble fluoride⁵⁰ and 5 ppm as suspended solids. Regenerated KOH scrub liquors are filtered and recycled to the process. There is a small liquid bleed of KOH and impurities with the moist filter cake. The off-gas system is designed to avoid water condensation

in the KOH scrubbers, so that all regenerated KOH can be recycled. No cost credit is taken for recovered KOH. The CaF_2 regenerated is low in radioactive materials and is stored on-site in a lined basin or pit. Fluoride treatment systems are in use at all domestic UF_6 production plants.^{1,51}

Lime treatment for sulfite. In F-F Case 4, lime is used to precipitate $\text{CaSO}_3 \cdot 1/2\text{H}_2\text{O}$ and to regenerate the KOH scrub liquor for the reduction off-gas system (Sect. 4.4.6.7). The mixture is filtered and the KOH recycled. The off-gas system is designed to avoid water condensation in the KOH scrubber so that all regenerated KOH can be recycled. No cost credit is taken for recovered KOH. The solids generated are low in radioactive materials and are pumped to a lined basin for storage. Liquid used to transport the solids is reused so that there is no liquid effluent from the pond. Some engineering development of this process is required since CaSO_3 may cause difficulties in both the scrubber piping systems and the line to the storage basin.

Neutralization for heavy metals. Neutralization of acidic effluents to a pH of 8 will precipitate 90% of the radium^{52,53} and most of the heavy-metal ions such as uranium and thorium as well as iron, copper, cobalt, arsenic, and vanadium as insoluble oxides or hydroxides. Neutralization also eliminates the excess acidity. Lime neutralization of sulfate-bearing wastes is somewhat more effective in removing radium, presumably because the CaSO_4 that precipitates serves as a carrier for the radium.⁵³ Calcium fluoride and CaSO_3 may also serve as carriers, although no data are available. In the absence of direct data for UF_6 plant wastes, it is assumed that 10% of the radioactive materials are released in the liquid effluents from fluoride treatment and 100% are precipitated with the CaF_2 . These maximizing assumptions, which are made to avoid underestimating the amount of radioactive materials in either the solid or liquid phase, result in a material balance of 110%.

Barium chloride treatment for radium. Barium chloride is effective in removing radium from sulfate-containing wastes by coprecipitating $(\text{Ba-Ra})\text{SO}_4$. Operating experience at the Uravan uranium mill shows that

0.14 g of BaCl_2 per liter will lower the radium concentration to the range of 1×10^{-9} to 3×10^{-9} $\mu\text{Ci/ml}$ (1 to 3 pCi/liter).^{54,55} Good settling of the fine particles of radium-bearing precipitate is essential. The efficiency is dependent on the radium concentration of the stream to be treated; for example, 99% radium removal was obtained from streams containing $\sim 400 \times 10^{-9}$ $\mu\text{Ci/ml}$,⁵⁴ while the more recent Uravan experience has been 93 to 96% removal from more dilute streams of $\sim 28 \times 10^{-9}$ $\mu\text{Ci/ml}$.⁵⁵ Other barium compounds such as BaCO_3 and BaSO_4 (barite) have been tried, but are neither as effective nor as convenient for sulfate-containing wastes.^{54,55} In F-F Case 3, BaCl_2 treatment is proposed for the $(\text{NH}_4)_2\text{SO}_4$ waste, which is chemically similar to the Uravan mill effluent (Sect. 4.4.11.5). Neither the need [i.e., the radium content of the $(\text{NH}_4)_2\text{SO}_4$ stream] nor the treatment efficiency has been demonstrated experimentally for UF_6 plant wastes. The case study assumes that BaCl_2 treatment will reduce the radium concentration to 3×10^{-9} $\mu\text{Ci/ml}$. The radium concentration in the precipitated solids is about six times higher than in typical uranium mill tailings; therefore, solids are dried and drummed for disposal.

Barium chloride and BaCO_3 are not effective on alkaline wastes which contain no sulfate. Barite (BaSO_4) can be used; however, reagent costs are higher than for copperas.⁵²

Copperas treatment for radium. Radium is the only radionuclide, except uranium, which dissolves to any significant extent during alkaline leaching, and most of it precipitates with the yellow cake in uranium mill circuits.⁵² Some of the dissolved radium in the liquid waste can be precipitated by treatment with 0.2 g of copperas ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, a flocculating agent). This process was tested in the AEC Monticello mill pilot plant but has not been used commercially. In F-F Case 3, copperas treatment is proposed for the carbonate leach liquid waste (Sect. 4.4.10.9). Neither the need (i.e., the radium content of the carbonate waste) nor the treatment efficiency has been demonstrated for UF_6 plant waste. The case study assumes that the behavior of radium in the ash leaching circuit is the same as in the milling circuit, and that single-stage copperas treatment has a removal efficiency of 75%.⁵² The radium

concentration in the solids is only slightly above background; however, as a matter of convenience, solid waste generated by copperas treatment is handled with the solids from barium chloride treatment and is dried and drummed.

4.3.2.5 Evaporators. Evaporation is commonly used in the chemical industry to concentrate aqueous solutions by boiling off water and volatile chemicals, leaving behind the soluble salts and materials having a lower vapor pressure than water. The separation (decontamination) of radioactive salts depends upon the amount of particulates entrained in the vapor and the efficiency of the demisting devices. Care must be taken to avoid too rapid boiling or foaming, which tends to cause entrainment. Also, the velocity of the vapor must be kept low and the disengaging space long to encourage particles and droplets to drop back into the liquid. An overall separation factor of more than 10,000 between condensate and concentrated liquor is generally attained for nonvolatile contaminants treated in a single-stage evaporator. Foam-producing materials such as laundry wastes must be excluded. The concentrated liquor is dried (Sect. 4.3.2.6).

The submerged combustion evaporator⁵⁶ used on the SX Case 2 raffinate stream (Part II) differs from conventional evaporators. Raffinate liquid is withdrawn from the storage pond and heated by injecting a natural gas flame directly into it. Some of the liquid is vaporized. Gaseous combustion products are separated from the vapor by passing the mixture through a spray demister which uses pond liquid and then through a stainless steel-mesh demister. Approximately 2-1/2% of the liquid withdrawn from the pond is evaporated directly.¹⁵ The remainder of the raffinate is heated to $\sim 150^{\circ}$ and returned to the storage pond. The increase in the temperature of the pond water causes additional evaporation from the pond surface. Overall, about 20% of the water disposal is by direct vaporization in the submerged combustion evaporator and 80% by evaporation from the pond. The high gas flow from the combustion burner will entrain liquid drops as it passes through the solution, resulting in a lower decontamination factor (DF) than with

a conventional evaporator. A DF of 30 is estimated for the submerged combustion evaporator; however, only 20% of the water is vaporized in this manner.

4.3.2.6 Drying and drumming. Moist solid waste or concentrated liquor from an evaporator can be dried and the dry solids packaged in 55-gal drums for shipment to a licensed burial ground. Off-gases, which consist of water and any volatile chemicals, carry entrained dust. Drying and drumming are included in the F-F case studies. Cost estimates are for a rotary dryer with dust cleaning equipment on the off-gas stream appropriate to the case study.

The rotary dryer is not suitable for SX raffinate waste containing NH_4NO_3 (potentially explosive) or NaNO_3 (causes caking problems).¹⁸

4.3.2.7 Fixation in cement. Incorporation in cement is an established method of waste disposal at nuclear installations. The cemented wastes are drummed and then transferred to a licensed burial ground. Cementing of slightly soluble wastes such as the fluorination ash (F-F Case 4) is beneficial in reducing the potential long-term leaching of radioactive materials by natural waters or the diffusion-controlled release of radon if the integrity of the drums should fail. A mixture of 15% solids, 45% cement, and 40% water is generally satisfactory.⁵⁷ Cementing is of little benefit for soluble salts which are readily leached from the cemented solids even when higher cement/salt ratios are used.⁵⁷

4.3.2.8 Process changes. In addition to treatment methods applied directly to the liquid waste, the case studies include several process changes which reduce the load to the waste treatment systems:

1. H_2 burner on reduction off-gas (eliminates sulfide from liquid waste, Part I, Sect. 4.4.6.4).
2. More efficient condensers on the fluorine cells (reduces fluoride liquid waste, Part I, Sects. 4.4.8.8, 4.4.9.6, and Part II).

3. Fluorine cleanup reactor or a more efficient fluorine cleanup reactor (reduces fluoride liquid waste, Part I, Sect. 4.4.8.2 and Part II).
4. UF_6 cleanup reactor or a more efficient UF_6 cleanup reactor (reduces uranium and fluoride liquid waste, Part I, Sect. 4.4.8.2 and Part II).
5. Recarbonation and recycle of carbonate leach solution (reduces F-F model carbonate liquid waste, Part I, Sect. 4.4.10.5).
6. Elimination of ammonium salts from the plant feed (eliminates ammonium ion from SX liquid waste, Part II).
7. Elimination of sodium salts from the plant feed (reduces the F-F ammonium sulfate liquid waste from sodium removal, Part I, Sect. 4.4.11.4, and facilitates recycle of SX raffinate, Part II).

4.4 Fluorination-Fractionation UF_6 Plant

4.4.1 Summary

Flowsheets for the fluorination-fractionation model plant showing Case 1 off-gas treatment are presented in Figs. 4.1.-4.4, and the advanced carbonate leach flowsheet is shown in Fig. 4.5. The first step in the process is to prepare feed suitable for fluid-bed operation by sizing and calcining. Feeds containing sodium are also treated with an ammonium sulfate wash to remove the sodium that would cause caking in the fluorination fluid bed. The crude yellow cake is then converted to gaseous UF_6 in a series of high-temperature, fluid-bed operations--reduction, hydrofluorination, and fluorination. Some purification occurs during conversion, and a final purification is accomplished by fractional distillation to produce a high-purity UF_6 product suitable for feed to the enrichment plant. A survey of the movement of the radionuclides in a UF_6 plant has never been reported; however, the chemistry of the radioactive impurities is such that, except for radon gas, they are expected to be nonvolatile and to accompany the uranium as far as fluorination. In this step, they are removed from

the process with the fluorination ash, while the UF_6 gas passes through the filters. After distillation, the UF_6 is collected in cold traps and transferred to cylinders for shipment to the enrichment plants. The fluorination ash, which is mostly CaF_2 bed material contaminated with the radioactive impurities in the feed to the plant, is stored in sealed drums to allow the ^{234}Th and ^{234m}Pa to decay. After decay, the ash is leached with sodium carbonate to recover uranium. The residue is then dried, drummed, and shipped to a burial ground. Still residues are stored because they contain insufficient uranium and vanadium values to justify recovery at the present time. A large number of dry materials handling operations require high-efficiency dust collectors. Wet scrubbers are used to remove noxious chemicals from the off-gases. The plant also produces fluorine by the electrolysis of HF , which generates fluoride wastes. Major processes at the F-F plant are:

1. Sampling.
2. Feed preparation.
3. Hydrogen reduction of UO_3 to UO_2 .
4. Hydrofluorination of UO_2 to UF_4 .
5. Fluorination of UF_4 to UF_6 .
6. Fractional distillation of UF_6 .
7. Electrolysis of HF to produce F_2 .
8. Carbonate leach (uranium recycle).
9. Sodium removal.

The model plant has two conversion lines for steps 3 through 6.

Advantages of the F-F process are: (1) relatively concentrated, relatively insoluble solid waste is produced which can be readily dried and drummed for disposal; and (2) no gaseous nitrogen oxide or liquid nitrate effluents are generated. The F-F process potentially releases more airborne radioactive materials than does the SX-F process because it contains more steps where semirefined yellow cake containing radium and thorium (major contributors to the dose) are handled. The F-F process is sometimes referred to as the "dry" process; however, this is somewhat misleading since liquid wastes are generated by off-gas

scrubbers, carbonate leaching, and sodium removal.

Summary tables of radioactive releases (source terms), chemical releases, treatment methods and efficiencies, and solid radwaste generated are presented in Tables 1.1 and 4.6-4.11 for gaseous, liquid, and solid wastes.

Case 1, the base case, represents the minimum treatment necessary to operate the process. Plant effluents are acceptable radiologically (i.e., releases are below the levels stipulated in 10 CFR 20, Appendix B, Table II Concentrations) but may not be acceptable chemically at all sites. The principal objective of the waste treatment is to recover uranium in cases where the economic value of the recovered material exceeds the treatment cost; a second objective is to reduce the quantities of noxious fumes such as HF and H₂S, whose release would create unacceptable working conditions within the plant. Waste treatment consists of the installation of primary and sometimes secondary filters and scrubbers on all process off-gas streams (Table 4.8). Large quantities of chemicals are released in untreated liquid effluents (Table 4.10). The cost of the waste treatment for Case 1 is considered to be a part of the base plant since it is essential for the operation of the process. Case 1 serves as the base for the cost/benefit analysis; it does not necessarily describe current industrial practices.

Case 2 off-gas treatment reduces the amounts of radioactive materials and chemicals released in the process off-gas (Tables 4.6 and 4.7). Treatment consists of the installation of efficient primary, secondary, and sometimes tertiary dust collectors and wet scrubbers on all process and materials handling streams (Table 4.8). This essentially represents the practical limit of existing technology in the public domain. Airborne radwaste releases from the process are low in Case 2 (Table 4.6). About two-thirds of the total airborne losses occur via the untreated building ventilation effluent. Case 3 applies treatment to the building ventilation and the UF₆ sampling line. In Case 4, HEPA filters are added to the process off-gas, and bag filters (99.9% efficient) are used on the building ventilation to collect additional radioactive materials.

Airborne chemical releases are further reduced by process changes (the F_2 and UF_6 cleanup reactors), HF condensers, and additional scrubbers. Most of the Case 4 technology is not available for immediate use either because it has not been fully developed or because it is proprietary.

The primary purpose of the Case 2 liquid treatment is to reduce chemical releases by the use of recycle systems, lime treatment of fluoride scrub liquors before release, and an internal process change to eliminate H_2S and sulfur (Table 1.1). This case study illustrates how chemical releases can be reduced if more severe restrictions on chemical releases are imposed (Table 4.10). None of the Case 2 treatments is designed specifically to reduce the radionuclide releases, although the concentrations of most radionuclides are reduced by a factor of 2 (Table 4.9). Case 2 has almost no effect on radium release, which is responsible for about 90% of the dose from liquid effluents (Sect. 7.0, Tables 7.12 and 7.13). Case 3 reduces releases of both radium and chemicals. Radium is precipitated from the major radium-bearing streams by using methods which have been tested on chemically similar wastes from uranium mills. In Case 3, a new restriction is placed on sodium salts in the UF_6 plant feed to eliminate the associated waste generated by sodium removal at the UF_6 plant. This is effective in reducing the releases of radium and chemicals from the UF_6 plant. The change in the mill process to produce a low-sodium yellow cake has no adverse environmental impact on the mill tailings impoundment. Case 4 incorporates an evaporator and a calciner for complete recycle of the water from all streams bearing radioactive materials. Treated scrub liquor from the fluorine cells is released. This water is surplus to the process, has not been in contact with radioactive materials, and, after treatment has a low concentration of chemicals.

In all F-F case studies, most of the radioactive materials entering the plant leave the plant in either the UF_6 product or are prepared for shipment to a licensed burial ground in the dried, slightly soluble fluorination ash. In Case 4, the fluorination ash is incorporated in cement to further isolate it from the environment in the event the integrity of the drums should fail. Most solid waste generated by the

liquid treatment systems is slightly soluble and so low in radioactive materials that it is barely distinguishable from ordinary chemical wastes containing naturally occurring radioactive materials (Table 4.11). These wastes are stored on-site. Radium-bearing wastes or soluble salts are prepared for shipping off-site in the advanced cases.

Details of the model fluorination-fractionation UF_6 plant processes, the waste treatment case studies, and source-term calculations are discussed in Sects. 4.4.2-4.4.17. Streams are assessed separately to show the benefit of the individual treatment methods. Many treatment methods could be applied independently; for example, a plant could employ any desired combination of the features of Case 1 and Case 2 off-gas treatment, Case 3 radium precipitation, and a Case 4 fluorine cleanup reactor.

4.4.2 Materials handling

Large quantities of airborne dusts, generated by the dry materials handling operations, are the source of more than 90% of the total airborne release of radionuclides (Table 4.6). Common to these operations is the need for high-efficiency dust collecting systems to minimize the loss of uranium and to protect the health of workers and the general public. The origin of these dusts is described in Sects. 4.4.3-4.4.11.

4.4.2.1 Case studies. The base plant, Case 1, includes 99.9% efficient pulse-jet bag filters on all dust control effluents from dry materials handling operations. Aside from regulatory requirements, these bag filters are essential to the economic operation of the process. The material collected is automatically returned to the process. Case 1 off-gas treatment is shown schematically in Fig. 4.6. Six types of dusts are collected - yellow cake in the sampling plant (Stream 1), yellow cake dusts during feed preparation (Stream 2), UF_4 dusts (Stream 5), ash dust in the conversion plant (Stream 6), ash dust after decay (Stream 9), and carbonate leached ash dust (Stream 10). For optimum efficiency, separate bag filters should be used on each individual stream in the plant since maximum efficiency is achieved when the equipment

operates near design capacity; that is, separate bag filters should be supplied for drum dumping (2a) drum cleaning (2b), the calciner (2c), etc. Since the model plant has two conversion lines, a Case 1 plant would need a minimum of 18 pulse-jet bag filters for optimum efficiency. The pulse-jet bag filters are in addition to the vacuum cleaner bags, which collect coarse particles and debris. Moist off-gases from the dryers must be preheated before passing through the bag filters. Airflows used for cost estimating are presented in Table 4.12.

Case 2 treatment consists of secondary pulse-jet bag filters on all streams associated with dry materials handling. This is about the practical limit of existing technology. The purpose of the second unit is to collect particles which leak around seals or through holes in the bags of the first unit. Ordinarily, the second unit collects relatively little material. The efficiency of the secondary bag filters is assumed to be 86%. The case study is shown schematically in Fig. 4.7.

Case 3 applies 93% efficient baffle (orifice, self-induced spray deduster) scrubbers to the building ventilation and process cooling effluent. Since two-thirds of the uranium losses in Case 2 occur through the building ventilation, greater dose reductions may be achieved by primary treatment on the building ventilation effluent than by tertiary treatment of effluents from materials handling or process off-gases. The treatment methods are shown schematically in Fig. 4.8.

Case 4 applies 99.9% efficient bag filters to the building ventilation effluent and 99.95% efficient HEPA filters to all process materials handling streams. Both capital and operating costs will be high. For cost estimating purposes, it is assumed that regular HEPA filters can be used since these streams are not in direct contact with HF. However, accidental contact with HF is possible and could shorten the life of the HEPAs or require the installation of HF-resistant HEPAs, thereby increasing operating costs. Treatment methods are shown schematically in Fig. 4.9.

4.4.2.2 Source term calculations. The airborne releases of uranium dusts from materials handling operations are estimated in Table 4.13. These releases were estimated by using the efficiencies given in Table 4.8 and Allied Chemical stack sampling data^a for a system of primary and secondary bag filters. The data were extrapolated to a processing rate of 10,000 metric tons/year, assuming that the releases are directly proportional to the processing rate.

The amounts of radionuclides released, that is, the source terms, are presented in Table 4.6. Except for radon,^b which is a gas, the radionuclides of interest in the feed are expected to be nonvolatile in the chemical processing up to the fluorination step. Here uranium is volatilized as UF₆ gas, leaving behind a fluorination ash of CaF₂ fluid-bed material contaminated with 1.8 wt % of the total uranium processed⁴⁵ and essentially all the radioactive impurities in the feed. It is assumed that the crude uranium dusts released from all materials handling operations prior to fluorination have the same composition as the feed; that is, for each curie of U(nat) released, the following are released: 1 Ci of ²³⁸U, 1 Ci of ²³⁴U, 2.43×10^{-2} Ci of ²³⁵U, 1 Ci of ²³⁴Th, 1 Ci of ^{234m}Pa, 4.25×10^{-2} Ci of ²³⁰Th, and 4.7×10^{-3} Ci of ²²⁶Ra.^c

Ash handling represents a significant source of ²²⁶Ra and ²³⁰Th (approximately 25%) and is a major contributor to the dose, even though the amount of uranium released is small. Ash handling operations consist of removing ash from the fluorination fluid bed and filters, drumming, storing a minimum of 6 months to allow decay of ²³⁴Th and ^{234m}Pa, drum dumping, wet grinding, carbonate leaching, drying, and redrumming. Ash dust releases were estimated by analogy to similar operations in UF₆ feed preparation and in yellow cake drying and packaging at a uranium

^aObtained through the courtesy of the Allied Chemical Corporation.¹⁴

^bRadon is discussed in Sect. 4.4.15.

^cThe "old" (prior to July 10, 1974) definition of a curie of U(nat).

mill (Table 4.14). Source terms were calculated from the estimated ash releases of Table 4.14 and the radionuclide compositions of Table 4.15.

4.4.3 Yellow cake sampling

The yellow cake feed to the plant is received in drums, weighed, and sampled by the falling-stream method. The drum is emptied into a hopper equipped with an internal rotating and stirring mechanism and then discharged from the hopper in such a manner that it falls in a continuous stream past straight-line automatic samplers. A 55-gal drum attached to the bottom of the chamber collects the material rejected by the sampler. Equipment is cleaned before and after use, and all material other than the sample is returned to the drum and redrummed. The sampling plant is located adjacent to the model UF₆ plant and is operated by an independent firm which serves as a referee between the mill and the UF₆ plant.

The airborne particulates and radon released by the sampling plant are assessed in Sects. 4.4.2 and 4.4.15 respectively.

4.4.4 Yellow cake storage

The yellow cake is stored in a sealed drum for 1 month (or longer)^a after sampling before being processed by the UF₆ plant. This allows time for analyses and blending feeds to smooth out chemical reactivity and impurities. It is assumed that the storage area is under roof so that any spillage on the outside of the drums is contained within the building. This study does not address potential releases from natural water or wind effects on outside storage areas.

Radon releases from sealed drums are discussed in Sect. 4.4.15.

4.4.5 Feed preparation^{2,45}

The flowsheet is shown in Fig. 4.1. A homogeneous feed which maintains physical integrity is required for fluid-bed processing.

^aLonger storage time has a negligible effect on the source terms.

Since the yellow cake produced by the mills ranges from fine powders only a few microns in diameter to large extruded pellets about 1/4 in. in diameter, a feed preparation step is required. The drums of yellow cake are dumped and the empty drums air-cleaned. Concentrates are precrushed and the products of different mills blended to smooth out the chemical reactivity and impurities. Sodium diuranate feeds are first sent to sodium removal (Sect. 4.4.11) since sodium causes caking in the fluidized beds. Blended, sodium-free concentrate is mixed with a measured amount of water in a high-velocity pug-mill-type mixer and formed into 1/8-in.-diam by 1/4-in.-long pellets in a rotary-extruder pelletizer. Wet pellets are dried, calcined at 700 to 900°F (370 to 480°C), crushed in a roll crusher, and passed through a vibrating 40 mesh screen. Oversize material is returned to the crusher. The -40 mesh fraction goes to an air classifier which separates the -200 mesh fraction and returns it to blending. The resulting -40 +200 mesh fraction is the feed for the fluidized-bed reactor system.

About half of the airborne radwaste released by the plant in Case 1 is dust from feed preparation (Sect. 4.4.2, Table 4.13). Radon release is discussed in Sect. 4.4.15. There is no liquid radwaste since all water is vaporized during drying and calcining.

Although attention is focused on preparing a feed with the desired physical properties, calcining at 700 to 900°F (370 to 480°C) will thermally decompose the ammonium diuranate according to:



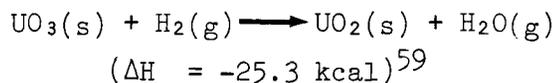
Most of the ammonia is driven off by heating to 320 to 370°C; all of it is volatilized by heating to 450°C.⁵⁸ The calculated NH₃ release, assuming Case 1 or 2 feed to the calciner [i.e., (NH₄)₂U₂O₇ in the plant feed plus the (NH₄)₂U₂O₇ from sodium removal]^a and complete thermal decomposition, is about 4000 lb/day. The calculated release

^aEssentially all Na₂U₂O₇ is converted to (NH₄)₂U₂O₇ prior to calcining by an (NH₄)₂SO₄ wash (Sect. 4.4.11).

assuming Case 3 or 4 calciner feed, which eliminates ammonium and sodium ions from the UF_6 plant feed but has about 2% recycle $(NH_4)_2U_2O_7$, is about 100 lb of NH_3 per day.

4.4.6 Reduction of UO_3 to UO_2

4.4.6.1 Reduction process. Uranium trioxide is reduced to UO_2 by H_2 at a temperature of 538 to 621°C (1000 to 1150°F) according to:^{59,60}



In the F-F model, hydrogen is supplied at 1.5 times the stoichiometric amount (i.e., 50% excess) required for reduction by cracking ammonia at 870°C (1600°F):⁵⁹



Although the reduction reaction is exothermic, a net heat input is required for operation to raise the temperature of the feed from ambient to operating temperature and to compensate for heat losses via volatile impurities, reactant gases, convection, and radiation.⁶¹ Careful temperature control is essential. If the temperature is above the optimum, sintering of the particle surfaces will interfere with further reaction in both the reduction and the hydrofluorination steps. Therefore, both heating and cooling must be supplied to the reduction reactor. Efficient reduction is required to permit maximum conversion to UF_4 . Unreduced oxide hydrofluorinates to UO_2F_2 , which in turn consumes more elemental F_2 in its conversion to UF_6 than does UF_4 , evolves more heat during fluorination, and does not fluorinate as well, resulting in more ash recycle.

All U.S. plants use fluidized-bed reduction units which have excellent gas-solid contact and temperature control of the powder bed (Table 4.1). Nitrogen is sometimes added to the cracked ammonia to maintain the fluidizing velocity of the bed. Both single-stage⁴⁵ and two-stage^{1,11,59,62} reduction are used. The product is a highly reactive uranium dioxide (98 to 99.7% UO_2),¹¹ which can be fluorinated with only a 5 to 10% excess of hydrogen fluoride.^{1,62}

Sulfate serves as a chemical promoter which increases the productivity of both the reduction and subsequent hydrofluorination steps.^{59,60,62} Sufficient sulfate for this purpose is present as an impurity in the blended reduction feed at the F-F plant.

In the F-F process, most of the sulfate and all of the arsenic are removed during reduction as volatile H₂S, sulfur vapor, and AsH₃ (Table 4.16).⁶¹ Efficient reduction is important to prevent sulfur corrosion in the hydrofluorination step.² Metallic impurities are reduced to their lower valence states.⁶¹ The calculations assume that all sulfur is lost as H₂S during reduction since the free sulfur/H₂S ratio is not known.

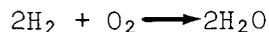
4.4.6.2 Reduction off-gas treatment, F-F Case 1. Flow diagrams for the base plant off-gas treatment are shown in Figs. 4.2 and 4.10. Most particulates are removed by passing the off-gas through primary and secondary sintered-metal filters having a mean pore size of 10 microns. The recovered uranium is returned to feed preparation since the fine dust is not suitable for fluid-bed processing. The off-gases then enter the wet scrubbing system consisting of (1) a water spray tower which is 50% efficient for total sulfur removal and 90% efficient for particulates, (2) a KOH high-energy venturi scrubber which is 85% efficient for H₂S and 98% efficient for particulates, and (3) a KOH packed tower which is 99% efficient for H₂S but has a negligible effect on particulates. The estimated efficiencies of the wet scrubbers take into account the average particle size of the effluent from the preceding unit. This is estimated as 2 microns for the sintered-metal filter effluent, 1 micron for the spray tower effluent, and 0.5 micron for the venturi effluent. The spray tower also serves to condense the water vapor that is a by-product of the reduction reaction. General descriptions of the filters and scrubbers are presented in Sect. 4.3.1.

The gaseous effluent from the F-F Case 1 reduction off-gas treatment system consists of 55 scfm of H₂ (excess H₂ over stoichiometric), 51 scfm of N₂ (from NH₃ decomposition), about 8 scfm of water vapor, 30 ppm of H₂S, and traces of crude uranium dusts. The H₂S release is 0.57 lb/day, and the crude uranium release is 0.2 g/day, which is negligible in

comparison with other sources (Table 4.6a). A large volume of liquid is generated by the scrubbers. Material flows which serve as the basis for the cost estimate are shown in Table 4.17. The KOH scrubbers are recirculating systems, operating between 10 and 2 wt % KOH; the water spray tower is a single-pass type.

4.4.6.3 Reduction scrub liquors, F-F Case 1. In Case 1, 30,000 gal of untreated scrub liquors per day containing 722 lb of sulfur as H₂S, K₂S, and free sulfur, 1100 lb of potassium, and 93 g (0.8 ppm) of crude uranium are released directly to surface streams. Source terms for this radwaste release are calculated (Table 4.9) by assuming that the ratio of the various radionuclides collected in the scrubbing system is the same as that in the feed to the plant (Table 4.2). Although Streams 3L and 3K are below the limits specified in 10 CFR 20, Appendix B, Table II, concentrations), they may not be acceptable chemically at all sites.

4.4.6.4 Reduction off-gas treatment, F-F Cases 2 and 3. The liquid waste from the reduction scrubbers is difficult to treat. Therefore, in Cases 2-4 the reduction off-gas treatment is modified to eliminate this waste stream by burning the H₂S and sulfur to SO₂ (Fig. 4.11). The H₂ present in the stream is simultaneously burned to H₂O. The material flows of Table 4.17 were calculated on the basis of the following equations:



Fifty percent excess H₂ is used in reduction and 200% excess air in the burner. The off-gas from the burner consists of 455 scfm of N₂, 154 scfm of H₂O, 36 scfm of O₂, 6 scfm of SO₂, and 0.2 scfm of CO₂, contaminated with traces of crude uranium oxide dust. The off-gas is passed through a high-energy venturi scrubber which is 99% efficient in removing the fine 2-micron particulates and condenses part of the water. The venturi operates on water condensed from the off-gas in order to minimize the amount of liquid waste. The system consists of a quencher,

venturi, gas cooling tower, fan, demister, water cooling tower, and water recirculation system. Water scrubbing is ineffective for SO_2 because of the low solubility. The removal efficiency for the flow rates of Table 4.17 is estimated as 10%. This assumes countercurrent flow of water and hot gases in the scrubber, a temperature of 70°C for the water as it exits from the scrubber, and an SO_2 concentration in the water which is two-thirds of the theoretical solubility of 2.54 g of SO_2 per 100 g of H_2O at 70°C .⁶³ In Cases 2 and 3 the SO_2 release is 1300 lb/day, or about 0.8 vol % of the effluent gas, and the uranium release is 0.9 g/day. In essence, the water pollution problem of Case 1 is converted to air pollution in Cases 2 and 3. The small increase in airborne radionuclides is negligible compared with total plant releases. Airborne source terms are given in Tables 4.6b and 4.6c.

4.4.6.5 Reduction scrub liquor, F-F Cases 2 and 3. About 950 gal of water scrub liquor per day carrying 93 g (26 ppm) of crude uranium solids is sent to the uranium settling basin, diluted with other plant wastes, and a neutral waste released to surface streams. The quantity of uranium is too small to justify a uranium recovery system. This stream is low in chemwaste. For purposes of calculating source terms, the effluent from the uranium settling pond is assumed to contain 20 ppm of uranium, based on a typical effluent from an acid-leach uranium mill.^{64,a} The ratio of the various radionuclides is assumed to be the same as that in the UF_6 plant feed. Liquid radwaste source terms are given in Table 4.9. Cases 2 and 3 have little effect on the liquid release of radioactive materials compared with the base plant.

4.4.6.6 Reduction off-gas treatment, F-F Case 4. In Case 4, a KOH high-energy venturi scrubber to remove 98% of the SO_2 and 99.95% efficient HEPA filters to lower the radwaste release are added to the Case 2 and 3 treatment system (Fig. 4.12, Tables 4.6d-4.8). Twenty-six pounds of SO_2 and 2×10^{-4} g of crude uranium dusts are released daily to the atmosphere. The water venturi serves as a condenser to remove water vapor from the off-gas prior to the KOH venturi. Careful control of the

^a Scouting tests of the effluent from one UF_6 plant uranium settling pond found 17.5 ppm of uranium.¹⁴ The effluent may have included dissolved uranium as well as suspended solids.

system is required to maintain the water balance in the KOH regeneration and recycle system discussed below. The calculations of Table 4.17 assume that the water venturi cools the gas to 40°C and the KOH venturi to 37°C with a small liquid bleed via the solid waste from KOH regeneration. The average particle size of the particulates passing the water venturi is assumed to be 0.5 micron, and the efficiency of the KOH venturi for 0.5-micron particles is assumed to be 50%. The purpose of the water venturi in F-F Case 4 is to simplify the liquid waste treatment. The water venturi provides minimal treatment for the SO₂, and if it were omitted from the system the KOH venturi scrubber would collect most of the particulates; thus its effect on the airborne radwaste release is small.

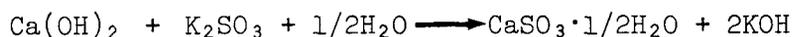
Case 4 illustrates one method for converting volatile H₂S and sulfur to solid waste which can be retained on-site. This method involves burning to SO₂, scrubbing with KOH, and precipitating with lime.^a Caustic scrubbing coupled with lime treatment to regenerate the KOH for recycle was selected in preference to limestone scrubbing because similar equipment is used for fluoride scrubbing elsewhere in the plant.

4.4.6.7 Reduction scrub liquors treatment, F-F Case 4. About 950 gal of water scrub liquor per day carrying 93 g of crude uranium solids is combined with other liquid wastes and sent to the plant evaporator system (Sect. 4.4.12). Water is recovered for reuse in the plant. The solids containing traces of radioactive materials are dried and drummed in preparation for disposal. The uranium in the evaporator feed is present as very fine particles (average particle size, 2 microns) at very low concentration (26 ppm) and cannot be recovered from the liquid by conventional filtration or chemical processes. This stream is

^aThe Allied Chemical Corporation has recently installed sulfur condensers and a H₂S burner on the reduction off-gas at the Metropolis UF₆ conversion facility.⁶⁵ This is another method of reducing the release of H₂S and sulfur to the environment; however, insufficient information was available to be included in the case studies.

low in chemicals. If desired, the water scrub liquor could be processed separately in the evaporator and the uranium recovered; however, this alternative was not costed.

About 4000 gal of spent KOH scrub liquor per day containing 0.5 g (0.03 ppm) of uranium is regenerated by treating with lime to precipitate $\text{CaSO}_3 \cdot 1/2\text{H}_2\text{O}$ (Fig. 4.28). The mixture is filtered to produce a clean KOH suitable for recycle, and the filter cake is slurried and pumped to a lined impoundment basin. The principal chemical reactions are:^a



The lime requirement, including 10% excess CaO, is 1400 lb/day. Solid waste (i.e., the moist filter) cake consists of 2900 lb of $\text{CaSO}_3 \cdot 1/2\text{H}_2\text{O}$, 170 lb of excess Ca(OH)_2 , 60 lb of CaCO_3 , and about 1700 lb (200 gal) of 10% KOH solution, on a daily basis. Essentially all the radioactive materials are carried with the solids. Since caustic creates difficulties in evaporators and calciners, it is important to operate the off-gas system so that all KOH can be recycled except for the liquid bleed associated with the moist filter cake. Water used to transport the filter cake is recirculated from the impoundment basin. Some engineering development will be required on this process since CaSO_3 may cause problems in both the scrubber piping system and the line to the storage basin.

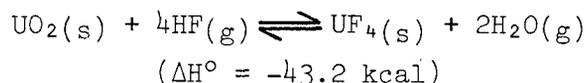
The case studies include the cost of the lined impoundment basin for storing the solids but not decommissioning the plant. No technical difficulties are anticipated in on-site burial. The CaSO_3 contains very small quantities of radioactive materials (Table 4.18). For example,

^aA small amount of SO_3 , which precipitates as $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, may be formed in the burner. This was ignored in the calculations.

ignoring radioactive impurities in the lime, the calculated uranium content of the CaSO_3 is 100-fold lower than the average uranium content of the earth's crust. The radioactive impurities are present as oxides and are incorporated in a matrix of CaSO_3 , which also has a low solubility so that long-term leaching by natural waters will be slow (solubilities shown in Table 4.19).

4.4.7 Hydrofluorination of UO_2 to UF_4

4.4.7.1 Hydrofluorination process. Uranium dioxide is hydrofluorinated to UF_4 by reaction with HF at temperatures of 350 to 590° (650 to 1100°F) according to:^{66,67}



A 10% excess (or more) of anhydrous HF is used. The hydrofluorination reaction is generally more difficult to handle than the reduction because the reaction is reversible at practical operating temperatures and is approximately twice as exothermic.^{67,68} The UF_4 product and partially reacted materials sinter at relatively low temperatures; operational difficulties due to bed caking and reduced reactivity are encountered. A temperature that is too low leads to HF-water condensation and the resultant problems of powder caking and corrosion. The hydrofluorination rate is markedly affected by the history of both the starting UO_3 and the reduction experience of the UO_2 (Part II). The 50% decrease in gas volume from 4 moles of HF reactant to 2 moles of H_2O product creates problems in controlling gas flow in fluidized beds.

A fluid-bed reactor has about 2-1/2 times the processing capacity of a screw reactor at the same conversion efficiency,⁶⁷ and is the preferred technique in the United States (Table 4.1). A small amount of N_2 diluent (30 to 50 cfm) is added to the HF to prevent caking.^{67,69} Two fluidized beds in series are used with 65 to 70% conversion occurring in the primary hydrofluorinator.^{1,61,67} This prevents sintering at localized hot spots in the primary reactor, where most of the heat is liberated, by limiting the amount of lower-melting UF_4

present (melting point 960°C vs 2176°C for UO_2).⁶¹ One stage in the fluid-bed hydrofluorination serves as the cleanup reactor for HF and the other stage for UO_2 , thus providing a high conversion to UF_4 and efficient HF utilization. External cooling is required for the primary hydrofluorinator to maintain the temperature below 510°C (950°F). Depending upon the flowsheet, heating⁶¹ or cooling⁶⁷ may be needed for the secondary hydrofluorinator. Conversion efficiency in the Paducah fluid beds ranges from 98.0 to 98.5%.⁶⁷ Overall uranium yield for the hydrofluorination step is 99.99%, or essentially no loss.¹¹

During hydrofluorination, silicon and boron are removed as volatile SiF_4 and BF_3 , while molybdenum and vanadium are partially removed as volatile fluorides and oxyfluorides (Table 4.16).^{45,61} Any sulfur remaining after reduction is also vaporized. The off-gas system to the wet scrubbers is heated to prevent condensation of volatile impurities which could result in line or filter blockage.^{61,69}

Sodium salt forms a relatively low-melting compound with uranium tetrafluoride ($7\text{NaF}\cdot 6\text{UF}_4$, melting point $\sim 675^{\circ}\text{C}$ vs 960°C for UF_4). This compound restricts the diffusion of HF to unconverted UO_2 and, if present in sufficiently high concentrations, forms a plastic mass which plugs the bed.^{4,45} For this reason, feeds containing more than 0.5% sodium are first washed with ammonium sulfate to remove the sodium ions (Sect. 4.4.11).

4.4.7.2 Hydrofluorination off-gas treatment, F-F Case 1. Flow diagrams for the base plant off-gas treatment are shown in Figs. 4.2 and 4.13. The dust-laden off-gas from hydrofluorination is cleaned by primary and secondary porous carbon filters which are 99.9995% efficient. Fines removed by the carbon filters go directly to fluorination (Sect. 4.4.8). Off-gases that are now low in radioactive materials then enter a wet scrubbing system consisting of (1) a medium-energy water venturi scrubber which is 90% efficient for HF and particulate removal, and (2) a medium-energy KOH scrubber which is 85% efficient for HF and 50% for particulates. Conservative efficiencies that have been confirmed by

plant experience are used for HF. The particle size of the particulates passing the carbon filters, although unknown, must be very fine; therefore, there is considerable uncertainty in the particulate-removal efficiencies estimated for the wet scrubbers. The water venturi also serves to condense the water vapor which is a by-product of the hydrofluorination reaction.

The gaseous effluent from the F-F Case 1 off-gas treatment system (Figs. 4.2 and 4.13, Stream 4A) consists of 60 scfm of N₂ (used to fluidize the beds), about 3 scfm of water vapor, and 0.7 vol % HF. The airborne chemwaste release consists of 37 lb of HF per day, while the radwaste release amounts to less than 0.3 g of crude uranium per day. The release of uranium in the hydrofluorination off-gas is negligible compared with releases of dust from materials handling operations (Table 4.13). There is a large volume of liquid waste from the scrubbers (Streams 4L and 4K). Material flows are shown in Table 4.20, assuming that 10% excess HF is used in hydrofluorination. The KOH scrubber is a recirculating system operating between 10 and 2 wt % KOH; the water scrubber is a single-pass unit.

4.4.7.3 Hydrofluorination scrub liquors, F-F Case 1. About 30,000 gal of untreated scrub liquors (Streams 4L and 4K) containing 2300 lb of fluorides, 600 lb of potassium, and 8 g of uranium (0.07 ppm) is diluted with other plant wastes and released to surface streams on a daily basis. The uranium release through the hydrofluorination scrub liquor is calculated from the analytical limit of detection by the industry and represents the probable upper limit rather than an average or actual release. Liquid radwaste source terms are estimated by assuming that the ratio of the various radionuclides is the same as in the plant feed (Table 4.9).^a Streams 4L and 4K are below the limits

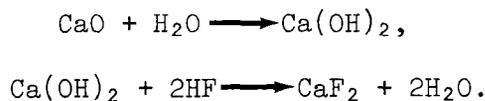
^aThe calculated ²²⁶Ra concentrations for the model water scrub liquor and the KOH scrub liquor are 1.2×10^{-10} $\mu\text{Ci/ml}$ and 1.3×10^{-10} $\mu\text{Ci/ml}$ respectively; scouting tests found less than 3×10^{-9} $\mu\text{Ci/ml}$ for the water scrub liquor and 4.5×10^{-7} $\mu\text{Ci/ml}$ for the KOH scrub liquor.¹⁴ The model does not consider possible radionuclides in the chemical feed (i.e., KOH) to the plant.

stipulated in 10 CFR 20, Appendix B, Table II but may not be acceptable chemically at all sites.

4.4.7.4 Hydrofluorination off-gas treatment, F-F Cases 2 and 3.

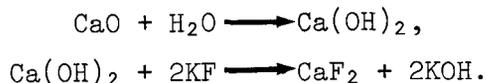
The gaseous HF release is reduced to 0.37 lb/day by adding a 99% efficient packed tower to the Case 1 system (Fig. 4.14). The packed tower has a negligible effect on the very fine uranium dusts that pass the venturi scrubbers. Liquid and gaseous flow rates are the same as in Case 1 (Table 4.20).

4.4.7.5 Hydrofluorination scrub liquor treatment, F-F Cases 2 and 3. About 29,000 gal of water scrub liquor per day, bearing 2100 lb of fluoride as HF and 8 g of uranium (0.07 ppm), is treated with lime to precipitate CaF_2 (Fig. 4.25, Stream 4L):



The CaF_2 is allowed to settle in a lined impoundment basin. The clear supernate is diluted with other plant wastes, neutralized, sampled for activity, and released to surface stream (Fig. 4.25, Stream 4LT). The lime requirement, including 10% excess CaO, is 2800 lb/day. The fluoride release is 6 lb/day, assuming that the effluent contains 25 ppm of fluoride. This is a 1000-fold reduction in the chemwaste release. Source terms for the liquid radwaste release are presented in Table 4.9, assuming that 10% of the radioactive materials are released and the remainder are carried by the CaF_2 precipitate. The solid waste generated daily consists of 4300 lb of CaF_2 , 410 lb of excess Ca(OH)_2 , and about 1650 lb of water which settles with the moist solids.

About 1000 gal of KOH scrub liquor per day, bearing 234 lb of fluoride as KF and 0.3 g of crude uranium (0.08 ppm) is treated with lime to precipitate CaF_2 and regenerate the KOH (Fig. 4.23, Stream 4K):



The mixture is filtered to produce a clean KOH for recycle. The filter cake is slurried (with water scrub liquor) and pumped to the lined impoundment basin. Lime requirements, including 10% excess CaO, are 310 lb/day. The solid waste (i.e., moist filter cake) generated daily consists of 480 lb of CaF₂, 46 lb of excess Ca(OH)₂, and about 185 lb (22 gal) of 10% KOH solution. The case study assumes that most of the water vapor from the hydrofluorination reaction is condensed in the water scrubbers, and that the only liquid bleed from the KOH circuit is in conjunction with the moist filter cake. This eliminates the direct liquid release of KOH scrub solution. Essentially all radioactive materials are carried with the solids during lime precipitation.

The case studies include the cost of the lined impoundment basin for storing the CaF₂ but not of decommissioning the plant; however, no technical difficulties are anticipated in disposal by on-site burial. If the radioactive impurities naturally present in the lime and KOH are ignored, the calculated uranium content of the CaF₂ is about the same as the average uranium content of the earth's crust (Table 4.18). Calcium fluoride and the fluorides and oxides of most of the radioactive and chemical contaminants are only slightly soluble; therefore, long-term leaching will be very slow.

4.4.7.6 Hydrofluorination off-gas treatment, F-F Case 4. This case study further reduces the airborne release of HF and radioactive materials, and recovers a 25 wt % aqueous HF solution for industrial use. Off-gases from the porous carbon filters pass to: (1) a water-and-brine-cooled condenser system which recovers HF (99% efficient for HF and 90% for particulates), (2) a KOH packed tower (99% for HF and 50% for particulates), (3) a KOH coke box (90% for HF and 0% for particulates), and (4) an HF-resistant HEPA filter (0% for HF and 99.9995% for particulates). The flow diagram is shown in Fig. 4.15; the material flows are given in Table 4.20. The gaseous effluent from the waste treatment system consists of 60 scfm of nitrogen and about 2 scfm of water vapor carrying 0.037 lb of HF (6.50 µg of fluoride per liter) and less than 2×10^{-5} g of crude uranium per day.

Hydrofluoric acid recovery (Stream 40) with the condenser system reduces the load to the liquid waste treatment system by a factor of 100 (Streams 4L and 4K, Table 4.20). A 15% excess of HF is used in hydrofluorination in order to recover directly an industrially usable concentration of 25 wt % HF. No practical means of breaking the HF-H₂O azeotrope to recover anhydrous HF for recycle within the UF₆ plant is known. The recovered hydrofluoric acid solution is acceptable radiologically for release off-site (i.e., below the limits specified in 10 CFR 20, Appendix B, Table II; see Table 4.21) but is of limited value today because of the chemical impurities, such as silicon, molybdenum, vanadium, and boron. Case 4 includes the cost of the condensers. No charge or credit is taken for disposing of the recovered HF. Fluorspar, the raw material in the manufacture of HF, is an imported mineral which has been rapidly escalating in price. Case 4 assumes that at some future time the HF will be worth recovering. Development work on the purification of hydrofluoric acid is required before Case 4 can be reduced to practice. If only the off-gas is considered, the Case 4 condenser system used with a 15% excess HF in hydrofluorination is essentially equivalent to the system consisting of a water medium-energy venturi plus a KOH medium-energy venturi used with a 10% excess of HF in Cases 1-3. The condenser system is effective in reducing the quantity of liquid and solid wastes.

HEPA filters are the most efficient means known for removing fine particulates from off-gases; unfortunately, however, they are made of silica and are corroded by HF. The primary purpose of the KOH coke box is to increase the life of the HEPA filters by lowering the HF concentration to about 6.5 µg/liter. The coke box will be of marginal value if durable HEPAs resistant to 60 to 100 µg of fluoride per liter are developed.

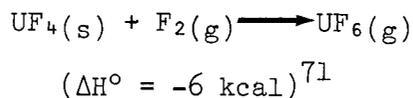
4.4.7.7 Hydrofluorination scrub liquor treatment, F-F Case 4.
There is no water scrub liquor in Case 4. The effect of shipping the condensed hydrofluoric acid solution off-site will depend upon the end use.

The KOH scrub liquor (Figs. 4.15 and 4.23, Stream 4K) is regenerated with lime and recycled. The system is similar to Cases 2 and 3, except that the material flows are lower by approximately a factor of 7. An estimated 154 gal of spent scrub liquor per day carrying 35 lb of fluoride and 0.3 g of crude uranium (0.5 ppm) is treated with 47 lb of lime. The moist filter cake generated daily consists of 72 lb of CaF₂, 7 lb of excess Ca(OH)₂, and about 28 lb (3 gal) of 10% KOH solution. In addition to the liquid bleed with the filter cake, there is also a small evaporative water loss from the KOH scrubber because the brine condenser has dehumidified the gas feed to the wet scrubber. There is no direct liquid bleed from the circuit. Solids are moved to a lined disposal pit. If one ignores radioactive materials present in the lime or KOH feed, the total activity going to the CaF₂ pit from hydrofluorination is about a factor of 50 lower in Case 4 than in Cases 2 and 3. The specific activity is higher in Case 4 than in Cases 2 and 3 since there is less CaF₂ diluent, but is still quite low (Table 4.18); for example, the estimated uranium content is only 9 ppm.

4.4.8 Fluorination and distillation

4.4.8.1 Fluorination and distillation process, F-F Cases 1-3.²,14,45,70

Fluid-bed fluorination. The fluorination-fractionation model plant uses fluid-bed fluorinators with CaF₂ diluent to control the highly exothermic reaction:



The fluorine utilization is 80 to 90%.² Impurities in the feed, particularly sodium, form relatively low-melting compounds which can cause caking and fusion unless careful temperature control is maintained.^a

^aThe tower flame fluorinator (Part II) is not suitable for the F-F plant. At the temperatures reached in the flame reactor, the impurities form a slag on the reactor walls.⁷⁰ As little as 1% sodium in the feed is sufficient to cause complete flow stoppage in a matter of hours at normal production rates.

The operating temperature is 800 to 1000°F (425 to 535°C).² Heat removal is the limiting factor in the design. The reaction rate is extremely fast under optimum conditions and increases rapidly with temperature. Heat generation can exceed the rate of heat transfer across the bed; therefore, CaF₂ is used as the bed material with only a small amount of UF₄. Uranium hexafluoride, VF₅, VOF₃, and MoF₆ are volatilized.⁴⁵ Phosphorus, antimony, chromium, and bismuth fluorides are also volatilized but are of little consequence since they are present at low concentrations and their volatilities differ significantly from UF₆. The fluorides of radioactive and other chemical impurities in the UF₄ feed are nonvolatile and remain with the bed material. Air drawn from the room is used for cooling and functions as part of the building ventilation.

Crude UF₆ collection. Dust-laden gases from the fluorination fluid beds, including UF₆, VOF₃, VF₅, MoF₆, excess F₂, HF (an impurity in the fluorine), and inert gases, pass through primary and secondary sintered-nickel or Monel filters to the first set of refrigerated UF₆ cold traps where UF₆, VOF₃, VF₅, and MoF₆ are condensed (Fig. 4.2). The bulk of the UF₆ is removed in the first cold trap which is chilled to 0 to -20°F; the remaining UF₆ is removed in smaller traps chilled to -40 to -60°F.⁷² Noncondensable gases (i.e., F₂, HF, and inert gases contaminated with 0.05 to 0.10 vol %⁷⁰ of UF₆) leave the system by means of an air ejector and pass to the fluorination off-gas treatment system (Sects. 4.4.8.3-4.4.8.9). The design of the heat exchanger surfaces to avoid premature plugging and minimize entrainment carry-over of condensed UF₆ is reviewed in ref. 72.

Distillation and pure UF₆ collection.^{2,45} After fluorination, the UF₆ contains some impurities which are separated by fractional distillation. Crude UF₆ is melted and transferred from the cold traps to the distillation feed tanks, where it is maintained in a molten state.² Most entrained HF is vaporized during melting and passes to the off-gas system.^a Uranium hexafluoride is vaporized into a 100-tray, low-boiler,

^aHydrogen fluoride forms a low boiling azeotrope with UF₆, causing difficulties in the low-boiler column. It is eliminated in the cold trap system prior to distillation.

Monel, bubble-cap column which separates UF_6 (sublimation point, $56^\circ C$; triple point, $64^\circ C$) from the more volatile VF_5 (boiling point, $48^\circ C$), MoF_6 (boiling point, $35^\circ C$), and traces of SiF_4 , CF_4 , SF_6 , etc. Vanadium oxyfluoride (VOF_3 , sublimation point, $110^\circ C$) has only limited solubility in UF_6 (0.7 wt % at operating conditions). Concentration of impurities in the top of the column leads to precipitation of solid VOF_3 in the condenser, which must be removed either by filtration or by vaporization with periodic purges. When present at high concentrations, VOF_3 is the limiting factor in the low-boiler separation. Off-gases from the low-boiler column pass through the VOF_3 condenser and UF_6 cold traps, and volatiles are then vented through the fluorination off-gas treatment system (Fig. 4.2). Liquid uranium hexafluoride containing high-boiling impurities passes to a 45-bubble cap tray column where high-purity UF_6 is volatilized and collected in a second set of UF_6 cold traps similar to the first. The pure UF_6 product is finally melted and drained into a 10-ton shipping cylinder. A typical analysis is shown in Table 4.22. Still bottoms consist principally of an unidentified molybdenum compound, probably an oxyfluoride, with a little UF_6 , VOF_3 , and traces of particulates which pass the filters. Still tops and bottoms are stored as the values contained do not presently justify recovery.^a The low-boiler column operates at about $200^\circ F$ and 85 psia at the condenser, and the high-boiler column at about $240^\circ F$ and 95 psia.² Vapor phase transfers are made by pressure difference because there is no dependable UF_6 pump. This survey treats distillation as a closed circuit with no releases of radioactive materials or chemicals. The flowsheet is shown in Fig. 4.2.

Ash. A portion of the fluid-bed material called ash is withdrawn (1) to avoid the buildup of nonvolatile impurities, such as sodium, which form low-melting complexes with UF_6 and may cause caking in the bed, and (2) to circumvent the accumulation of nonvolatile radioactive daughter products of uranium in the bed. The fluorination ash, including filter fines, is drummed, stored a minimum of 6 months to permit decay of ^{234}Th and ^{234m}Pa , and leached with sodium carbonate to recover uranium

^aAdditional discussion of still tops and bottoms is presented in Sect. 4.4.13.

(Sect. 4.4.10). Essentially all the radioactive impurities in the crude uranium feed to the plant are converted to dry solid waste. The principal radioactive materials in the ash before and after decay are estimated in Table 4.15, assuming that the ash contains 1.8%⁴⁵ of the total uranium processed and all of the nonvolatile uranium daughters. The total quantity of ash is about 0.1 ton per ton of uranium processed.⁷³

Fluorine and UF₆ cleanup reactors, F-F Cases 1-3. The fluorination-fractionation model plant does not have cleanup reactors in Cases 1-3. Consequently, there is a heavy load to the waste treatment system.

4.4.8.2 Fluorination and distillation process, F-F Case 4

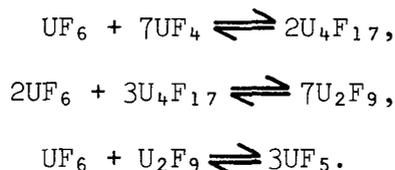
Fluorine cleanup reactor.⁷⁴ An internal process change is made in Case 4 to increase the fluorine utilization, thereby decreasing the load to the waste treatment system. Tail gases from the primary fluorination UF₆ cold traps, which contain significant values of fluorine, are passed to a UF₄ fluidized bed operated at 750°F, where the fluorine is reacted with an excess of UF₄. Uranium tetrafluoride is added at a rate up to five times stoichiometric to provide dilution control of bed temperature and to avoid coalescence of unstable uranium fluoride intermediates such as U₄F₁₇, U₂F₉, and UF₅. An advantage of the fluidized-bed reactor is that an excess of UF₄ is always available, regardless of the inlet fluorine concentration - a condition not always true with tower cleanup reactors. Exit gases consisting of UF₆ product, HF (from the HF impurity in the fluorine), inert impurities, and traces of F₂ are passed through sintered-metal filters to a UF₆ cold trapping system and the waste treatment system. Solids withdrawn from the fluorine cleanup reactor are then fluorinated in the primary fluorinator to obtain essentially complete conversion to UF₆. The cleanup reactor recovers greater than 95% of the fluorine; on-stream time is 90%.

The installation of a fluorine cleanup reactor will increase the airborne dust losses from UF₄ handling. For a 10% excess F₂ feed to the primary fluorinator and addition of UF₄ feed to the cleanup reactor at a rate five times stoichiometric, half of all the UF₄ processed will

be handled first through the cleanup reactor and then through the primary fluorinator--in essence handled twice. This might increase UF₄ dust releases by up to 50%, and total crude uranium releases by up to 8%.

Although the ERDA flowsheet for the fluorine cleanup reactor has been described in the open literature, part of the technology is still classified. Case 4 assumes that, at some future time, either comparable technology will be developed by private industry or the ERDA technology will be made available to the general public. No costs are assessed for the fluorine cleanup reactor since the savings in fluorine costs justified the installation at the ERDA plants.^a

Uranium hexafluoride cleanup reactor.^{74,75} The recovery of UF₆ is increased (and the load to the waste treatment system reduced) in Case 4 by adding a UF₆ cleanup reactor after the F₂ cleanup system. This reactor is a UF₄ fluidized-bed type which is similar to the F₂ cleanup reactor except that it is operated at 300 to 400°F and 14 to 16 psi. Under these conditions, the UF₆ gas reacts with the UF₄ solids to form nonvolatile compounds:



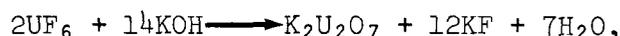
The UF₆ content of the gas is reduced from an inlet concentration of 300 to 1000 ppm to an exit concentration of 20 ppm under plant conditions.⁷⁴ The UF₄ can absorb up to 0.38 lb of UF₆ per pound of UF₄. Solids withdrawn from the UF₆ cleanup reactor are fluorinated in the primary fluorinator to obtain essentially complete conversion to UF₆. Only about 1% of the total UF₄ is needed for the UF₆ cleanup reactor; therefore, the additional materials handling has little effect on the airborne dust releases. No costs are assessed to the UF₆ cleanup reactor since the savings in uranium recycle justified the installation at the ERDA plants. Part of the ERDA technology is presently classified.

^aALARA studies do not consider development costs.

Again, Case 4 assumes that either comparable technology will be developed by private industry or the ERDA classified technology will be made available to the public.

4.4.8.3 Fluorination off-gas treatment, F-F Case 1. Flow diagrams for the base plant off-gas treatment system are shown in Figs. 4.2 and 4.16. Fluorine, prepared by the electrolysis of HF, is passed through a relatively inefficient (27%) condenser which returns some HF to the electrolytic cells (Sect. 4.4.9). This HF condenser is considered with the fluorination off-gas treatment since the HF impurity in the F₂ is a significant part (one-third) of the waste treatment load. Off-gases from fluorination consisting of excess F₂, HF, inert gas, UF₆ product, and various impurities are cleaned by primary and secondary sintered Monel or nickel filters and the UF₆ cold trap system (see Sect. 4.4.8.1). Noncondensable gases (F₂, HF, and inert gases bearing traces of UF₆) are ejected to a KOH scrubbing system which serves the dual functions of recovering uranium and removing noxious gases. The spray tower is assumed to be 80% efficient on UF₆, F₂, or HF, and the packed tower is assumed to be 99% efficient. Efficiencies for chemicals are based on experimental measurements.¹⁴

The technology for the operation of KOH scrubbers in industry is proprietary. This survey assumes that the scrubbers are recirculating systems which operate between 10 and 2 wt % KOH, and that the principal chemical reactions are:



Potassium diuranate is insoluble and precipitates in the scrubbers, while the compound K₄UO₈ is soluble.⁷⁶ A number of other peroxy uranium compounds, including fluoride-containing complexes, are known and might

be formed.⁷⁶ These other compounds are only slightly soluble and would precipitate in the scrubber. Peroxy uranium compounds are expected only when there is an excess of F_2 . Since UF_6 is only a minor component of the fluorination off-gas, the exact chemical behavior of uranium in the scrubbers has little effect on the overall assessment.

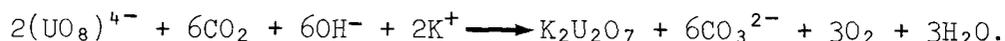
Fluorination waste streams and material flows are presented in Table 4.23. The load to the waste treatment system, Stream 8, is estimated as 346 scfm of "inert" gases (nitrogen used to fluidize the bed, seal leakage, and oxygen from the fluorination of oxide or oxyfluoride impurities in the UF_4), 8.2 scfm of F_2 (90% F_2 utilization, i.e., the highest reported by Ruch et al.²), 8.0 scfm of HF (8 vol % HF impurity in the F_2 feed to fluorination - Stream 7F), and 0.28 scfm of UF_6 (0.08 vol % of the effluent gas from the cold traps, i.e., the average reported by Smiley⁷⁰). The total fluoride load is 2000 lb/day, and the uranium load is 270 lb/day. The fluorination-fractionation model plant does not have cleanup reactors in Cases 1-3. Consequently, the treatment system receives a heavy load. The gaseous effluent released to the atmosphere from the fluorination scrubbing system carries 4.2 lb of HF and 245 g of uranium per day. Elemental fluorine is very reactive with water, forming HF, and therefore is not released. About 9100 gal of the 10% KOH solution are used in the scrubbers per day. The calculations are based on the assumption that all the uranium goes to the soluble K_4UO_8 , which increases the KOH requirements by about 3% compared with basing the calculations on $K_2U_2O_7$.

The release of radioactive materials other than uranium is low because the daughters (except radon) are nonvolatile during fluorination. Particulates are removed from the off-gas by the sintered-metal filters. The impurities remaining after burning the UF_4 are lighter than the CaF_2 bed material and tend to concentrate in the filter fines. This assessment assumes (1) that the amount (i.e., pounds) of dust passing the fluorination filters is the same as the amount passing the reduction filters and (2) that the concentrations of ^{234}Th , 234mPa , ^{230}Th , and ^{226}Ra in this dust are about ten times higher than their concentrations in the plant feed.⁵¹ The UF_6 cold trapping system is

assigned an efficiency of 95% for 2-micron particulates since it contains fins, baffles, and a demister⁷² and resembles an impingement dust collector to some extent. Although the dust passing the sintered-metal filters is extremely fine, UF₆ is expected to condense on the particles, increasing the particle size and hence the collection efficiency of the cold trap system. The wet scrubbing system of spray tower plus packed tower collects 80% of the particulates passing the cold traps. Source terms based on these assumptions are presented in Table 4.6. Considerable uncertainty is associated with these source terms.

4.4.8.4 Uranium recovery from scrub liquors, F-F Cases 1-4.

Uranium is recovered from the spent KOH scrub liquor by destroying the soluble peroxy complex and allowing the uranium to precipitate. The chemistry is unknown. The flowsheets assume that CO₂ destroys peroxy-uranate by analogy to the chemistry of alkali peroxides:⁷⁷



Ferrous and cuprous ions catalytically decompose peroxides and may also be added. The precipitated K₂U₂O₇ is recovered and sent to the ammonium sulfate wash (Sect. 4.4.11) for recycle to the process. The calculations assume that all the uranium is present as the soluble peroxy complex and that a 100% excess of CO₂ is necessary to destroy this complex. The uranium content of the waste KOH solution (Fig. 4.16, Stream 8K) is estimated as 30 ppm^a based on a typical soluble loss for an alkaline leach uranium mill which precipitates Na₂U₂O₇ from carbonate solutions.⁷⁸ Source term estimates assume that half the fine particulates (i.e., the radium and thorium) are carried by the uranium precipitate (Fig. 4.16, Stream 8Ub) and half remain suspended in the spent KOH solution (Fig. 4.16, Stream 8K).

4.4.8.5 Fluorination scrub liquor, F-F Case 1. About 9100 gal of spent KOH scrub liquor containing 2000 lb of fluoride, 5200 lb of potassium, and 1034 g of uranium (30 ppm) is mixed with other plant wastes

^aSpot test showed 21 ppm of uranium in this stream.¹⁴

and released to surface streams on a daily basis. Source terms for ^{234}Th and $^{234\text{m}}\text{Pa}$ allow 14-day holdup of the uranium after precipitation (Table 4.9). Longer holdup times would allow more ^{234}Th and $^{234\text{m}}\text{Pa}$ daughters to grow back. The amounts of ^{230}Th and ^{226}Ra released were estimated with the assumptions discussed in Sects. 4.4.8.3 and 4.4.8.4. Stream 8K is below the limits specified in 10 CFR 20, Appendix B, Table II Concentrations (Table 4.9) but may not be acceptable chemically at all sites (Table 4.10).

4.4.8.6 Fluorination off-gas treatment, F-F Cases 2 and 3.

The gaseous HF release is reduced to 0.42 lb/day and the uranium to 24.5 g/day by adding a KOH coke box to the Case 1 system (Fig. 4.17). This unit is 90%^a efficient for the removal of F_2 , HF, and UF_6 , and 50% efficient for fine particulates (i.e., thorium and radium). Liquid and gaseous flow rates are the same as those in Case 1 (Table 4.23).

4.4.8.7 Fluorination scrub liquor treatment, F-F Cases 2 and 3.

Spent KOH solution is regenerated and recycled to the process by precipitating the fluoride with lime (Fig. 4.23, Stream 8K). The system is similar to the hydrofluorination KOH liquor treatment (Sect. 4.4.7.5), except that the flows are about nine times higher. About 9100 gal of spent scrub liquor carrying 2000 lb of fluoride, 410 lb of carbonate, 1.0 kg of uranium, and traces of other radioactive materials is treated with 3500 lb of CaO on a daily basis. The resulting filter cake consists of 4070 lb of CaF_2 , 680 lb of CaCO_3 , 440 lb of $\text{Ca}(\text{OH})_2$ (10% excess), and about 1800 lb (215 gal) of 10% KOH solution. Most of the radioactive materials are found in the solids. Lime treatment precipitates uranium by breaking the soluble tricarbonatate complex and carries fine suspended solids with the CaF_2 precipitate. The uranium concentration in the dry solids is about 450 ppm, or 150 times higher than the average for the earth's crust. The ^{230}Th and ^{226}Ra concentrations are negligible

^aThe KOH coke box is a proprietary development of the Allied Chemical Corporation. The efficiency was downgraded from 99.9%¹⁴ to 90% because the technology is not in the public domain.

(Table 4.18). Although most of the KOH is recycled to the process, the liquid bleed associated with the moist filter cake mixes with other liquid effluent in the CaF_2 impoundment basin and is potentially released to surface streams. Source terms are estimated in Tables 4.9 and 4.10, assuming that 90% of the radioactive materials are lime precipitated and that 2.36% of the KOH solution is released.

4.4.8.8 Fluorination off-gas treatment, F-F Case 4. The flowsheet is shown in Fig. 4.18. The addition of a 95% efficient F_2 cleanup reactor and a 97.5% efficient UF_6 cleanup reactor (Sect. 4.4.8.2), along with replacement of 27% efficient HF condensers with 65% efficient condensers on the fluorine feed (Stream 7F), reduces the fluoride load to the wet scrubbing system by a factor of 6 and the uranium load by a factor of 40 in Case 4. The KOH scrubbing system is the same as in Cases 1-3. A 99.95% efficient, HF-resistant HEPA filter is added as a final cleanup for fine particulates. None of this technology is available for immediate use by the industry. Case 4 assumes that either similar technology will be developed by private industry or that the ERDA technology will be made available to commercial firms.

Fluorination waste streams and material flows are presented in Table 4.23. The load to the wet scrubbing system, Stream 8, is estimated as 346 scfm of "inert" gases, 0.41 scfm of F_2 , 4.0 scfm of HF, and 0.007 scfm of UF_6 . The total fluoride load is 342 lb/day, while the uranium load is 6.8 lb/day. The gaseous effluent from the system carries only 0.07 lb of HF and 3×10^{-4} g of uranium on a daily basis. Source terms for radioactive materials are estimated in Table 4.6d. About 1600 gal of 10 wt % KOH per day is used in the scrubbers. While the fluorine cleanup reactor is beneficial in conserving natural resources and reducing liquid and solid waste management problems, it does increase the airborne release of crude uranium dusts by up to 8% because of the increased materials handling (Sect. 4.4.8.2).

4.4.8.9 Fluorination scrub liquor treatment, F-F Case 4. Spent KOH solution is regenerated with lime and recycled to the scrubbers.

The system is similar to Cases 2 and 3 except that the load has been reduced by a factor of about 6. Solids are moved to a lined disposal pit with no liquid release from the pit. The daily load to the treatment system is about 1600 gal of solution carrying 340 lb of fluoride and 174 g of uranium. The lime requirement is 74 lb/day. The resultant moist filter cake consists of 700 lb of CaF_2 , 10 lb of CaCO_3 , 75 lb of $\text{Ca}(\text{OH})_2$, and about 275 lb (33 gal) of 10% KOH solution. On a unit weight basis, the CaF_2 waste in Case 4 is very similar to that in Case 2 or 3 -- the uranium concentration is about the same and the ^{230}Th and ^{226}Ra concentrations are near or below the average for the earth's crust (Table 4.18). The principal difference is that Case 2 or 3 produces six times as much solid waste as does Case 4.

4.4.9 Fluorine production

4.4.9.1 Fluorine production process.^{47,79} Production of UF_6 requires large quantities of fluorine gas which is produced on-site by electrolysis of HF in an anhydrous fused electrolyte, $\text{KF}\cdot 2\text{HF}$ (melting point, 71.5°C , 160.7°F). When a direct current is passed through the electrolyte, both fluorine and hydrogen are evolved. The fluorine and the hydrogen collect in the anode and cathode compartments, respectively, above the electrolyte surface. These gases are removed through separate piping systems, and the hydrogen fluoride that is consumed is replaced continuously. The fluorine and hydrogen streams are piped to electrolyte entrainment separators. The gases are then admitted to surge tanks which dampen pressure fluctuations. At this point in the system, the fluorine gas contains 11 vol % HF and the hydrogen gas contains 9 vol % HF.⁴⁷ Part of the HF is recovered by condensation for recycle to the electrolytic cells. From the heat exchangers, the fluorine is piped to the primary fluorination unit; the hydrogen is waste. Cell operating characteristics are given in Table 4.24. The cells operate under corrosive conditions and must be rebuilt periodically. Approximately 80% of the electrolyte from failed cells is decanted and reused.⁴⁷ The model plant generates an estimated 26,000 lb of nonradioactive cell sludges

per year. This waste is drummed and buried (in Case 1) or treated with other fluoride wastes (in Cases 2-4).

Cases 1 through 3 have relatively inefficient (27%) HF condensers; Case 4 has 65% efficient, -120°F condensers on the fluorine cell. A lower limit on the amount of HF impurity in the gases is fixed by the polymerization of HF.⁴⁷ The Case 4 condenser system is not presently available to private industry. Case 4 assumes that either industry will develop comparable technology or that the ERDA technology will be made available. The HF recovery streams are shown in Fig. 4.3 and detailed in Table 4.25. The flows to the condensers (Streams 7D and 7E) are about 10% lower in Case 4 because of more efficient fluorine utilization in fluorination (Sect. 4.4.8.2).

The off-gas treatment system for the fluorine cell hydrogen (Fig. 4.3, Stream 7C) is described in the following subsections. This off-gas is not radwaste, since it has never been in contact with radioactive materials; however, it does contain a noxious chemical, HF, whose release would be unacceptable. The off-gas treatment for the fluorine cell fluorine (Fig. 4.3, Stream 7F) is discussed in Sect. 4.4.8.

4.4.9.2 Fluorine cell hydrogen off-gas treatment, F-F Case 1.

The hydrogen waste from the HF condenser (Stream 7C, Figs. 4.3 and 4.19) is burned in 50% excess air to destroy the hydrogen, and the resulting mixture water-scrubbed in a medium-energy venturi scrubber (90% efficient for HF). The feed to the burner is 90 scfm of H_2 and 5.9 scfm of HF. The effluent released is 256 scfm of N_2 , 22 scfm of O_2 , 0.59 scfm of HF (0.2 vol %), and about 12 scfm of H_2O . The total HF release is 47 lb/day. The venturi condenses most of the water vapor produced when the hydrogen is burned. No radioactive materials are released. Material flows are shown in Table 4.25.

4.4.9.3 Fluorine cell hydrogen scrub liquor, F-F Case 1.

A total of 14,000 gal of untreated scrub liquor per day is equalized with other plant wastes and released to surface streams (Fig. 4.22). This volume of liquor contains about 450 lb of fluoride, as HF, but no

radioactive materials.

4.4.9.4 Fluorine cell hydrogen off-gas treatment, F-F Cases 2 and 3.

A 99% efficient KOH packed tower is added to the Case 1 system to reduce the HF release to 0.47 lb/day (20 ppm of the effluent, Fig. 4.20). Water vapor is condensed in the water venturi to avoid a direct liquid bleed from the KOH circuit. Material flows are shown in Table 4.25.

4.4.9.5 Fluorine cell hydrogen scrub liquor treatment, F-F Cases 2 and 3. The water scrub liquor is treated with lime to precipitate fluoride, and the CaF_2 is allowed to settle; the clear supernate is then equalized with other plant wastes, neutralized, and released to surface streams. The 14,000 gal of waste treated daily (Fig. 4.25, Stream 7LT) contains 3 lb of fluoride but no radioactive materials. The KOH scrub liquor is regenerated with lime and recycled to the scrubber. There is a small bleed stream associated with the moist filter cake, but no direct liquid bleed from the KOH circuit. Total lime requirements are 600 lb/day. The solid waste generated daily amounts to 920 lb of CaF_2 and 90 lb of $\text{Ca}(\text{OH})_2$, which is stored in the settling basin. This chemwaste contains no radioactive material.

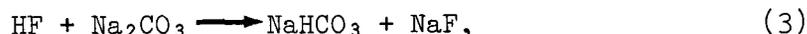
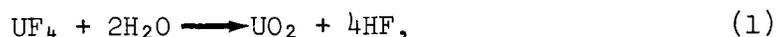
4.4.9.6 Fluorine cell hydrogen off-gas, F-F Case 4. The load to the off-gas treatment system is reduced by a factor of 2 by substituting more-efficient, -120°F condensers (67% efficient vs 27%) and improving the fluorine utilization (99.5% vs 90%, Fig. 4.21). This technology is not available to the industry at the present time. In addition, a 90% efficient KOH coke box is added to the wet scrubbing system. Only 0.020 lb of HF per day is released to the atmosphere. Material flows are presented in Table 4.25.

4.4.9.7 Fluorine cell hydrogen scrub liquor, F-F Case 4. Liquid treatment in Case 4 is similar to that in Cases 2 and 3, although the load has been reduced by a factor of 2 and the solids are handled differently (Fig. 4.27, Table 4.25). The water scrub liquor is treated with lime and pumped to a separate impoundment basin where the solids

settle. Clear supernate is released to surface streams. This stream is low in chemwaste (3 lb of fluoride per day) and carries no radioactive materials. It contains water condensed from the process and is surplus to the water balance in the plant. In Case 4, it is important to keep the fluorine cell water scrub stream, which is released, completely separate from all other CaF₂ streams. If mixed with filter cakes from other streams, this stream might potentially carry noxious materials from the filter cake liquid bleeds. The moist filter cake from KOH regeneration is moved to the lined pit where other CaF₂ is stored so that there is no release of caustic. Lime requirements in Case 4 are 250 lb/day, and 420 lb of solid waste is generated each day.

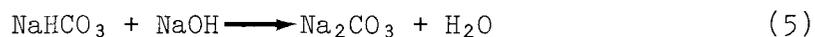
4.4.10 Carbonate leach (uranium recycle)

4.4.10.1 Carbonate leach process, F-F Case 1. Uranium is recovered from fluorination ash and miscellaneous solid wastes by carbonate leaching (Fig. 4.4).¹⁴ The process is similar to the carbonate leach process used at uranium mills,⁸⁰ but the feed is predominantly UF₄ in CaF₂ rather than uranium oxides in limestone (CaCO₃) or sandstone. The model is adapted from uranium mill circuits and does not necessarily correspond to current UF₆ plant practice. Drums of fluorination ash (which have been stored 6 months to permit decay of ²³⁴Th and ^{234m}Pa) are dumped. The ash is wet ground to 70 to 80% minus 200 mesh in Na₂CO₃ solution before passing to the leach tanks. The primary chemical reactions are assumed to be:



The CaF₂ and most impurities in the ash do not dissolve appreciably. Leaching is conducted in covered tanks at about 80°C using 0.1 to 0.25 scfm of air per pound of uranium to agitate the tanks and oxidize the uranium. The leach tanks are covered, and the exhaust gases are vented

through a demister which removes froth and condensate. Two stages of filters in series are used for solution recovery. The filter cake is repulped between stages and washed on the filters with progressively weaker solutions using fresh, dilute Na_2CO_3 in the final stage. Uranium is precipitated with caustic from the carbonate solution as $\text{Na}_2\text{U}_2\text{O}_7$. Any bicarbonate present must be neutralized before the uranium will precipitate.



Two stages of filters in series with repulping between stages and washing of the cakes on the filters are used to recover the yellow cake. Effective washing of the yellow cake is complicated by a high residual moisture content, a strong tendency for some cakes to crack on the filter, and some difficulty in dispersing the cake during repulping. The moist yellow cake, which is high in sodium, is washed with $(\text{NH}_4)_2\text{SO}_4$ (Sect. 4.4.11) and recycled to feed preparation (Sect. 4.4.5). The leached ash -- CaF_2 contaminated with uranium, radium, thorium, and other metal fluorides -- is dried and drummed ready for shipment to an approved repository (burial ground).

The material flows that serve as the basis for estimating the liquid and solid wastes from carbonate leaching are presented in Table 4.26. Actual flows may vary considerably from the model. The model serves to illustrate the various waste treatment methods but does not necessarily represent either current or future industrial practice. The daily feed to carbonate leaching is 1320 lb of uranium, as UF_4 (1.8% of the uranium processed by the conversion plant),⁴⁵ and 7180 lb of CaF_2 contaminated with small quantities of other radioactive and chemical impurities which are insoluble and have a negligible effect on the process. The assumption that the uranium is present as UF_4 tends to maximize the quantity of the liquid waste. Lower liquid and carbonate flow rates are possible if part of the uranium is present as oxide or oxyfluoride, or if the full-scale industrial plant has a lower uranium recycle rate than the pilot plant described in ref. 45. Because of the

high uranium content of the feed (15% vs about 0.2% in uranium ores), the leach solution contains 120 g of Na_2CO_3 per liter, which is double the concentration used at uranium mills⁸⁰ but below the solubility limit of 227 g/liter at 25°C.⁸¹ The necessary NaHCO_3 is generated by reaction (3). The uranium content of the leach solution is 43 g/liter. Solubility data for the $\text{NaF-Na}_2\text{CO}_3\text{-NaHCO}_3\text{-H}_2\text{O}$ system are not available; however, by analogy to the $\text{NaF-NaOH-H}_2\text{O}$ system,⁸¹ the solubility of NaF is assumed to be 16.8 g/liter so that almost half the fluoride from Eq. (3) precipitates. Ash is washed with 257 gal per thousand pounds of ash (4 parts wash per part of retained solution in the filter cake) of a 21-g/liter Na_2CO_3 solution to keep the uranium in solution and minimize soluble losses. This is double the wash ratio used at carbonate leach uranium mills⁸² because of the higher uranium concentration in the leach solution. Overall washing efficiency is 99%; the ash filter cake contains 35 wt % residual moisture. The bicarbonate is neutralized and the uranium precipitated with 15 wt % NaOH solution. A 25% excess of caustic is used to provide the customary 5 to 6 g excess of NaOH per liter during precipitation.⁸⁰ No credit is taken for possible decomposition of bicarbonate to CO_2 and water in the leach tanks. The yellow cake is washed with 2.2 gal of water per kilogram of uranium;⁸² overall washing efficiency is 98%. The yellow cake wash assumption tends to maximize the liquid effluent problem. Yellow cakes vary considerably in the volume of wash water required because of differences in the amount of residual moisture they contain, the degree of cracking of the cake on the filter, and dispersion during repulping.

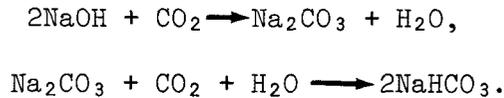
4.4.10.2 Leached ash, F-F Case 1. About 1000 metric tons of leached and dried ash per year are drummed for shipment to an approved repository (Fig. 4.4). The waste is predominantly CaF_2 contaminated with small quantities of other metal fluorides and traces of radioactive materials. It is in a chemically stable, slightly soluble, nonvolatile form appropriate for permanent disposal. The model waste is estimated to contain, on an annual basis, 0.1 Ci of natural uranium (0.035 wt %), 141.7 Ci of ^{230}Th , and 15.67 Ci of ^{226}Ra , that is, essentially all the ^{230}Th and ^{226}Ra in the feed to the plant. The sealed drums are stored

for 6 months (or longer) before shipping to permit decay of the ^{234}Th and $^{234\text{m}}\text{Pa}$. The ^{226}Ra daughters - ^{222}Rn , ^{218}Po , ^{214}Pb , ^{214}Bi , and ^{214}Po - grow back to 99% of secular equilibrium with the ^{226}Ra in about 40 days so that a total of 236 Ci/yr is shipped in the waste. The ^{230}Th activity in the waste is about 1.4×10^{-1} $\mu\text{Ci/g}$; the ^{226}Ra and radium daughter activities are about 1.6×10^{-2} $\mu\text{Ci/g}$ each. In comparison, tailings from a typical 0.2% uranium ore contain only about 5.7×10^{-4} $\mu\text{Ci/g}$ each of ^{230}Th , ^{226}Ra , and radium daughters. On a longer-term basis, ^{210}Pb , ^{210}Bi , and ^{210}Po slowly grow back to secular equilibrium with the radium in the UF_6 plant waste; ultimately secular equilibrium of daughter products with the ^{230}Th will be attained.

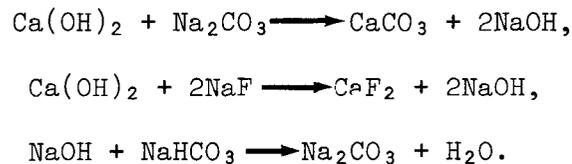
4.4.10.3 Off-gases, F-F Cases 1-4. Dust control effluent from dry materials handling operations is discussed in Sect. 4.4.2. Process off-gases from the leach tanks (air used for agitation and oxidation) are passed through a demister which collects mist and foam. Negligible quantities of radioactive materials and noxious chemicals are released from the leach tanks.

4.4.10.4 Carbonate liquid waste, F-F Case 1. The flowsheet for this case is shown in Fig. 4.22. About 7400 gal of untreated waste containing 2300 lb of sodium, 2200 lb of carbonate, 350 lb of fluoride, and 842 g of uranium (30 ppm) is sent, on a daily basis, to the uranium settling basin, diluted with other plant wastes, and released to surface streams. Since data are not available, the source terms given in Table 4.9 are estimated by analogy to effluents from carbonate (alkaline) leach uranium mills, that is, $\text{U}(\text{nat})$, 1.0×10^{-5} $\mu\text{Ci/ml}$; ^{226}Ra , 1.0×10^{-7} $\mu\text{Ci/ml}$; and ^{230}Th , 2.0×10^{-6} $\mu\text{Ci/ml}$.⁷⁸ The ^{234}Th and $^{234\text{m}}\text{Pa}$ are calculated from the uranium based on 14-day holdup before release. Longer holdup times will result in higher releases up to secular equilibrium with the uranium. The stream requires dilution by a factor of 3 to meet MPC for radium and may be unacceptable chemically at some sites. Considerable uncertainty exists in these source terms since ash leaching and ore leaching are not identical chemical treatments.

4.4.10.5 Carbonate leach process, F-F Cases 2-4. The volume of liquid effluent can be reduced by a factor of 10, and chemical releases by a factor of 20, via recarbonation of the spent leach solution (to convert excess caustic to carbonate and bicarbonate) and recycling of the leach solution (Fig. 4.5, Table 4.26):



The primary purpose of recarbonation is to destroy the hydroxide ion, which interferes with leaching if the solution is recycled; the amount of Na_2CO_3 generated is small. Recarbonation is conducted in a vertical tower with the solution flowing downward by gravity and natural gas-fired boiler flue gas containing CO_2 passing upward. Either a packed tower or a conventional bubble-cap tray can be used. The amount of bicarbonate generated in ash leaching is much higher than in leaching uranium ores. If caustic is used exclusively to neutralize bicarbonate and precipitate uranium, the soda content of the solution tends to build up to a point where a relatively large chemical bleed from the circuit is required. This problem is overcome by substituting lime for part of the caustic in order to reduce the bicarbonate content of the solution. Both CaCO_3 and CaF_2 are precipitated in the model:



The bicarbonate ion concentration must be maintained above 2.0 g/liter to prevent premature precipitation of uranium.⁸⁰ The relative precipitation of CaF_2 vs CaCO_3 in this system is not known. There is a higher probability of precipitating CaCO_3 , which requires only one "collision", than CaF_2 , which requires two collisions. For purposes of this study, it is assumed that

$$\text{CaCO}_3/\text{CaF}_2 \text{ mole ratio} = 1.75.$$

Material flows are presented in Table 4.26. Leaching is essentially the same as in F-F Case 1. The ash carries slightly more NaF because the fluoride in the recycle solution reduces the amount that can be dissolved during UF_4 dissolution. It also carries slightly more Na_2CO_3 because recycle solution is used for washing. This causes a 10% increase in the amount of ash. On a daily basis, lime neutralization generates 440 lb of CaF_2-CaCO_3 precipitate containing 0.1 lb of uranium. The filter cake is washed with 257 gal of water per thousand pounds of precipitate. Yellow cake wash water is used as makeup for the NaOH solution. The water balance is maintained via a bleed of 220 gal/day from the main carbonate circuit and a bleed of 536 gal/day from the yellow cake washing in addition to the 35% moisture carried by the filter cakes. The filter cake washing assumptions tend to maximize the liquid bleeds; it may be possible to operate a closed circuit with smaller bleeds. An idealized recarbonation is shown in Table 4.26, with all caustic being converted to Na_2CO_3 . In practice, however, some bicarbonate is formed. A flow of air through the solution will destroy 30% of the carbonate in 30 min and 84% in 24 hr.⁸⁰ Case studies 2-4 assume that any bicarbonate formed in recarbonation is destroyed during leaching but do not take credit for destroying the bicarbonate from the UF_4 dissolution. The bicarbonate assumptions primarily affect the lime precipitation since sufficient excess Na_2CO_3 is available for leaching even if part of it is converted to bicarbonate.

4.4.10.6 Leached ash, F-F Cases 2-4. About 1100 metric tons of dried leached ash per year are drummed for shipment to a burial ground (Fig. 4.5). This is about 10% more than in Case 1 because chemicals formerly released in surface streams are precipitating in the ash instead. The total amount of activity in the ash is the same as in Case 1. In Case 4, the ash is incorporated in cement and drummed. Cementing reduces the potential for long-term leaching by natural waters and decreases the diffusion-controlled radon release in the event of drum failure. The average specific activities are lower in Case 4 because of the dilution by the cement (Table 4.11).

4.4.10.7 CaCO₃-CaF₂ solid waste, F-F Cases 2-4. An estimated 440 lb of CaCO₃-CaF₂ precipitate per day is generated by lime treatment. This precipitate is stored in the lined fluoride settling basin in Cases 2 and 3, and the lined fluoride storage pit in Case 4 (Figs. 4.25-4.27). The solids carry an estimated 50 kg of uranium per year, plus negligible quantities of ²²⁶Ra and ²³⁰Th (Table 4.18). The study assumes that conditions are controlled to avoid precipitation of uranium and other radioactive materials, that the filter cake retains 35 wt % moisture, and that the washing efficiency is 95%. The carbonate solution during lime precipitation contains uranium at 31 g/liter, ²²⁶Ra at 4.9×10^{-2} μ Ci/liter, assuming that 1.8% of the ²²⁶Ra in the ash dissolves during leaching by analogy to carbonate leach mill circuits, and ²³⁰Th at 2.0×10^{-5} μ Ci/liter by analogy to carbonate leach mill tailings solution.⁷⁸ There is considerable uncertainty in the estimates since the model UF₆ plant circuit is not chemically identical to a uranium mill circuit.

4.4.10.8 Carbonate liquid waste, F-F Case 2. The recarbonation and carbonate recycle system reduce the volume of liquid waste by a factor of 10 and the chemical releases by a factor of 20. About 760 gal of bleed streams from the circuit pass through the uranium settling basin on a daily basis, are diluted with other plant wastes, and then released to surface streams (Fig. 4.25). The resulting effluent contains 12 lb of fluoride, 112 lb of sodium, 115 lb of carbonate, and 86 g of uranium. The source terms in Table 4.9 for U(nat), ²³⁰Th, and ²²⁶Ra are estimated by analogy to uranium mill circuits.⁷⁸ The ²³⁴Th and ^{234m}Pa are calculated for 14-day holdup in the pond. The stream requires dilution by a factor of 3 to meet MPC for radium.

4.4.10.9 Carbonate liquid waste treatment, F-F Case 3. The liquid bleed from the carbonate circuit is treated with 0.2 g of copperas (FeSO₄·7H₂O, a flocculating agent) per liter in order to precipitate 75% of the radium (Fig. 4.26).⁵² Solids are permitted to settle, and a clear supernate is released to surface streams. This

effluent meets MPC for release without dilution. Copperas requirements are 1.3 lb/day. The radium activity in the solids is 3.8×10^{-6} $\mu\text{Ci/g}$, which is only slightly above background (Table 4.18). As a matter of convenience, only one radium settling basin is used in the case studies for both the carbonate leach and the sodium removal effluent; the solids are handled together (Sect. 4.4.17.3). The considerable uncertainty in the radium content estimated for the bleed solution raises doubts concerning the benefit realized by copperas treatment. Other radionuclides are estimated in Table 4.18, assuming that the filter cakes carry 35% moisture.

4.4.10.10 Carbonate liquid waste treatment, F-F Case 4. Liquid bleeds totaling about 760 gal from the carbonate circuit and carrying 240 lb of chemicals, principally Na_2CO_3 , and 86 g of uranium are combined with other plant liquid wastes and sent to the plant evaporator system (Fig. 4.27, Sect. 4.4.12). Water is recovered for reuse in the plant. Dried waste containing the radioactive materials is drummed for shipment.

4.4.11 Sodium removal

4.4.11.1 Sodium removal process. Sodium forms a low-melting compound, $7\text{NaF} \cdot 6\text{UF}_4$ (melting point, $\sim 675^\circ\text{C}$), which causes caking and sintering in the fluorination fluid beds.⁴⁵ Sodium ions are removed prior to feed preparation by chemical metathesis with hot, 10 wt % $(\text{NH}_4)_2\text{SO}_4$ solution (Fig. 4.1):



The process is capable of decreasing the sodium content to 0.5% or less but may result in either excessive SO_4^{2-} contamination or formation of a slimy, hard-to-handle precipitate unless conditions are rather carefully controlled.⁸³

Feed to the sodium removal process consists of:

1. Yellow cake from the model alkaline leach uranium mill which has been precipitated with caustic and is assumed

- to contain 11.3 wt % sodium on a uranium basis (Sect. 4.2; Fig. 4.1, Stream 2U).
2. Yellow cake recovered from carbonate leaching of fluorination ash and miscellaneous solid wastes which is assumed to contain 10 wt % sodium on a uranium basis (Sect. 4.4.10; Fig. 4.4 or 4.5, Stream 9U).
 3. $K_2U_2O_7$ recovered from fluorination scrubbers and assumed to contain 19.2 wt % potassium on a uranium basis (equivalent to sodium on a mole basis; Sect. 4.4.8.4; Fig. 4.2, Stream 8Ub).

Material flows for sodium removal are presented in Table 4.27. The ammonium diuranate product contains 0.5% sodium (uranium basis), and the liquid effluent contains 2.91 moles of $(NH_4)_2SO_4$ (~ 9 wt %) and 0.416 mole of Na_2SO_4 plus K_2SO_4 (~ 0.5 wt % sodium) per gallon. The principal radionuclides are estimated as: $U_{(nat)}$, 20 ppm or 6700×10^{-9} $\mu Ci/ml$; ^{226}Ra , 500×10^{-9} $\mu Ci/ml$; and ^{230}Th , 20×10^{-9} $\mu Ci/ml$. Since data are not available, source terms are estimated from uranium mill circuits.⁷⁸ The tailings solution from an acid-leach uranium mill (a sulfate system) served as the model for uranium and radium.⁷⁸ The radium estimate is probably an upper limit because radium oxide (a basic oxide) would have less tendency to dissolve in weakly acidic $(NH_4)_2SO_4$ than in the strong H_2SO_4 used for leaching at the mill. Thorium oxide is unreactive in weak acids and is not expected to dissolve significantly. Tailings solutions from the alkaline-leach uranium mill served as the model for the behavior of thorium in near-neutral solution.^{78,a} There is considerable uncertainty in the estimated source terms.

4.4.11.2 Sodium removal off-gas, F-F Cases 1-4. About 100 lb of ammonia, from the reaction of ammonium sulfate with hydroxide and possibly carbonate impurities in the yellow cake, is evolved daily from the hot wash tanks in Cases 1 and 2. Ammonia is not presently regarded

^aThorium dissolves in the H_2SO_4 leaching circuit at uranium mills.⁷⁸

as a noxious gaseous effluent; thus no treatment is provided for it. Eliminating sodium from the feed to the plant in Case 3 reduces the load to sodium removal, and hence the ammonia release by a factor of 8 (see Sect. 4.4.11.4). The addition of the UF₆ cleanup reactor to the fluorination process in Case 4 (Sect. 4.4.8.2) further reduces the load and the ammonia release by about 17%.

No significant airborne releases of radioactive materials occur. Dust from dry materials handling of Stream 2U (Fig. 4.1) is included under the drum dumping operation in feed preparation. Streams 8Ub, 9U, and 11U are handled in a moist state and consequently do not represent significant contributions. No major gaseous products are released to carry radioactive materials (the ammonia results from reaction with the caustic impurity in the yellow cake).

4.4.11.3 Sodium removal liquid waste, F-F Cases 1 and 2. About 31,400 gal of untreated waste carrying 19,000 lb of SO₄²⁻, 6100 lb of NH₄⁺, 1300 lb of sodium, and 2 kg of uranium (20 ppm) is sent on a daily basis to the uranium settling basin, diluted with other plant wastes, and released to surface streams (Figs. 4.22 and 4.25). The estimated radium activity is 5.0×10^{-7} $\mu\text{Ci/ml}$, which means the stream requires dilution with other plant wastes by a factor of approximately 17 to meet the MPC for radium. Other source terms are presented in Table 4.9. The system has a 14-day holdup, during which ²³⁴Th and ^{234m}Pa grow back to 40% of secular equilibrium with ²³⁸U.

4.4.11.4 Changes in mill circuits to eliminate sodium salts from UF₆ plant feed, F-F Cases 3 and 4. There is no simple treatment for sodium removal waste which permits recycle of spent (NH₄)₂SO₄ solution or removes the ammonium salts prior to release. Natural evaporation ponds are impractical in the wet midwestern environment where UF₆ plants are currently sited. Since about 90% of the sodium removal waste is generated in processing fresh feed from the mills, it is simpler technically to eliminate sodium salts from the UF₆ plant feed^a by

^aI.e., restrict sodium to 0.7 wt % on a uranium basis, which can be tolerated in fluorination.

changing the mill circuits than to treat the sodium removal waste at the UF_6 plant. An alkaline-leach uranium mill initially must precipitate with sodium hydroxide, but it can dissolve the yellow cake in sulfuric acid and reprecipitate with peroxide or ammonia.^{84,85} The sodium ions and sulfuric acid waste will have relatively little impact on the existing mill tailings pond, which already contains Na_2CO_3 , $NaOH$, and usually some lime in the ore residues. In contrast, the same waste at the UF_6 plant represents an expensive disposal problem in the advanced cases which minimize liquid effluents. Acid-leach uranium mills can use ammonia, magnesia, or peroxide precipitation in place of sodium hydroxide precipitation.⁸⁶

4.4.11.5 Sodium removal liquid waste, F-F Case 3. Liquid radwaste and chemwaste releases from sodium removal are reduced by a factor of 8 by eliminating high-sodium feed to the plant, that is, Stream 2U (Table 4.27). Only recycle material recovered by carbonate leaching and from the fluorination scrubbers is processed through sodium removal. Alternate processes such as nitric acid or sulfuric acid leaching² offer no environmental advantages over carbonate leaching followed by the ammonium sulfate wash.

Liquid waste from sodium removal is treated with a barium chloride solution containing 0.14 g $BaCl_2$ /liter to coprecipitate $(Ba-Ra)SO_4$ (Fig. 4.26).^{54,55} Solids are permitted to settle in the radium settling basin, and a clear supernate containing 3×10^{-9} $\mu Ci/ml$ of radium is released to surface streams. The stream is below MPC, and no dilution is required. A 30-day settling time is allowed. Barium chloride requirements are 4.2 lb/day. About 4.7 lb of $BaSO_4$, containing an estimated 3.2×10^{-3} μCi of ^{226}Ra per gram, accumulates in the settling pond daily. In comparison, tailings from a typical 0.2% uranium ore contain only about 5.7×10^{-4} μCi of ^{226}Ra per gram. Since the $BaSO_4$ solids are about six times more hazardous than mill tailings, they are dried and drummed for final disposal. As a matter of convenience, the same radium settling basin is used for the copperas solids from treating carbonate solution (Sect. 4.4.10.9), and the solids are dried together.

Airborne releases of radioactive materials from handling 2×10^{-3} Ci of radium in BaSO_4 and 7×10^{-5} Ci in copperas on an annual basis are negligible compared with drying and drumming 15.7 Ci in the fluorination ash. The considerable uncertainty in the radium content estimated for the effluent from sodium removal raises questions concerning the benefit of the barium chloride treatment. The treatment is in use today at one U.S. uranium mill^{54,55} and could be applied to the effluent in Case 2 without altering the plant feed.

Source terms for liquid releases are presented in Table 4.9. The estimated radionuclide composition of the solids, assuming they settle with 35 wt % moisture, is given in Table 4.18.

4.4.11.6 Sodium removal liquid waste, F-F Case 4. The addition of the UF_6 cleanup reactor to fluorination (Sect. 4.4.8.2) results in about a 17% decrease in the feed to sodium removal in Case 4 vs Case 3. About 2930 gal of liquid waste containing 1800 lb of SO_4^{2-} , 570 lb of NH_4^+ , 120 lb of sodium, and 222 g of uranium is combined with other plant wastes on a daily basis and sent to the plant evaporator-dryer system (Sect. 4.4.12, Fig. 4.27). Water is recovered for reuse in the plant. The dried salt containing the radioactive materials is drummed for disposal.

4.4.12 Liquid waste evaporator-dryer system, F-F Case 4

The liquid wastes that are unsuitable for chemical treatment, that is, the reduction water scrub (Sect. 4.4.6.7, Stream 7L), the carbonate leach bleed (Sect. 4.4.10.10, Stream 9L), and the sodium removal waste (Sect. 4.4.11.6, Stream 11L) are combined and the water recovered for recycle by the plant evaporator system (Fig. 4.27). Stream 7L is principally water contaminated with traces of very fine yellow cake powder and SO_2 . Stream 9L contains Na_2CO_3 with a little NaOH , NaF , and traces of radioactive materials. Stream 11L is principally an $(\text{NH}_4)_2\text{SO}_4$ - Na_2SO_4 solution with traces of radioactive materials. It is important to destroy the carbonate and neutralize the caustic in Stream 9L with sulfuric acid before combining streams. This avoids the formation of volatile

compounds such as NH_4OH and $(\text{NH}_4)_2\text{CO}_3 \cdot 2\text{NH}_4\text{HCO}_3 \cdot 2\text{H}_2\text{O}$ when streams 9L and 11L are combined. Condensate from the evaporator is recycled to the process. Evaporator residues are dried and drummed for shipping. Dryer off-gas is treated similarly to off-gas from the feed preparation dryer, that is, with primary and secondary bag filters and HEPA filters. A total of 4600 gal of liquid is evaporated, 200 lb of sulfuric acid is required, and 2800 lb of low-level solid waste is generated per day (Table 4.28). Airborne releases from handling 4.0×10^{-2} Ci of $\text{U}(\text{nat})$, 4.8×10^{-4} Ci of ^{230}Th , and 1.8×10^{-3} Ci of ^{226}Ra per year in the liquid waste evaporator-dryer system are negligible compared with dust releases from feed preparation where 3300 Ci of $\text{U}(\text{nat})$, 140 Ci of ^{230}Th , and 16 Ci of ^{226}Ra are handled per year. Ammonium sulfate is relatively stable, and no significant ammonia releases are anticipated under normal drying conditions.

The dried salts have low concentrations of radioactive materials (Table 4.11), that is, only 1×10^{-4} $\mu\text{Ci/g}$ of $\text{U}(\text{nat})$, 5×10^{-6} $\mu\text{Ci/g}$ of ^{226}Ra , and 1×10^{-6} $\mu\text{Ci/g}$ of ^{230}Th ; on the other hand, they are water soluble and will require special disposal measures such as concrete or asphalt-lined storage to ensure isolation from waters used by man.

If desired, ammonia could be recovered from Stream 11L [$(\text{NH}_4)_2\text{SO}_4$ - Na_2SO_4] by neutralizing with lime and distilling; however, this option was not costed in the case studies. The solid residue, CaSO_4 - Na_2SO_4 , would also require special disposal because Na_2SO_4 is soluble and would be leached rapidly on contact with water.

4.4.13 Still tops and bottoms

Still residues are stored since the values contained do not presently justify recovery. These are reactive compounds which hydrolyze to yield HF. Storage in this chemical form is not a permanent solution, and at some future time there may be small releases of radioactive materials from this source. It is difficult to predict whether the material will simply be hydrolyzed, dried, and stored or whether, as raw material costs rise, the vanadium and/or uranium values will be recovered. It is uncertain which process is likely to be used in the event that recovery is

justified.

The composition of the still residues is proprietary information. Estimates of the quantity of material accumulated by the model F-F plant (Table 4.11) assume that:

1. Approximately half (range, 25 to 99%)⁴⁵ of the vanadium is volatilized during hydrofluorination, while the other half is found in the still residues as VOF_3 . The amount of VOF_3 accumulated in still residues by the model plant amounts to $\sim 4.11 \times 10^4$ lb/year.
2. Approximately 80% (range, 73 to 88%)⁴⁵ of the molybdenum is volatilized during hydrofluorination, while the remainder is found in the still residues as MoF_6 . The amount of MoF_6 accumulated in still residues totals $\sim 1.35 \times 10^4$ lb per year.
3. Approximately 0.05% of the total uranium processed is found in still residues as UF_6 (arbitrary estimate of "acceptable" loss which would be competitive with the industry). A total of $\sim 3.40 \times 10^4$ lb of UF_6 per year accumulates in still residues.
4. Ninety-five percent of the particulates passing the fluorination filters are collected in the UF_6 cold traps (Sect. 4.4.8.3) and ultimately are found in the still residues.

It is beyond the scope of this study to estimate possible future releases from processing still tops and bottoms. There is insufficient information concerning the composition of the residues, as well as a lack of basic chemical and physical data on which to base an assessment. For example, if still residues are dissolved in Na_2CO_3 , the chemical form(s) of vanadium and molybdenum are not known or even whether they form soluble species such as sodium vanadate and sodium molybdate or insoluble fluorides or oxyfluorides. Vanadium is known to interfere with the caustic precipitation of yellow cake, presumably due to the formation of a uranium-vanadium complex which is more soluble than the simple uranium product; however, it does precipitate in sufficient

quantity to contaminate the yellow cake. The study team briefly considered several schemes for uranium-vanadium separations developed for uranium mills,⁸⁷ but none was readily adaptable to scrap recovery of a mixture containing fluoride. For example, fluoride might interfere with the vanadium-uranium separation (which is based on solubility differences in a carbonate system) used at United Nuclear's Homestake mill, while it would be corrosive in the sulfuric acid system used at Union Carbide's Uravan mill.⁸⁷

4.4.14 Miscellaneous sources

4.4.14.1 UF₆ cylinder wash. The enrichment plant may recycle empty cylinders to the UF₆ conversion plant for reuse. At present, only part of these cylinders have been returned as some customers are storing the depleted UF₆ tails from enrichment for possible future use.

The returned cylinders are washed with Na₂CO₃ solution to recover traces of uranium and remove other impurities. The spent solution requires filtration through 10-, 5-, and 1-micron filters to remove ²³⁴Th and ^{234m}Pa.¹⁴ Uranium is precipitated with NaOH. It is beyond the scope of this study to quantify this source. The case studies assume that the 25% excess carbonate used in carbonate leaching (Sect. 4.4.10) is sufficient to cover the cylinder wash, that the U(nat), ²³⁰Th, and ²²⁶Ra contents of the effluent are the same as from carbonate leaching since the estimates are for slightly soluble substances, and that the ²³⁴Th and ^{234m}Pa are removed by filtration and/or decay to approach secular equilibrium with the uranium.

4.4.14.2 UF₆ cylinder sampling and degassing ash. A small quantity of UF₆ gas is lost when cylinders are sampled, and when fluorination bed material and filter fines are removed from the system due to degassing of entrained UF₆. This is vented through the plant vacuum cleaner system. Bag filters are ineffective on gaseous effluents, although they will remove hydrolysis products if any moisture is present. This is a small source, and no treatment is provided in Cases 1 and 2. A KOH high-energy venturi scrubber (99% efficient) is added in Case 3, and the venturi scrubber plus an HF-resistant HEPA are used in Case 4.

4.4.15 Radon release

A small quantity of ^{222}Rn gas (71.8 Ci/year) is released by the model F-F plant (Table 4.6). In Case 1, it contributes only 0.2% of the total body dose and 1.6% of the lung dose (Table 7.7); therefore, no treatment is provided. Radon is an inert gas which is unaffected by the wet scrubbers or dust collectors. In general, conservative assumptions which tend to maximize releases are used in estimating radon source terms. A radon emanation coefficient (fraction of the radon that escapes the particles) of unity is assumed for yellow cake;^a no credit is taken for holdup within the plant which permits decay (half-life, 3.8 days). Sealed drums are assumed to be tight with only diffusion-controlled releases through the gasket. It is beyond the scope of this survey to estimate leaks from drums.

4.4.15.1 Radon release from sampling. The maximum radon release from sampling is estimated as 16.30 Ci/year. This assumes that:

1. The yellow cake feed to the plant has aged 1 month or longer in a sealed drum since milling so that ^{222}Rn has grown back to secular equilibrium with the ^{226}Ra .
2. The secular-equilibrium amount of radon is released when the drum is opened (i.e., 15.67 Ci/year).
3. A total of 0.63 Ci of radon per year is generated within the plant based on a residence time in the sampling plant of 8 hr, operation of the sampling plant for two shifts per day, 300 days per year, and no inventory (except sealed drums) when the sampling plant is not operating.
4. All the radon generated in the plant is released.

4.4.15.2 Radon release from yellow cake storage. Godbee and Joy⁸⁹ estimate from diffusion theory that a sealed 55-gal drum of yellow cake

^aThe emanation coefficient of yellow cake has never been measured. The emanation coefficient for the sand fraction of Grand Junction tailings is 0.2;⁸⁸ that is, only 20% of the radon generated escapes from the sand particles and is free to migrate.

containing 465 lb (2.11×10^5 g) of uranium with a ^{226}Ra concentration of 1.34×10^{-9} Ci per gram of uranium releases 1.7×10^{-10} Ci of ^{222}Rn to the atmosphere. If 10,000 metric tons of uranium are in storage, then a total of 8.1×10^{-6} Ci of ^{222}Rn per year is released from the drums. This evaluation assumes that the metal and the seams of the drum are sound and that the gasket is properly sealed (i.e., no radon bypasses the gasket) so that the only path for radon escape is by diffusion through the rubber gasket which seals the lid to the body of the drum. Diffusion of radon through the metal walls of the drum is negligible compared with diffusion through the gasket.

The mathematical model is derived from diffusion in a plane sheet (the gasket). Radon that enters the gasket has been separated, for all practical purposes, from its long-lived parent (^{226}Ra with a half-life of 1.6×10^3 years) so that it decays with its characteristic half-life (3.8 days) while diffusing through the gasket. With the assumptions that the gasket is initially free of radon, that the concentration of radon in the drum is constant, and that the radon leaving the gasket is immediately swept away, the solution for this case is:

$$Q = C_0 \left(\frac{D}{\lambda L} \right) \left[\lambda t + 2 \sum_{n=1}^{\infty} (-1)^n \left\{ \frac{1}{1 + n^2 \alpha} \left(1 + \lambda t - \frac{1}{1 + n^2 \alpha} \right) - \frac{e^{- (1+n^2 \alpha) \lambda t}}{1 + n^2 \alpha} \left(1 - \frac{1}{1 + n^2 \alpha} \right) \right\} \right],$$

where

Q = total amount of diffusing substance passed through the sheet (gasket) per unit of surface, amount/cm²,

C_0 = concentration of source, amount/cm³,

D = diffusivity, cm²/sec,

λ = $\ln 2/t_{(1/2)}$, radioactive decay constant, sec⁻¹

$t_{(1/2)}$ = half-life, sec,

t = elapsed time, sec,

L = sheet width, cm,

α = $\pi^2 D / \lambda L^2$, dimensionless.

The diffusivity for radon in rubber is not readily available, but the diffusivity⁹⁰ of argon in neoprene (2.6×10^{-7} cm²/sec at 35°C) adjusted according to kinetic theory for the molecular weights of the gases [$2.6 \times 10^{-7} (18/86)^{1/2}$] gives 1.2×10^{-7} cm²/sec as an approximation. Each 55-gal drum is reported to hold 465 lb (2.11×10^5 g) of uranium with a ²²⁶Ra concentration of 1.34×10^{-9} Ci per gram of uranium. With the assumptions of secular equilibrium (²²⁶Ra and ²²²Rn), an emanation coefficient (fraction of radon formed that escapes from a particle) equal to unity, and 35% voids in the drum, the concentration of ²²²Rn in the drum (C_0) is 3.9×10^{-9} Ci/cm³. Assume that the gasket is 1 in. wide (L). Also, assume that the gasket is approximately 2 ft in outside diameter and 1/8 in. thick so that the exposed free surface is about 61 cm². Under the above conditions, Eq. (1) predicts that 1.7×10^{-10} Ci/year would be released from each drum.

4.4.15.3 Radon release from UF₆ conversion. The maximum radon release from the main UF₆ conversion plant is estimated as 29.47 Ci/year. This includes one secular-equilibrium release (15.67 Ci/year) of radium when the drums are dumped and 13.80 Ci/year generated within the plant based on a 4-day residence time.⁹¹ The drum dumping release can be reduced if feed is processed shortly after sampling, that is, before the radon has grown back to secular equilibrium. Some storage time should be allowed for analyses and for blending feed materials to achieve a more uniform chemical reactivity.

4.4.15.4 Radon release from ash storage. Godbee and Joy estimate that 3.2×10^{-6} Ci of ²²²Rn per year is released from the storage of 1000 metric tons of CaF₂ ash containing 15.67 Ci of radium (i.e., a 1-year ash accumulation) in 55-gal drums sealed with rubber gaskets.⁹² The analysis is similar to that discussed in the subsection on yellow cake storage.

4.4.15.5 Radon release from ash leaching and drying. During the 6-month storage of ash before leaching to permit decay of ²³⁴Th and ^{234m}Pa, radon will grow back to secular equilibrium with uranium, and the potential release during drum dumping is estimated as 15.67 Ci/year. Assuming a 3-day residence time, another 10.35 Ci/year will be generated

during processing. The maximum potential release from ash leaching and drying is estimated as 26.02 Ci/year.

4.4.16 Liquid waste treatment summary, F-F model plant

The liquid waste treatment methods are outlined in Table 1.1 and Figs. 4.22-4.28. The origins of the wastes and application of the treatment methods to the individual streams are discussed in the preceding sections. Summaries of liquid chemwaste-radwaste effluents, solid chemwaste-radwaste generated, and chemical usage are presented in Tables 4.9, 4.10, 4.18, 4.28, and 4.29.

In estimating source terms for liquid waste treatment, it is assumed that 10% of the radioactive materials are released from lime treatment,^{52,53} 25% of the radium is released from copperas⁵² treatment, and 3 $\mu\text{Ci/liter}$ (about 1%) of the radium from BaCl_2 treatment.^{54,55} The effluent from fluoride treatment is assumed to contain 25 ppm of fluoride. The uranium settling basin has a holdup time of 14 days in Cases 1 and 2, and 30 days in Case 3. The fluoride and radium settling basins have a holdup of 30 days in all case studies.

4.4.16.1 F-F Case 1 liquid waste management. About 123,000 gal of process wastes per day which have received minimum treatment for uranium recovery are diluted by approximately a factor of 10 to meet MPC for radium and then released to surface streams (Fig. 4.22). The effluent may not be acceptable chemically at all sites. Estimated chemical releases per day are: 5000 lb of fluoride, 700 lb of sulfide and sulfur, 19,000 lb of sulfate, 2600 lb of carbonate, 6100 lb of ammonium ions, 7000 lb of potassium ions, and 3600 lb of sodium ions (Table 4.10). The uranium content of the combined process wastes before dilution is 9 ppm. The radwaste release amounts to 4.38×10^{-1} of U_{nat} , 1.40×10^{-3} Ci of ^{230}Th , and 1.88×10^{-2} Ci of ^{226}Ra per year (Table 4.9).

4.4.16.2 F-F Case 2 liquid waste treatment. The primary purpose of the Case 2 liquid treatment (Fig. 4.25) is to reduce chemical releases, since the effluent may not be acceptable chemically at all sites and more stringent regulations seem likely in the near future. None of the Case 2 treatments is specifically designed to reduce the radionuclide releases,

although most radionuclides except radium are reduced by approximately a factor of 2 (Table 4.9). Sulfide and sulfur are eliminated from the liquid waste by changing the reduction off-gas treatment which, in essence, consists of converting a water pollution problem to an airborne release (Sects. 4.4.6.4 and 4.4.6.5). No treatment other than uranium settling is applied to the reduction scrub liquor per se. Potassium hydroxide scrub liquors are treated with lime to precipitate CaF_2 and then recycled to the process, eliminating most of the KF salt from the effluent (Fig. 4.23, Table 4.10, Sects. 4.4.7.5 and 4.4.9.5). Water fluoride scrub liquors are treated with lime, the CaF_2 is permitted to settle in a lined pond with a 1-month holdup, and the clear supernate is released (Fig. 4.25, Sects. 4.4.7.5 and 4.4.9.5). Lime treatment of the water fluoride scrub liquors essentially eliminates the major sources of fluoride in the effluent (Table 4.10). The sodium carbonate regeneration and recycle system greatly reduces this source of salts, although there is a small liquid bleed from the circuit (Table 4.10, Figs. 4.5 and 4.25, Sects. 4.4.10.5 and 4.4.10.8). Calcium fluoride waste from the carbonate recycle circuit, as well as from treating the KOH scrub liquors, is placed in the fluoride settling basin. Solution bleeds retained with the moist filter cakes are potentially released with the water overflow. No relatively simple treatment is known for the $(\text{NH}_4)_2\text{SO}_4\text{-Na}_2\text{SO}_4$ waste from sodium removal; therefore, no treatment is applied in Case 2. Sodium removal is the principal source of chemicals in Case 2 effluent.

In summary, Case 2 liquid effluent contains 21 lb of fluoride, 19,000 lb of sulfate, 115 lb of carbonate, 6100 lb of ammonium ion, 1400 lb of sodium ions, and 170 lb of potassium ions per day, but no sulfide or sulfur (Table 4.10). The uranium content of the combined process wastes is 9 ppm (before dilution). Major radionuclides released per year are 2.55×10^{-1} Ci of ^{238}U , 2.55×10^{-1} Ci of ^{234}U , 6.20×10^{-3} Ci of ^{235}U , 1.03×10^{-3} Ci of ^{230}Th , and 1.80×10^{-2} Ci of ^{226}Ra (Table 4.9). Case 2 has almost no effect on the radium release because the sodium removal waste, which is not treated, is the principal source of radium. Since radium contributes roughly 90% of the dose, Case 2 liquid treatment has a negligible effect on the radiological dose (Sect. 7.0, Tables 7.12 and 7.13), even though it is very beneficial in terms of chemical impact. In Case 2, 58,700 gal of liquids are treated, the

total lime requirement is 7500 lb, and 11,800 lb of very low-level solid waste is generated per day (Table 4.29). Case 2 liquid waste treatment generates one and one-half times as much solid waste as does the conversion process itself, although the waste is much lower in radioactive materials than the leached CaF_2 ash (Sect. 4.4.17).

4.4.16.3 F-F Case 3 liquid waste treatment. The primary purpose of Case 3 is to reduce the radiological impact by decreasing the amount of radium released (Fig. 4.26). In addition, the amount of chemwaste from sodium removal is reduced by eliminating high-sodium feed to the plant so that only recycle uranium is processed through sodium removal (Sect. 4.4.11.4). All liquid treatments of Case 2 are retained in Case 3. Radium is precipitated from the carbonate leach stream with copperas ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, Sect. 4.4.10.9), and from the sodium removal waste with BaCl_2 (Sect. 4.4.11.5). Radium-bearing solids are permitted to settle, and a clear supernate is released. In Case 3 the radium release is reduced by about a factor of 260, $\text{U}(\text{nat})$ by about a factor of 6, and the $(\text{NH}_4)_2\text{SO}_4$ - Na_2SO_4 waste by about a factor of 8 compared with Case 2 (Tables 4.9 and 4.10). Note that the liquid treatment per se only affects the radium, and that the other reductions result from changes in the plant feed which will mean higher costs at the mill. About 4400 gal of liquids containing radium are treated per day; the associated chemical requirements for radium precipitation are 1.3 lb of copperas and 4.2 lb of BaCl_2 (Table 4.29). The amount of solids generated by the radium treatment is small (i.e., only 6 lb/day). The radium content is about ten times higher than that of typical uranium mill tailings; therefore, solids are dried and drummed for disposal.

4.4.16.4 F-F Case 4 liquid waste treatment. There is no direct liquid release of radioactive materials to surface streams, although a nonradioactive effluent from the fluorine cell H_2 water scrubber (Stream 7L) is treated with lime to precipitate CaF_2 and then discharged (Fig. 4.27, Sect. 4.4.9.7). Aqueous hydrofluoric acid is condensed from the hydrofluorination off-gas and recovered for industrial use (Sect. 4.4.7.6).

This stream has a very low concentration of radioactive materials (Table 4.21); its effect on the environment will depend upon the end use. All other liquid wastes are either lime treated and recycled or handled in the liquid waste evaporator-dryer system (Sect. 4.4.12). Potassium hydroxide scrub liquors are treated with lime and recycled. The HF condenser replaces the water scrubber on the hydrofluorination off-gas, so that there is no water hydrofluorination scrub liquor in Case 4. Uncontaminated CaF_2 waste (Fig. 4.27, Stream 7X) is stored separately from slightly contaminated waste to avoid the possible release of radioactive materials via the supernate overflow. Case 4 has a KOH regeneration system for SO_2 scrubber liquor using lime to precipitate $\text{CaSO}_3 \cdot 1/2\text{H}_2\text{O}$ (Fig. 4.28, Sect. 4.4.6.7). This liquid stream is not present in the earlier case studies. A lined basin for storing solids produced by sulfite regeneration is included in the costs.

Case 4 incorporates several internal process changes which reduce the load to the fluoride treatment systems -- condensers on the hydrofluorination off-gas (Sect. 4.4.7.6), more efficient condensers on the fluorine cells (Sects. 4.4.8.8 and 4.4.9.6), and both a fluorine cleanup reactor and a UF_6 cleanup reactor on the fluorination off-gas (Sect. 4.4.8.2).

Case 4 contains no provisions for direct release of radioactive materials to surface streams, and the release of noxious chemicals has been reduced to 3 lb of fluoride per day (as CaF_2). This case treats 25,300 gal/day by chemical methods (Table 4.29) and 4630 gal/day in the evaporator-dryer system (Table 4.28). Chemical requirements are about 2600 lb of lime and 200 lb of H_2SO_4 per day. The liquid waste treatment systems generate, per day, about 380 lb of uncontaminated CaF_2 , 1000 lb of very low-level CaF_2 , 3000 lb of very low-level $\text{CaSO}_3 \cdot 1/2\text{H}_2\text{O}$, and 2800 lb of dried low-level evaporator residues.

4.4.17 Solid waste treatment summary, F-F model plant

Solid waste treatment methods are summarized in Table 1.1, and the amount of solid chemwaste-radwaste generated is shown in Table 4.11.

The origin of the wastes is shown in Figs. 4.2, 4.4, 4.5, and 4.25-4.27. Wastes that contain greater than 1 nanocurie of radium per gram or are readily water soluble are prepared for shipment to an approved repository. Wastes that are low in radioactive materials are stored on-site. The study includes the cost of preparing wastes for shipment or of lined on-site storage basins. It does not address the costs associated with final disposal such as shipment, burial, or decommissioning the plant.

In estimating source terms for solid wastes generated by liquid waste treatment systems, it is assumed that lime precipitates 100% of the radioactive materials dissolved or suspended in the solution, and BaCl_2 or copperas precipitates 100% of the radium. These assumptions tend to maximize the amount of radioactive materials in the solid waste.^a

4.4.17.1 F-F Case 1 solid waste treatment. In the base case, there are two solid radwastes -- ash and still residues -- which are an unavoidable part of the process. About 2.2 million lb of fluorination ash per year (Sect. 4.4.8.1) is carbonate leached, dried, and drummed (Sects. 4.4.10.1 and 4.4.10.2) for shipment to an approved burial ground. This waste is principally CaF_2 contaminated with essentially all of the radioactive impurities in the feed to the plant plus small quantities of other metal fluorides such as sodium and iron. It is in a chemically stable, highly insoluble, nonvolatile form appropriate for disposal. The concentrations of radionuclides are estimated as U(nat), 1.2×10^{-4} $\mu\text{Ci/g}$; ^{230}Th , 1.4×10^{-1} $\mu\text{Ci/g}$; and ^{226}Ra and short-lived daughter products, 1.6×10^{-2} $\mu\text{Ci/g}$ each. On a long-term basis, all the daughters will gradually grow back to secular equilibrium, first with ^{226}Ra and ultimately with ^{230}Th . Radon release from the sealed drums is quite low (Sect. 4.4.15.4). About 89,000 lb of still residues per year are stored in sealed containers since the uranium and vanadium

^aTo avoid underestimating source terms, different assumptions are used for the solid and liquid phases. The sum of assumptions is therefore greater than 100%. For example, 10% of the radionuclides are released in the liquid effluent from lime treatment (Sect. 4.5.16) and 100% are precipitated with the CaF_2 solids (Sect. 4.5.17).

values do not presently justify recovery (Sect. 4.4.13). Still residues are principally vanadium, molybdenum, and uranium fluorides and oxyfluorides. These compounds are chemically reactive and, at some future date, will require additional processing for conversion to a more stable form for disposal. The amounts of ^{230}Th and ^{226}Ra in the still residues are quite low (Table 4.11).

4.4.17.2 F-F Case 2 solid waste treatment. Ash and still residue handling is the same as in Case 1. The liquid waste treatments (Sect. 4.4.16) generate a total of 3.6 million lb of CaF₂ scrubber waste per year, which is stored in a lined basin to minimize potential underground migration of materials via liquid seepage or leaching by natural waters. These CaF₂ scrubber wastes are in a chemically stable, nearly insoluble, nonvolatile form. The concentrations of radioactive materials are very low -- comparable to the average composition of the earth's crust (Table 4.11).^{a,b} The case studies cost a lined storage basin with a lifetime (capacity) of 15 years but do not address final disposal. Fluorspar, the raw material in the manufacture of HF, is an imported mineral which has been escalating rapidly in price. It is possible that, at some future time, the CaF₂ scrubber wastes will be purified and recycled to make HF. No technical or environmental difficulties are anticipated with on-site burial, providing the burial site is situated a reasonable distance away from natural watercourses and above the water table, etc.; however, there may be legal restrictions.

4.4.17.3 F-F Case 3 solid waste treatment. Ash, still residues, and CaF₂ scrubber wastes are handled in the same manner as in Case 2.

^aOnly radioactive materials in the yellow cake feed to the plant are included in this assessment.

^bAnalyses at the Allied Chemical Corporation Metropolis UF₆ Plant indicate that the CaF₂ sludge in the No. 1 pond contains $\sim 1 \times 10^{-4}$ μCi of $\text{U}_{\text{nat}}/\text{g}$ and the sludge in No. 2 pond contains $\sim 1 \times 10^{-5}$ μCi of $\text{U}_{\text{nat}}/\text{g}$ compared with 6×10^{-6} μCi of $\text{U}_{\text{nat}}/\text{g}$ in the raw lime.⁵¹ The ^{226}Ra contents are 4×10^{-7} $\mu\text{Ci}/\text{g}$ for No. 1 pond sludge and 8×10^{-7} for No. 2 pond sludge, or essentially indistinguishable from the 5×10^{-7} $\mu\text{Ci}/\text{g}$ in the raw lime.⁵¹ All analyses are on a dry basis.

The radium precipitation treatment for liquid wastes from sodium removal and carbonate leaching generates 1800 lb of solid waste per year, consisting primarily of BaSO_4 with some $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ (Sects. 4.4.10.9, 4.4.11.5, and 4.4.16.3). Solids are settled in a lined basin, dried, and drummed for shipment to an approved burial ground. The average radium content of the dried waste is 2.6×10^{-3} $\mu\text{Ci/g}$, which is approximately five times higher than the radium content of typical uranium mill tailings. The radium treatment wastes carry traces of other radioactive materials in the solution retained by the moist solids.

4.4.17.4 F-F Case 4 solid waste treatment. Ash is cemented as a 15% ash--45% cement--40% water mixture and drummed for shipment to an approved burial ground. Cementing the ash provides additional protection from potential long-term leaching by natural waters or radon release in the event of drum failure. The benefit of cementing the ash will depend upon the environment of the disposal area. The additional shipment and burial costs for the cemented product are not included.

Still residues and CaF_2 scrubber wastes are, in general, handled similarly to Case 2. Contaminated CaF_2 waste is stored separately from uncontaminated waste to avoid liquid releases of radioactive materials via solution sorbed on the moist filter cake (Sect. 4.4.16.4). Because of more efficient fluorine and HF utilization within the process, the amount of fluoride scrubber wastes in Case 4 is only about 15% of that in Cases 2 and 3. The concentrations of radioactive materials in the contaminated fluoride scrubber waste are low (2×10^{-4} $\mu\text{Ci/g}$ of U_{nat} , 5×10^{-7} $\mu\text{Ci/g}$ of ^{226}Ra), although they are higher than in Cases 2 and 3 because there is less CaF_2 diluent.

In Case 4, treatment of the reduction off-gas scrub liquor generates 940,000 lb of $\text{CaSO}_3 \cdot 1/2\text{H}_2\text{O}$ per year -- a waste not present in earlier case studies (Sects. 4.4.6.7 and 4.4.16.4). This waste is stored in a lined impoundment basin. Sulfite waste is stored separately from fluoride wastes to facilitate possible future fluoride recovery. Calcium sulfite is a nonvolatile, nearly insoluble compound. Oxidizing conditions might tend to convert it to CaSO_4 , which is also nearly insoluble.

The radioactive contaminants are present as oxides at very low concentrations (Table 4.11).

In Case 4, the liquid waste evaporator system generates 840,000 lb of $(\text{NH}_4)_2\text{SO}_4\text{-Na}_2\text{SO}_4$ annually -- a waste not present in the earlier case studies (Sect. 4.4.12). Evaporator residues are dried and drummed for shipment. Although low in radioactive materials (Table 4.11), these salts are water soluble and a special means of storage, such as concrete or asphalt-lined vaults, is required. The costs include only the drying and packaging and do not take into account shipping or special vaults at the burial ground.

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5.0 NONRADIOACTIVE WASTE

The origin and treatment of chemwaste and radwaste are discussed in Sect. 4.0. Airborne chemical releases from the process are summarized in Table 4.7 and Fig. 5.1, and liquid chemical releases in Table 4.10 and Fig. 5.2. The release of noxious chemicals such as HF, H₂S, NO₂, nitrate, fluoride, sulfide, and other salts is also of concern. Uranium is a valuable commodity, and industry today uses sophisticated technology to minimize losses during processing. Waste streams have high chemical contents because excess reagents are used, but are contaminated with only small amounts of radioactive materials. The advanced treatment methods to reduce the amount of radioactive releases must be designed on the basis of the chemical flowsheets. Consequently, the engineering part of this survey evaluates the methods and costs for reducing the releases of both chemical and radioactive materials. The case studies also consider the effect on radioactive releases and on the generation of solid radwaste-chemwaste if more stringent regulations are adopted concerning chemical releases in the future.

The operation of a UF₆ plant will generate miscellaneous wastes in addition to the radwaste-chemwaste. These include sanitary waste, packaging materials from supplies, combustion products from the power plant, oils and greases from equipment maintenance, and chemical wastes from the fluorine cell rework area. The sanitary wastes are disposed of in a septic tank and drain field facility. Nonradioactive solid wastes and oils are incinerated or placed in a landfill. Combustion products which may contain SO₂ are dispersed through a stack.

6.0 COSTS

Costs for the various gaseous and liquid chemwaste and radwaste treatment cases for the 10,000-metric ton/year model UF_6 conversion plant are estimated as additions to the base plant. The waste treatment costs for the cases are subdivided into dust control effluent, process off-gas, building ventilation effluent, and liquid chemwaste-radwaste costs. The liquid chemwaste-radwaste systems are very complex, and no attempt is made to proportion the liquid waste treatment costs between chemwaste and radwaste. The capital costs, annual fixed charges, annual operating cost, total annual cost, and contribution to the cost of power for the various cases are summarized in Table 6.1. A detailed breakdown of the installed equipment costs is given in Tables 6.2-6.4.

Annual fixed charges are estimated at 26% of total capital investment. This is typical of investor-owned fuel reprocessing and waste treatment facilities.¹ The basis for calculation of the fixed charge rate and the operating cost is discussed in Sect. 6.2. An annual operating expense is added to the annual fixed charge on capital to give the total annual cost of a radwaste treatment case. The annual operating (and maintenance) expense is calculated as follows: for conventional chemical processing equipment, such as packed towers, tankage, pumps, etc., it is estimated at 40% of the annual fixed charge; for dust collecting equipment, such as bag filters and liquid scrubbers, it is calculated based on published information developed primarily by Stairmand,²⁻⁴ and for HEPA filters, it is based on the experience at ORNL.⁵⁻⁷ No operating expense is added for certain capital costs such as lagoons, pipelines, and ductwork, while in other cases where the material cost is appreciable, such as for lime, cement, and drums, a higher operating expense is used (Sect. 6.2). The total annual cost for each case is divided by the equivalent annual electricity production of the fuel to obtain the contribution to power cost for each waste treatment case. A UF_6 conversion plant with a nominal production rate of 10,000 metric tons/year can service a nuclear economy of approximately seventy-seven 1000-MW(e) LWRs (based on a burnup of 33,000 MWd/metric ton, an 80% load factor, and a 32.5% thermal efficiency).

Costs are estimated in terms of 1973 dollars to make this report consistent with other reports in this series.^{4,8-10} No attempt is made to include the effect of inflation; however, based on the Marshall and Swift (M and S) Equipment Cost Index¹¹ for chemical equipment, the costs in early 1977 will be about 45% 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 Cost

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

6.1.1 Direct costs

The major equipment components were sized and a base price estimated, based on the general methods used to cost conventional chemical plant equipment for conceptual designs. Appropriate factors were applied to the equipment cost to estimate the expense of installation, piping, instruments and controls, electrical, and quality assurance.¹²⁻¹⁴

The costs of a general plant structure, warehouse buildings, or other related facilities are not included. The total direct cost for each waste (gaseous and liquid chemwaste-radwaste) treatment case is the complete equipment installed (material and labor) cost.

6.1.2 Indirect costs

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

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

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

6.2 Annual Fixed Charges and Operating Costs

The annual fixed charges on invested capital are based on the Fuel Recycle Task Force¹⁵ annual fixed rate of 24%, which was, in turn, based on the following assumptions:

Plant lifetime (amortization)	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%

The 5% bond interest rate is probably low by present-day standards. Increasing it to 8% would increase the fixed charge rate to about 26%; therefore, a fixed charge rate on invested capital of 26% is assumed for this study.

The annual operating and maintenance cost is calculated as 40% of the annual fixed charges for the solid and liquid chemwaste and radwaste treatment systems. Additional specific operating charges are also included, such as an annual expense for lime of \$31,500 for Cases 2 and 3 and \$9100 for Case 4, and \$128,000 for cement, \$41,800 for drums for evaporator solids, and \$374,000 for drums for fluorination ash waste in Case 4. The cost for on-site storage of the drums or shipping off-site for storage or burial is not included. Calculation of the annual operating cost of the gaseous waste treatment systems is based on published information for equipment, such as bag filters and liquid scrubbers, and on experience at ORNL for the HEPA filters. Annual operating costs are not assessed for the lagoons, pipelines, or ventilation ducts.

6.3 References

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7.0 ENVIRONMENTAL IMPACT FOR PLANT FEED CONTAINING
"HIGH" LEVELS OF ^{230}Th AND ^{226}Ra IMPURITIES^{a,b}

The radiological impact of the model UF_6 plant is assessed by estimating radiation dose commitments to individuals, populations, and selected biota which may result from exposure for 1 year to the expected radionuclides discharged during normal operations. The effluents are dispersed in the environment by atmospheric or aquatic transport. The resulting concentrations of radionuclides in the air and on the soil surface at various distances and directions from the model plant, or the concentrations in the waters around the plant, are then used to estimate the doses. Doses are calculated for each site and radwaste treatment case.

Potential pathways for radiation exposure to man from radionuclides originating in a nuclear facility are presented schematically in Fig. 7.1. Although those shown in the figure 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 surface. Internal doses result from the inhalation of contaminated air and the ingestion of contaminated food and drinking water. Conservative assumptions are used which tend to maximize doses; for example, doses from atmospheric releases assume exposure to contaminated air and ground 100% of the time with no shielding and consumption of food that is produced entirely at the location of the dose calculation. Doses from liquid releases assume that all drinking water or fish is obtained from the streams or rivers around the plant.

^aPlant feed contains 14,200 pCi of ^{230}Th and 1600 pCi of ^{226}Ra per gram of U_{nat} .

^bSee Addendum for assessment of a model plant processing a more realistic, "low-impurity" feed.

Radioactive materials introduced into the body via inhalation or ingestion (internal exposure) continuously irradiate the body until removed by processes of metabolism and radioactive decay. A dose calculated for 1 year of radionuclide intake (internal-exposure pathways) is an estimate of the total dose an individual will receive integrated over the next 50 years of his life as a result of that 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: that is, the annual dose rate is about the same as the dose commitment. This is the case for most radionuclides in this study since ^{234}U , ^{235}U , and ^{238}U are eliminated from the body fairly rapidly and the half-life of ^{234}Th is short. However, ^{226}Ra and ^{230}Th 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; that is, approximately equal doses are received over a 50-year period. Thus the average annual dose rate from ^{226}Ra and ^{230}Th is only one-fiftieth of the dose commitment. If an individual is exposed to UF_6 plant effluents for the 30-year operating life of the facility, his annual dose rate from ^{226}Ra and ^{230}Th during the thirtieth year is about 30 times the annual dose rate for 1 year of exposure (i.e., $\sim 3/5$ the dose commitment for 1 year of exposure) and his total dose commitment is the summation of the 50-year dose commitments for each of the 30 years that apply in the 30th year. 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 presented in ORNL-4992.¹

Organ doses may vary considerably for internal exposure from ingested or inhaled materials because some radionuclides concentrate in

certain organs of the body. Estimates of doses are considered for all pathways of exposure based on parameters applicable to an average adult. The population total-body and organ dose estimates are the sums of the total-body and organ doses to the individuals within 55 miles of the plant, and are based on adult doses in all cases.

Radiation doses to the internal organs of children in the population vary from those of an average adult because of differences in metabolism, organ size, and diet. Differences between the organ doses of a child and those of an average adult by more than a factor of 3 would be unusual for all pathways of internal exposure except the atmosphere-pasture-cow-milk pathway. Total-body doses are relatively independent of age.²

7.1 Radiological Impact of Airborne Effluents During Operations

The release of radioactive materials to the atmosphere is the principal mode of environmental contamination from UF₆ production facilities.

7.1.1 Models and assumptions

7.1.1.1 AIRDOS.³ AIRDOS, a FORTRAN IV computer code, is used to estimate individual and population doses resulting from the continuous atmospheric release of airborne radioactive materials from the model UF₆ 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) immersion (swimming) in water subjected to surface deposition from plumes. Doses are estimated for the total body as well as the following organs: GI tract, bone, thyroid, lungs, muscle, kidneys, 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 and dairy 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 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) developed by Booth, Kaye, and Rohwer.⁴ This model estimates radionuclide intakes via ingestion of radionuclides deposited on crops, soil, and pastures. The intakes result from eating beef and vegetable crops and drinking milk. Ingestion of fish or other foods produced in water areas is not included in the present version of AIRDOS.

Population doses are summarized in the output tables of AIRDOS in a number of ways - by nuclides, pathways, and organs. The highest individual doses in the area for each organ are tabulated for each radionuclide, and the highest organ doses from all radionuclides in the source term are listed. The highest individual dose is specified.

7.1.1.2 Atmospheric dispersion (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. Daughters produced during plume travel must be added to the AIRDOS source term. Concentrations in air for each sector are used to calculate dose via inhalation and submersion in air. Ground surface concentrations are used for external radiation exposure. 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. Meteorologic data⁷ from representative first-order weather stations in the Midwest (St. Louis, Missouri) and New Mexico (Albuquerque) 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_d . 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 surface. Methods for estimating scavenging coefficients can be found in Meteorology and Atomic Energy - 1968.¹⁰ Scavenging coefficients for particulates¹⁰ of $2.0 \times 10^{-5} \text{ sec}^{-1}$ and $4.6 \times 10^{-6} \text{ sec}^{-1}$ are assumed for the midwestern and New Mexico sites, respectively.^a

Most radionuclides released to the atmosphere by UF_6 plants have long half-lives (e.g., ^{238}U , ^{234}U , ^{235}U , ^{230}Th , and ^{226}Ra) or are in secular equilibrium with a long-lived parent so that effectively no significant radioactive decay occurs as the plume travels. However, gaseous ^{222}Rn will decay as the plume travels, producing particulate daughters. Decay of ^{222}Rn is taken into account by the AIRDOS code. Its daughters are added

^aScavenging was not considered in the earlier study in this series on uranium mills.¹¹

to the source term to take their buildup into account. A period of 7 min was conservatively assumed to be required for the airborne plume to reach the plant boundary in the prevailing wind direction for the purpose of determining the buildup of ^{218}Po and ^{214}Pb daughters from ^{222}Rn in order to estimate maximum individual doses. In estimating population doses, it was assumed that the daughters were in secular equilibrium with ^{222}Rn . The production of ^{222}Rn from the ^{226}Ra particulates in the plume was not taken into account because the quantity produced is insignificant as compared with that released by the plant initially.

For a 5-m release height (the condition assumed in this study), the maximum ground-level concentration of radioactive materials in air occurs near the point of release. If we assume a site boundary of 0.5 mile (800 m), the maximum off-site χ/Q value (least dilution) for long-lived radionuclides released as particulates after adjusting for plume depletion processes of deposition and scavenging, for example, is $4.28 \times 10^{-6} \text{ sec}\cdot\text{m}^{-3}$ for the midwestern plant and $6.16 \times 10^{-6} \text{ sec}\cdot\text{m}^{-3}$ for the New Mexico plant. The χ/Q values decrease by more than three orders of magnitude at a distance of 55 miles from the source. Concentrations at distances nearer the plant than 0.5 mile (800 m) are higher by the following factors: 100 m, 13.3; 200 m, 8.20; 300 m, 5.50; 400 m, 3.63; 500 m, 2.48; and 600 m, 1.32. The maximum concentrations are found downwind from the plant in the prevailing wind direction. Average concentrations at 0.5 mile from the plant are about 47% of the maximum levels.

The 5-m release height is a conservative assumption. Higher release heights result in slightly lower χ/Q values because of greater dilution, while lower release heights produce even lower χ/Q values because of greater ground deposition of particulates near the point of release with consequent greater depletion of the plume within the plant boundary. For example, at 0.5 mile from the midwestern plant, maximum values of χ/Q for long-lived radioactive particulates are 2.57×10^{-6} , 4.28×10^{-6} , and $4.07 \times 10^{-6} \text{ sec}\cdot\text{m}^{-3}$ for release heights of 0, 5, and 10 m, respectively.

7.1.1.3 Population. Population distributions representative of midwestern and western (milling) environments were derived. The population distribution for the midwestern site is the average population distribution around two fuel fabrication plants and one reprocessing plant in the area. Distributions for a site near a large city, St. Louis, Missouri, are included in the averaging. The distribution for the western site is the average for five actual sites of uranium mills in New Mexico and Wyoming.

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 western (milling) regions (Tables 7.2 and 7.3). The computer code PANS¹² 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 whereas the population records are reported in a single sector. Averaging data from several locations smooths the major discontinuities.

Population distributions for the two sites of the model UF_6 production facilities have different characteristics (Tables 7.2 and 7.3). The midwestern site includes small towns and one large city as well as rural agricultural areas within the 55-mile radius, while the western (milling) site is in a sparsely settled, arid region. The population density of the midwestern site within the 5-mile radius of the plant is 95 individuals per square mile. The density increases to 126 individuals per square mile in the 10- to 25-mile annulus and to 440 individuals in the 25- to 55-mile annulus, which includes the large city. Cumulative population in the area encompassed by the 55-mile radius is estimated to be about 3.6 million persons. By comparison, average data for western

milling sites (Table 7.3) show no individuals at distances of less than 1 mile, four individuals per square mile in the 1- to 5-mile annulus (4% of the midwestern density), ten in the 5- to 10-mile annulus (8% of the midwestern density), three in the 10- to 35-mile annulus, and only seven in the 35- to 55-mile annulus even though it includes several small towns. Cumulative population in the area encompassed by the 55-mile radius is only about 53 thousand persons, or about 1.5% of the population around the midwestern site.

7.1.1.4 Dose conversion. Concentrations of radionuclides in the air and on the soil surface are used to estimate the radiation dose to individuals at various distances and directions from the model plant. The dose conversion factors for submersion in the airborne effluent, exposure to contaminated ground surface, and intake of radionuclides through inhalation and ingestion are calculated with computer codes^{13,14} which use dosimetric criteria of the International Commission on Radiological Protection and other recognized authorities. The dose conversion factors for most radionuclides are based on ICRP-2.¹⁵ However, the new value proposed in ICRP-10¹⁶ is used for ^{226}Ra . The new ^{226}Ra value is about one-sixth of the ICRP-2 value. Estimates of the intake of radionuclides by man through terrestrial food chains are made with a model and a computer code,⁴ incorporated within AIRDOS, which considers transfer of all radionuclides to man via ingestion of crop plants, beef, and milk. A reference handbook on the methods used in estimating radiation doses has been prepared (ORNL-4992).¹

Many of the basic environmental parameters used in this model are conservative (i.e., the values are chosen to maximize intake by man). Many factors which would reduce the radiation dose, such as shielding provided by dwellings and time spent away from the reference location, are not considered. It is assumed that an individual lives outdoors in the reference location 100% of the time. Doses are calculated for the final period of plant operation when there is a 30-year accumulation of deposited radioactive materials on the ground surface outside the property. In estimating doses via ingestion of plants, meat, and milk, an individual

is assumed to obtain all his food at the reference location specified in the dose calculation. This event, although not impossible, is extremely unlikely. Thus individual dose estimates calculated by these methods are higher than actually expected.

7.1.2 Radiation dose commitments from airborne effluents

7.1.2.1 Doses to individuals. The maximum annual total-body and organ doses to individuals from all airborne effluents at 0.5 mile (800 m) from the operating model F-F UF₆ plant are summarized in Table 7.4, assuming a 5-m release height and production of all food locally. Appropriate dose reduction factors can be applied when (1) the release height is lower or higher than 5 m (Sect. 7.1.2.5), (2) the food source is known (Sect. 7.1.2.4), or (3) the ²³⁰Th and ²²⁶Ra impurity contents in the plant feed are known (Sects. 4.2.1, 7.1.2.3, and 8.0. The doses to organs not listed are equal to or less than the value shown for total-body dose.

At the midwestern site, the maximum annual individual total-body dose (Table 7.4) decreases from 9.9 mrem in Case 1 to 3.8 mrem in Case 2, which is about the practical limits of present technology (Sect. 4.0). Additional dose reduction to 1.9×10^{-2} mrem is illustrated in Case 4. The dose to the bone (130 mrem in Case 1) is approximately 13 times higher than the total-body dose, while the doses to lungs and kidneys are, respectively, 4 and 3 times higher. Treatment Case 2 is effective in reducing doses to body organs by more than one-half those for Case 1. Maximum individual doses for the western (New Mexico) site are about 30% higher than for the midwestern site; however, the population distribution indicates that there is a low probability that an individual would reside within a 1-mile radius of the plant (Table 7.3).

Doses attributable to the different types of airborne plant effluents are presented in Tables 7.4a-7.4d. Dose reductions beyond Case 2 for the dust control effluent (12 mrem to the bone in Case 2 at the midwestern site, Table 7.4a) and process off-gas (2 mrem to the bone in Case 2, Table 7.4b) are of marginal value compared with reduction of the dose from the building ventilation effluent (36 mrem to the bone in Case 2, Table 7.4c).

7.1.2.2 Doses to population. The annual dose commitments from airborne effluents to the population living within 55 miles of the model F-F UF₆ plant are summarized in Table 7.5. At the midwestern site the population total-body dose decreases from 9.3 person-rem in Case 1 to 3.6 person-rem in Case 2, and the population bone dose from 110 person-rem to 44 person-rem. Population doses are much lower at the sparsely settled New Mexico site, for example, less than 1 person-rem total body and less than 3 person-rem bone in all cases.

7.1.2.3 Exposure modes and radionuclides. The relative contributions of exposure modes to the maximum annual individual total-body dose from airborne effluents are given in Table 7.6 for Case 1. Internal exposure from inhalation and ingestion accounts for 68% of the total-body dose; exposure from contaminated ground accounts for essentially all of the remaining 32%.

The relative contributions of the principal radionuclides to the doses from airborne effluents are presented in Table 7.7. About half (52.6%) the total-body dose is due to uranium isotopes and half to ²²⁶Ra and ²³⁰Th combined (29.5% and 17.8%, respectively). Seventy percent of the bone dose, 62% of the kidney dose, and 45% of the thyroid dose are due to ²²⁶Ra and ²³⁰Th combined, with the remainder due to uranium isotopes. Radium and thorium enter the plant as impurities in the feed. There is considerable uncertainty in the source terms for ²²⁶Ra and ²³⁰Th and, consequently, considerable uncertainty in total-body, bone, and thyroid dose estimates (see Sects. 4.2.1 and 8.0). The uranium isotopes are the principal contributors to the lung (70%) and GI tract (79%) doses. Radon gas is a very minor source of exposure, contributing only 0.2% of the total-body dose and 1.6% of the lung dose; therefore, no treatment for it is provided in the case studies.

The relative contributions of the principal radionuclides to the exposure modes for airborne effluents are shown in Table 7.8. Almost 65% of the total-body dose via the ingestion pathway is due to ²²⁶Ra, while approximately 75% of the inhalation dose is due to ²³⁰Th. Almost all of the total-body dose resulting from contaminated ground is accounted for by the uranium radionuclides, mainly ²³⁸U (68.9%). The dose via

submersion in air, which is quite small (Table 7.6), is due almost entirely to ^{222}Rn and its daughters ^{214}Pb and ^{218}Po . Radium-226, ^{234}U , and ^{238}U are important contributors to the doses to the bone, kidney, and lungs via the ingestion pathway, while ^{230}Th is a significant contributor to the doses to bone and kidney via the inhalation pathway. Radiation doses to organs are largely dependent on the specificity of certain radionuclides to accumulate in certain organs.

7.1.2.4 Effect of food source on dose. It is unlikely that the entire food supply of the individual receiving the maximum exposure would be produced locally, that is, 0.5 mile downwind from the plant in the prevailing wind direction. Doses which may be applied when the food source is known are presented in Tables 7.9a-7.9d. In Cases 1-3, if only 10% of the food is produced locally, the total body and the bone (the critical organ) doses are only about 60% of the doses based on 100% local food. A diet of food produced 2 miles downwind of the plant in the prevailing wind direction or 1 mile from the plant in an average wind direction would be roughly equivalent to a diet of 10% food produced 0.5 mile downwind and 90% imported food. The food ingestion pathway has little effect in Case 4, where the doses are very low (Table 7.9d).

7.1.2.5 Effect of release height on dose. Factors for estimating doses to individuals as a function of the release height from ground level to 30 m (100 ft) are presented in Table 7.10. At the midwestern site, the maximum individual total-body dose for a 30-m-high release is 32% of the dose from a 5-m-high release, while the dose from a 1-m-high release is 63% of that from the 5-m-high release. With a low release height, more particulates are deposited on the ground within the site boundary; with a high release height, there is greater atmospheric dilution. Thus a 30-m stack on a UF_6 plant whose effluents are predominantly particulates will reduce the dose to the individual at the site boundary because of greater dilution, but it will also increase the population exposure because more radioactive materials are dispersed beyond the site boundary.

7.1.2.6 Effect of distance from the plant on dose. The dose to the individual decreases rapidly with increasing distance from the plant (Table 7.11). For example, the dose at 5 miles is only 1% of that at 0.5 mile. In the model, all exposure within the 0.5-mile radius is of occupational origin, which is not part of this study, and no food is produced on-site. If the site boundary were less than 0.5 mile, the dose factors for a low-level release would be approximately proportional to the χ/Q air concentrations given in Sect. 7.1.1.2.

7.1.2.7 Doses to biota other than man. The estimated maximum doses to man (total body) in F-F Case 1 range from 10 to 13 mrem/year for individuals located 0.5 mile from the facility. The radiation doses to terrestrial animals living around the site would be similar. Small mammals, such as rodents and rabbits, and larger animals, such as deer, would also be subjected to exposures via immersion in air, contaminated ground, and inhalation. These animals would receive additional exposure via their particular food chains.

7.2 Radiological Impact of Liquid Effluents

The model UF_6 plant has a liquid effluent in Cases 1-3 which may potentially contribute to the radiation dose to man. In Case 4 there is no liquid effluent containing radioactive materials and hence no potential dose via aquatic pathways. Two types of sites are considered: (1) release to a small, 15-cfs stream, and (2) release to a 1300-cfs river. Doses to individuals are estimated for submersion in water (swimming), ingestion of water, and eating fish from the waters around the model plant. Use of waters for irrigation is not included. It is difficult to predict population distribution along a river; therefore, no attempt is made to estimate population doses for liquid effluents. Dose conversion factors for most radionuclides are based on ICRP-2.¹⁵ The new value proposed in ICRP-10¹⁶ is used for radium.

7.2.1 Doses to individuals

Annual dose commitments to total body and bone from using the waters around the model F-F UF₆ plant are presented in Table 7.12. In Case 1, doses from using the 15-cfs stream are about 50% (5.6 mrem total body) of those from the Case 1 airborne effluents, while doses from using the 1300-cfs river (0.07 mrem total body) are less than 1% of those from airborne effluents. It is unlikely that individuals would routinely use the 15-cfs stream as a source of drinking water or fish or for swimming because of its small size and the presence of non-radioactive chemicals. Thus, individuals are unlikely to receive the 15-cfs stream dose. It is more probable that the river would serve as the water supply for a segment of the population.

Drinking the water and eating fish account for about 60% and 40% of the dose respectively, with swimming contributing about 0.001% (Table 7.12). In Cases 1 and 2, ²²⁶Ra contributes over 80% of the dose from drinking water and over 95% of the dose from eating fish (Table 7.13). There is considerable uncertainty in both the radium source terms (Sect. 4.4.11) and consequently considerable uncertainty in the dose estimates. The dose estimates for Cases 1 and 2 could easily be high by a factor of 2 or 3. Although liquid radwaste treatment Case 2 is effective in reducing the amounts of most of the radionuclides released, it has little effect on the ²²⁶Ra release (and consequently little effect on the doses via aquatic pathways). The Case 3 radium treatment is effective in reducing doses from liquid effluents to very low levels (e.g., 1×10^{-3} mrem total body and 2×10^{-2} mrem bone from the 1300-cfs river or 0.1 mrem total body and 1.6 mrem bone from the 15-cfs stream). Thorium-234 and ²³⁵U are the principal contributors to the dose due to swimming (Table 7.13); however, this is a negligible part of the total dose.

7.2.2 Doses to biota other than man

Radiation doses to aquatic plants, invertebrates, fish, and water-fowl are estimated in Table 7.14 for the 15-cfs stream and the 1300-cfs

river near the F-F UF₆ plant. It is unlikely that higher organisms, such as fish or waterfowl, could tolerate living in direct liquid effluents due to the presence of nonradioactive chemicals and to the fact that these effluents would not be found in a physical habitat conducive to higher aquatic life. Doses to organisms living in the 15-cfs stream are about 100 times higher than those estimated for biota living in the river where appreciable dilution takes place. Liquid radwaste treatment Case 2 results in approximately a 30% dose reduction to algae, invertebrates, and fish, but has little effect on doses to muskrat and waterfowl. Case 3 results in a tenfold reduction in doses to algae, invertebrates, and fish, and a 100-fold reduction in doses to muskrat and waterfowl. Uranium-234, ²³⁸U, and ²²⁶Ra are important contributors to the doses to plants, invertebrates, and fish (Table 7.15). Due to the relatively high bioaccumulation factor, ²²⁶Ra contributes almost 100% of the doses to muskrat and waterfowl.

7.3 Total Radiation Dose from All Pathways

The annual individual total-body dose commitment of 10 to 13 mrem (Case 1, 1300-cfs stream) from liquid and airborne effluents from the model fluorination-fractionation UF₆ plant through both the terrestrial and the aquatic pathways is about 10% of the normal background dose of 100 to 170 mrem/year in the United States.

7.4 Radiation Dose from Long-Lived Radionuclides After Closure of the UF₆ Plant

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 surfaces as a result of UF₆ plant operation. These estimates involve many complex considerations. All of the information necessary to make accurate predictions is not available. In the absence of complete information, estimates are made using the best current knowledge. Conservative assumptions are used in areas where deficiencies of knowledge exist. These assumptions make it likely that the estimates of health consequence are well above the

probable effects. A more-detailed assessment of the radiation exposure to future generations from long-lived elements has been included in a recent environmental analysis of the LMFBR program.¹⁷

7.4.1 Postoperational source terms

The model UF₆ plant releases airborne dusts and small amounts of radon gas throughout each year of operation. During this time, individuals and populations are exposed to a radioactive cloud from which they receive radiation doses due to immersion in the cloud and to inhalation. Radionuclides are deposited on the ground from the cloud and accumulate in the environment around the facility, causing external radiation exposure from contaminated ground and the ingestion of contaminated food. The radionuclides with long half-lives continue to expose the population after the plant has ceased operations. The total quantities of long-lived radionuclides released in Case 1 from the model fluorination-fractionation UF₆ plant during a 30-year operation are listed in Table 7.16. These long-lived radionuclides (²³⁴U, ²³⁵U, ²³⁸U, ²²⁶Ra, and ²³⁰Th) will remain in the environment for generations.

The distribution of these radionuclides around the UF₆ 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 materials are deposited within a 55-mile radius of the plant. Estimates of the deposition of particulates indicate that as much as 70% of the materials are deposited within 50 miles when the release point is the top of a 100-m-high stack.⁹ Deposition for the 5-m release point assumed in this study is expected to be higher.

The average exposure to individuals and to the population is estimated by using the assumption that the radionuclides that are deposited during the operational lifetime of the model UF₆ plant are uniformly distributed within the 55-mile radius area (2.46×10^{10} m²). The use of this assumption causes an underestimation of the dose to individuals living near the facility or in areas of the prevailing wind direction and an overestimation of the dose to individuals living in the outer annulus of the 55-mile radius of the plant.

7.4.2 Postoperational pathways of exposure

7.4.2.1 Resuspended air activity. After airborne particulates have been removed from the atmosphere and reach the ground by deposition and washout, they may again enter 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 parameters of host soil, the vegetation cover, and the meteorological conditions. These highly variable factors and others related to land use, such as the disturbance of soil surfaces by human activity, must be considered in preparing a precise estimate of resuspended radioactivity.

A resuspension factor can be estimated from measurements made above aged contaminated soil and from consideration of natural tracers such as ^{238}U . Resuspension factors of 10^{-9} and 10^{-10} m^{-1} were obtained from recent measurements of ^{239}Pu made at the Nevada Test Site in an area contaminated 17 years previously.¹⁷ Measurements of ^{239}Pu in the vicinity of the Rocky Flats Plant several years after deposition indicated a resuspension factor of 10^{-9} m^{-1} .¹⁷ Discounting airborne material of industrial origin, the data concerning movement of natural ^{238}U indicate that a realistic estimate of the resuspension of aged radioactive material in surface soil lies between 10^{-8} and 10^{-10} m^{-1} .⁹ This is in agreement with the field measurements for ^{239}Pu . An intermediate value of 1×10^{-9} is used in this survey to estimate the amounts of radioactive materials resuspended over a long period of time in the regions around a UF_6 plant facility. The resultant airborne concentration is used to estimate the inhalation dose. It is assumed that the resuspension value remains constant even though the deposited radionuclides may not remain on or near the surface of the soil. Actually, a continuation in the reduction of the availability of these materials beyond the current measurement experience of 20 years can be expected. Thus, the use of a constant resuspension factor is a conservative assumption which will maximize the estimated dose. Resuspended radionuclides are also assumed to enter terrestrial food pathways (vegetables, milk, and beef) via redeposition

on foliage of crops and pastures. The following expression is used to estimate intake via inhalation of resuspended radionuclides:

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

7.4.2.2 Ingestion of food. Plants may be contaminated by deposition of resuspended particulates onto foliar parts and by root uptake of isotopes leached from, or exchanged with, particles deposited in soil. Plant uptake studies show that uranium, radium, and thorium are strongly excluded from plant uptake and poorly translocated by plant systems. The general findings from experiments indicate that the concentration factors (ppm of dried plant material divided by ppm of dried soil) are about 10^{-3} to 10^{-4} . Lower factors may occur under field conditions. Although various plant and soil types have been tested, the list is not all-inclusive. Long-term changes in plant uptake are unknown. These changes would depend on the effects of several competing processes, including a downward movement of radioactive materials in soil, which may reduce their availability to higher plants, and reactions with soil organic matter and microbial transformations, which may increase their availability.

The fraction of these 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 use conservative parameters and assumptions to estimate the amounts that may be ingested by the population. It is assumed that (1) plant material accumulates a concentration, C_f , of radionuclides in the soil in which the plants grow, (2) downward movement of the radionuclides in the soil does not continue beyond the root zone (15 cm), and (3) radionuclides are not lost by drainage of

water. With a soil density of 1.5 g cm^{-3} , the radionuclides deposited on a square meter are contained in $2.25 \times 10^5 \text{ g}$ of soil. The following expression is used to estimate the intake via ingestion of plants:

$$\text{Ci year}^{-1} \text{ ingested} = (\text{Ci m}^{-2} / 2.25 \times 10^5 \text{ g m}^{-2}) \times C_f \times 9.12 \times 10^4 \text{ g plant ingested year}^{-1},$$

where the C_f values are 2.5×10^{-3} for uranium, 3.0×10^{-4} for radium, and 4.0×10^{-3} for thorium. Additional intake from the ingestion of plants contaminated via resuspended radionuclides is calculated using the TERMOD code.⁴

7.4.2.3 Contaminated ground. Exposure via contaminated ground is also estimated. It is assumed that no deposited radionuclides are lost from the soil surface except through radioactive decay.

7.4.3 Estimates of postoperational doses

The radiation dose to an individual residing within the uniformly contaminated area of 9.5×10^3 square miles ($2.46 \times 10^{10} \text{ m}^2$) is estimated both for total body and for organs that are known to accumulate the long-lived radionuclides. Population doses are expressed as person-rems per 3.6×10^6 persons, the population within 55 miles of the midwestern plant. No assumptions for population change are included. 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 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, dose commitments may approximate annual doses in situations where people are continually exposed over long periods of time and radionuclides have reached steady-state conditions in the environment.

7.4.3.1 Individual and organ doses. As a result of the deposition of long-lived radionuclides, persons living within a 55-mile radius of the model F-F UF_6 plant will continue to receive some radiation dose above background long after plant operation has been terminated, or actually

until the ultimate decay of all the radionuclides. The doses per year of exposure to the average individual living within a 55-mile radius of the plant for the various radionuclides and exposure modes are shown in Table 7.17. Ninety-two percent of the total-body dose (1.3×10^{-3} mrem in Case 1) results from exposure to contaminated ground. The three uranium isotopes (^{234}U , ^{235}U , and ^{233}U) contribute about 92% of the total-body dose. These are average doses out to 55 miles. 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 are shown for the major internal pathways in Table 7.17. The bone receives the highest organ dose (1.5×10^{-3} mrem in Case 1), which is about six times the dose to the kidney or the lungs. Major contributors to the bone dose are ^{230}Th (42%) and ^{226}Ra (34%).

7.4.3.2 Population doses. The annual population total-body dose is 4.7 person-rem per 3.6×10^6 persons in Case 1 after the UF_6 plant closes and until the long-lived radionuclides show significant decay (Table 7.18). The total-body dose is primarily due to uranium isotopes, while the bone dose is about half due to ^{230}Th and ^{226}Ra , and half to uranium isotopes.

7.5 References

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8.0 CORRELATION OF RADIOLOGICAL DOSE WITH COST OF WASTE TREATMENT
FOR A PLANT FEED CONTAINING "HIGH" LEVELS OF ^{230}Th AND ^{226}Ra
IMPURITIES^{a, b}

The relationships between the annual costs of the radwaste treatment systems described in Sects. 4.0 and 6.0 and the environmental impact of radioactive releases (50-year dose commitment) described in Sect. 7.0 are presented here. The accuracy of the cost estimates is about $\pm 30\%$, and the dose commitments represent maximum values. The effect of the various waste treatment methods on chemical releases is also noted, although the study does not address the environmental effects of chemical releases. Emphasis is placed upon the midwestern site, which is representative of the industry today and seems likely to be typical for the near future.

The base case, Case 1, represents the minimum treatment necessary to operate the process. The principal objective is to recover the uranium when the economic value of the recovered product exceeds the treatment cost, and to reduce the emission of noxious fumes such as HF, NO_x , and H_2S , whose release would create unacceptable working conditions within the plant. Plant effluents are below the limits stipulated in 10 CFR 20, Appendix B, Table II, but may not be acceptable chemically at all sites. Case 2 treatment is about the practical limit of existing technology in the public domain. Much of the technology used in the advanced cases is not available for immediate use either because it is not fully developed 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 various assumptions made in estimating the makeup of the feed to the plant, selecting the flows to the waste treatment systems, and determining treatment efficiency

^a Plant feed contains 14,200 pCi of ^{230}Th and 1600 pCi of ^{226}Ra per gram of U_{nat} .

^b See Addendum for an assessment of a model plant processing a more realistic "low-impurity" feed.

ratings for equipment are realistically conservative.^a Conservative (i.e., maximizing) assumptions are used to define the movement of radionuclides in the environment and to select food and liquid consumption patterns. Costs, which are based on 1973 dollars to be consistent with other reports in this series, do not include redundant (parallel) treatment units to ensure continued operation of complex systems in the event that one of the units should become inoperable.

Cost/benefit correlations are presented in the following section for a model fluorination-fractionation UF₆ plant. The annual costs of treatment systems that would reduce the amount of radioactive materials released in airborne effluents are analyzed in conjunction with the maximum doses to individuals and to population out to a distance of 55 miles. The dose commitments from the gaseous effluents are reported both for total body and for organs receiving doses higher than the total-body average (i.e., bone, lungs, and kidney). Other body organs which are discussed in Sect. 7.0 but will not be considered here are GI tract, thyroid, muscle, liver, spleen, testes, and ovaries. The annual costs of treatment systems that would reduce the amount of radioactive materials released in liquid effluents are correlated with the total-body and bone doses to individuals from a 15-cfs stream and a 1300-cfs river. All settling basins and ponds are lined with synthetic material and provided with an underground seepage assessment system to minimize losses of radioactive materials. Case 4 also includes the incorporation of the solid radwastes which contain the bulk of the radioactive materials in cement. The cement medium provides additional isolation from the environment in case the integrity of the drum should fail and reduces the potential for leaching by natural waters as well as providing a radon diffusion barrier. This would probably be considered a conservative treatment at a semiarid site. At other sites with high rainfall, high water tables, or geologic faults, such treatment becomes more beneficial.

^a I.e., source terms and flows are based on operating data if available. When data are not available, assumptions are chosen which tend to make the doses or costs slightly high.

The cost of Case 1 waste treatment is considered to be a part of the base plant rather than an environmental protection cost since most Case 1 treatments are essential to the economic operation of the conversion process. The total annual costs for Cases 2-4 include all costs above Case 1 for treatment of airborne and liquid effluents and for storing solid waste on-site or packaging solids ready for shipment off-site. They do not include the costs of uranium recovery in cases where the economic value of the uranium justifies the treatment, shipment of solid waste off-site, final disposal of solids, decommissioning of the facility, or the added expense incurred by a uranium mill (in Cases 3 and 4) of altering the chemical composition of the yellow cake. Changing the mill processes to eliminate ammonium and sodium ions from the yellow cake is expected to add about 3% to the cost of producing alkaline-leached yellow cake and 1% to the cost of producing acid-leached yellow cake (Sect. 8.3.4). No credit is taken for recovered chemicals; however, credit is taken if Case 1 treatment is replaced by an advanced method.

Cost/benefit comparisons are presented first in summary form for the combined waste treatment packages for each case and then separately for the major components. The gross comparisons mask many features, including the relative cost/benefit of alternative procedures.

8.1 Cost/Benefit Summary for the F-F Model Plant

The total annual costs for reduction of the radiological dose commitment and chemical exposure to the population surrounding the model fluorination-fractionation UF_6 production plant are summarized in Tables 8.1 and 8.2 for the midwestern and New Mexico sites. The amount of solid waste generated by the advanced liquid waste treatment systems is included since this waste increases the amount of land permanently committed. The total annual cost increases over the base case range from \$683,000 for Case 2 to \$2,908,000 for Case 4, and are equivalent to a contribution to power cost of 0.0013 to 0.0054 mill/kWhr.

The estimated capital cost of the base plant is \$35 million, including the Case 1 off-gas treatment. The increases in capital costs range from \$2.02 million for Case 2 to \$7.35 million for Case 4, or 6% to 21% of the cost of the base plant.

The total annual cost increase for reduction of the dose from all airborne effluents is presented in Table 8.3 and Figs. 8.1 and 8.2 for the midwestern site. For the base plant, the maximum annual individual dose commitments at 0.5 mile are 9.9 mrem to the total body and 130 mrem to the bone (the highest organ dose), and the annual total population doses out to 55 miles are estimated as 9.3 person-rem to the total body and 110 person-rem to the bone. These doses are for a base plant containing only treatment essential to the economic operation of the process. The addition of secondary bag filters and secondary or tertiary scrubbers on the process reduces the maximum individual doses to 3.8 mrem total body and 51 mrem bone. The annual cost of this dose reduction from Case 1 to Case 2 is high -- \$48,000/mrem total body and \$3600/mrem bone for the fence-post individual, or \$51,000/person-rem total body and \$4100/person-rem bone for the general population, out to 55 miles at the midwestern site (Table 8.4). Case 2 represents about the practical limits of present-day technology. Further dose reductions using advanced technology are possible, but the incremental annual cost/benefit is high--that is, \$14,000/person-rem bone from Case 2 to Case 3 and \$91,000/person-rem bone between Case 3 and Case 4 for the general population (Tables 8.3 and 8.4).

In the base case, the dust control effluent from dry materials handling contributes about 65% of the dose, the building ventilation effluent about 27%, and the process off-gas about 8% (Fig. 8.3). Consequently, additional treatment of dust control air is of first priority. Secondary bag filters are added in Case 2 at a total annual cost of \$252,000, which lowers the individual total-body dose from dust control air from 6.4 mrem to 0.9 mrem and the bone dose from 89 mrem to 12 mrem (Table 8.3a). The incremental annual cost/benefit for the total population is \$49,000/person-rem total body and \$4000/person-rem bone (Table 8.4a). Additional scrubbers on the process off-gas are helpful in reducing chemical releases (Sect.

8.1.3) but have little effect on the total airborne release from the UF_6 plant since the process off-gas is a relatively small source of radioactive materials. Cost/benefit relationships for the process off-gas are presented in Tables 8.3b and 8.4b. Treatment of the building ventilation effluent is of second priority after installation of secondary bag filters on the dust control effluent. This is expensive because of the large volume of air that must be processed--\$180,000/person-rem total body and \$15,000/person-rem bone for baffle (orifice) scrubbers.

The cost/dose relationships for treating liquid effluents are presented in Table 8.5. With no treatment, the doses from the 15-cfs stream are 5.6 mrem total body and 59 mrem bone; doses from a 1300-cfs river are 0.07 mrem total body and 0.7 mrem bone. It is unlikely that individuals would routinely use the 15-cfs stream as a source of drinking water or fish or for swimming due to its small size and the presence of non-radioactive chemicals. From the radiological standpoint, treating liquid wastes is of lower priority than treating airborne effluents; however, more stringent regulations with regard to chemical releases seem likely in the near future. The annual cost of the most expensive case is \$461,000, and this case has no liquid releases of radioactive materials. The liquid-case studies are not directly comparable because the feed to the liquid waste treatment systems is a variable which affects both costs and doses. Therefore no incremental dollar-per-rem assessment is drawn for liquid-case studies, although some incremental relationships are presented in Sect. 8.4. The costs given in the summary Tables 6.1, 8.1, and 8.5 include all costs of liquid waste treatment and storing or packaging the solids generated but do not include the expense involved in process changes that affect the feed to the liquid waste systems. The Case 2 treatment systems that reduce the chemical releases (Sect. 8.4) are of marginal value in reducing the dose (Table 8.5). The $BaCl_2$ treatment to precipitate radium in Case 3 is beneficial and moderately inexpensive (Table 8.5, Sect. 8.4.1). Some features of Case 4 off-gas treatment such as the fluorine and UF_6 cleanup reactors are useful in terms of decreasing the liquid waste treatment costs, but the technology is not presently available to industry. The F-F Case 4 evaporator system is expensive and

provides marginal dose reductions. The advantage of reducing the releases of $(\text{NH}_4)_2\text{SO}_4$ and Na_2CO_3 depends on the characteristics of the receiving stream at a particular site.

Case 4 includes an annual cost of \$514,000 for incorporating the fluorination ash in cement. Cementing provides additional protection in case the integrity of the drums should fail. It reduces the potential for long-term leaching by natural waters and serves as a radon diffusion barrier. The benefit will depend on the environment at the storage site. The wastes as generated have a very low solubility in water (i.e., are essentially insoluble), and contain only 1.4×10^{-1} μCi of ^{230}Th per gram (the ^{230}Th parent is the long-term source of ^{226}Ra and ^{222}Rn); thus the potential for leaching is low even if no treatment is applied. The benefit of cementing to reduce potential long-term radon releases will depend on the radon attenuation factor of the earth cover, which is a function of the thickness and the moisture content of the soil.¹ It is beyond the scope of this study to assess the off-site burial ground.

The principal radionuclides that contribute to the doses are ^{226}Ra , ^{230}Th , ^{238}U , and ^{234}U . Although ^{226}Ra and ^{230}Th represent only a small part of the total activity released, together they contribute 47% of the total-body dose, 70% of the bone dose, 28% of the lung dose, and 62% of the kidney dose from airborne effluents. Radium-226 alone contributes nearly 90% of the dose via aquatic pathways. There is considerable uncertainty in the amounts of ^{226}Ra and ^{230}Th entering UF_6 plants in the yellow cake, and in their movement within the plant (Sect. 4.0). Consequently, there is considerable uncertainty in the estimated ^{226}Ra and ^{230}Th source terms used in the dose estimates as well as in the amount of activity in the solid wastes. Radon is only a minor contributor to the airborne dose, that is, 1.6% of the lung dose and 0.2% of the total-body dose in Case 1. No radon treatment is provided in the case studies.

The effect of the case studies in reducing gaseous and liquid chemical releases is presented in Table 8.1 and Figs. 5.1 and 5.2. Although reduction of the radiological dose is the primary purpose of this study, chemical releases are also reduced to very low levels.

In Sects. 8.2-8.4, the total costs are separated into costs for treating the major waste streams, and these costs are correlated with a reduction in the amount of radioactive materials and/or chemicals released. Costs for common facilities such as a settling basin are prorated among the various systems that use the facility.

8.2 F-F Dust from Dry Materials Handling

The estimated cost/effectiveness of treating individual air streams used to control process dust from dry materials handling operations is shown in Table 8.6. Feed preparation is the largest single source, contributing roughly three-fourths of the uranium and half of the radium and thorium. Next in importance are UF_4 handling, which contributes about 18% of the uranium and 12% of the radium and thorium, and the ash handling associated with carbonate leaching, which contributes about one-fourth of the radium and thorium releases. Sampling and withdrawing ash from fluorination are smaller, but still significant, sources of radioactive particulates. It is more cost efficient to apply Case 2 treatment (i.e., secondary bag filters) to process dust control effluents prior to treatment of the building ventilation effluent.

8.3 F-F Process Off-Gases

8.3.1 F-F radioactive materials

Fluorination is the principal source of radioactive materials in the process off-gas, contributing about 80% of the U_{nat} and 95% of the ^{230}Th and ^{226}Ra in Case 1 (Table 8.7). Additional treatment of the fluorination stream will give almost as good dose reductions as treating all the process off-gas streams, but has little effect on the chemical releases. Treatment of the fluorination stream commands lower priority than treatment of the dust control streams in Table 8.6. In Case 4, most of the benefit comes from the fluorine cleanup reactor, the UF_6 cleanup reactor, and the HEPA filter. The studies assume that savings in fluorine and uranium recycle costs will be sufficient to cover the cleanup reactors once the technology becomes available. The annual cost for the condensers

used to remove HF from the fluorine prior to fluorination is estimated at \$57,000. These condensers have a negligible effect on the radiological releases and reduce the HF release by only 0.07 lb/day. Although they are probably not justified from an off-gas standpoint, they are instrumental in reducing the load to the liquid waste treatment system (Sect. 8.4.3).

Treating the UF₆ sampling and ash degassing stream is of marginal benefit since this stream carries little uranium and no ²³⁰Th or ²²⁶Ra.

Off-gases from reduction, hydrofluorination, and the fluorine cells carry negligible quantities of radioactive materials. Treatment beyond the base case is designed primarily to reduce chemical releases and is of little benefit radiologically.

8.3.2 F-F hydrogen fluoride

Fluorides are a matter of concern in the environment.² The most important effect appears to be fluorosis of cattle caused by ingestion of vegetable matter that has collected fluoride-containing dusts. In addition, many plants are susceptible to HF in concentrations as low as 0.02 to 0.05 ppm. Hydrofluorination and the fluorine cells are major sources of HF in the base case, contributing 42% and 53%, respectively, of the total released (Table 8.7). Hydrogen fluoride releases can be reduced from 88 lb/day to 4 lb/day by adding a KOH scrubber to each of these off-gas treatment systems at a total annual cost of about \$35,800. If another KOH scrubber is added to the fluorination stream, the HF release is further reduced to 1.3 lb/day at an annual cost of \$12,600. The condensers used in Case 4 to lower the HF concentrations in the process off-gases have an annual cost of \$32,000 more than the base-case condensers for hydrofluorination, and \$114,000 more than the base-case condensers for the fluorination and fluorine cell streams, which share a refrigeration unit. The more-efficient condensers reduce the HF release by only about 1 lb/day. Although condensers are not justified from an off-gas standpoint, they serve as a means of reducing the load to the liquid waste treatment systems (Sect. 8.4.3).

8.3.3 F-F hydrogen sulfide and sulfur dioxide

Hydrogen sulfide is a toxic, odiferous gas that can be readily detected by smell in concentrations as low as 0.0005 ppm.² It reacts with lead pigments, causing darkening of painted surfaces after prolonged exposure in humid atmospheres. The base case lowers H₂S releases to very low levels with wet scrubbers, but the waste scrub liquors are difficult to treat and are therefore a potential water pollution problem (Table 8.7, Sect. 8.4.4). In Cases 2 and 3, the H₂S is converted to SO₂ and released, thus avoiding the liquid waste problem except for a small water stream used to scrub particulates. There is a dollar cost saving in replacing Case 1 treatment with Case 2, but there is an environmental cost in the release of 1300 lb of SO₂ per day. Sulfur dioxide is an air pollutant known to cause respiratory irritation and damage to vegetation; however, the quantities released by the model F-F plant are modest compared with those associated with the combustion of coal in power plants (the pounds of SO₂ released per ton of coal burned equals 38 times the percentage of sulfur in the coal).² Case 4 includes a caustic scrubber to remove the SO₂ from the reduction off-gas. The cost shown in Table 8.7 is incomplete since it does not include the expense involved in treating the liquid waste generated by the scrubber.

8.3.4 F-F ammonia

Small gaseous releases of ammonia are generally considered to be relatively innocuous. In Cases 3 and 4, the elimination of ammonium and sodium ions from the plant feed reduces the ammonia release from 4000 lb/day to 130 lb/day (Table 8.7). This study did not attempt a detailed estimate of the cost to the mill operator of changing the chemical composition of the yellow cake; however, a very rough estimate based on data presented by Merritt³ and extrapolated to 1973 dollars is an annual cost increase of \$1,700,000, assuming new mills and no backfitting costs. This represents an increase of about 1% in the cost of mining and milling at an acid-leach mill and 3% at an alkaline-leach mill. It increases the capital cost of the mill alone by roughly 3% for an acid-leach mill and

8% for an alkaline-leach mill. This cost is not included in any of the summary tables since it is an expense incurred by the mill rather than the UF_6 plant. Wet scrubbers for ammonia in the F-F plant off-gas would convert a relatively innocuous airborne release into a more objectionable liquid waste problem. The ammonia is surplus to the UF_6 process and cannot be recycled.

8.4 F-F Liquid Wastes

In Case 1, radium contributes about 90% of the radiological dose from liquid effluents, and 95% of this radium comes from sodium removal (Sect. 7.0, Table 8.8). Carbonate leach is second with 4-1/2% of the radium. Treating fluoride and reduction scrub liquors is beneficial in reducing chemical releases but has a negligible effect on the radiological dose. There is considerable uncertainty in the radium source terms and, consequently, in the quantitative cost/benefit relations presented in Table 8.8. The following discussions show some of the intermediate steps between the case studies and include the costs of process changes in addition to the liquid treatment. This is to show features that would otherwise be masked by the variations in the feed to the liquid waste treatment systems.

8.4.1 F-F sodium removal

In Case 1, radium in the sodium removal effluent contributes about 85% of the total dose from all liquid effluents, while uranium contributes another 5%. This stream is also the source of ammonium salt, which is a matter of concern at some sites (i.e., the province of Ontario, Canada).⁴ The $BaCl_2$ precipitation of radium in the sodium removal waste (case increment 2/3) is effective and relatively inexpensive ($\$13/\mu Ci$ of ^{226}Ra) but has no effect on the chemical releases (Table 8.8). About 90% of the sodium removal waste is generated in processing fresh feed from the model alkaline-leach uranium mills; the remaining 10% is the result of scrap recovery operations. One method of reducing the sodium removal effluent is to eliminate $Na_2U_2O_7$ from the plant feed (hypothetical Case 2). The

annual cost to the alkaline-leach uranium mill operator of meeting new specifications is estimated as about \$550,000, which is equivalent to a waste treatment cost at the UF_6 plant of \$30 per microcurie of ^{226}Ra and \$100 per pound of NH_4^+ . The prorated annual cost of the Case 4 evaporator-dryer system and of packaging the residues for the sodium removal waste generated in scrap recovery is about \$87,000, or \$44 per microcurie of ^{226}Ra and \$120 per pound of NH_4^+ . However, this is not the total real cost since it does not include the expense of shipping the evaporator residues to the burial ground or of special burial, such as concrete or asphalt-lined storage to isolate these soluble salts from waters used by man. There is considerable uncertainty in the estimated source terms and, consequently, in the cost/benefit analysis.

8.4.2 F-F carbonate leach

Carbonate leaching is the second most important contributor to the dose from liquid effluents in Case 1, with 4.5% of the total radium ($\sim 4\%$ of the total dose) and about 20% of the uranium ($\sim 2\%$ of the total dose). In addition, the carbonate leach stream is the source of nearly 5000 lb of salts per day. A process change to regenerate and recycle the sodium carbonate leach solution with only a small bleed stream to waste will reduce the UF_6 plant releases of Na_2CO_3 by about 95%, the radium release by about 3.5%, and the uranium release by about 17%. The annual cost is estimated as \$94,000, or about \$120 per microcurie of ^{226}Ra and \$43 per pound of CO_3^{2-} (Table 8.8, Case 2). An added 0.3% of the radium can be removed by copperas treatment in Case 3 at an annual cost of \$10,000; however, this treatment is of marginal benefit radiologically and has no effect on chemical releases. The prorated share of the Case 4 evaporator-dryer system is costly and of marginal benefit radiologically to the carbonate leach stream. The value of reducing the Na_2CO_3 releases would depend on the characteristics of the receiving stream. There is considerable uncertainty in the estimated source terms and, consequently, in the cost/benefit analysis.

8.4.3 F-F fluoride scrub liquors

The concern with these wastes is primarily chemical since they have low concentrations of radioactive materials, especially radium. Although traces of fluoride are beneficial in drinking water, the upper limit for a public water supply is only 3 ppm.⁵ Chemical releases of caustic scrub liquors can be eliminated by a KOH regeneration system at an annual cost of \$142,000, and chemical releases via water scrub liquors can be reduced to low levels by lime treatment at an annual cost of \$156,000 (Table 8.8, Cases 2 and 3). Condensers and cleanup reactors on the process significantly reduce the cost of liquid fluoride treatment in Case 4. Since the condensers are of negligible benefit in terms of off-gas releases, the costs of the condensers are also shown as a liquid treatment cost in Case 4. The analysis indicates that, if Case 4 technology were available, the savings in the liquid treatment costs would justify the installation of the condensers. Added benefits are conservation of natural resources and less land permanently committed to solid waste disposal.

8.4.4 F-F reduction scrub liquors

These liquors have such low concentrations of radioactive materials that the treatment methods serve primarily to reduce chemical releases. The base case has a sizable liquid release of sulfide ions (Table 8.8). This stream is difficult to treat and is eliminated by a change in the off-gas treatment to a H₂ burner which also converts the H₂S to SO₂. The reduction scrub liquor in Case 2 has a low chemical content and contains only 0.2% of the total radium released in Case 1. There is no cost increase for the Case 2 reduction off-gas treatment, but there is a gaseous SO₂ release. The prorated annual cost of the Case 4 evaporator-dryer system for the water scrub liquor is \$15,900, and the benefits are marginal [Table 8.8, Case 4(3L)]. The Case 4 KOH scrubber to collect SO₂ generates a liquid waste which is not present in the earlier case studies. The annual cost of the KOH regeneration system for the SO₂ scrubber is \$96,300.

8.5 F-F Radon

There is a small release of ^{222}Rn gas (71.8 Ci/year) from the operating plant for which no treatment is provided.^a At 0.5 mile from the model midwestern plant, radon contributes only 2×10^{-5} mrem to the maximum individual total-body dose and 6×10^{-4} mrem to the lung dose (the critical organ). Because radon is a gas, it can spread beyond the immediate vicinity of the plant. The annual radon release from the model F-F UF_6 plant is comparable to the natural radon emanation from about 0.9 square mile (2.4 km^2) of ground or about $3 \times 10^{-5}\%$ of the radon release from soils in the conterminous United States.^b The half-life of radon is short (3.8 days), and the particulate daughters are removed from the atmosphere by deposition and washout. The average residence time is about 4 days for aerosols of radon daughters in the atmosphere near the earth's surface.⁷ In urban areas around New York City, even the short-lived daughters that contribute most of the radon dose are not in secular equilibrium with the natural background radon. For example, ^{218}Po , the first daughter (half-life, 3 min), is present in concentrations of about 80% of secular equilibrium, and ^{214}Pb , the second daughter (half-life, 27 min) at about 50% of secular equilibrium.⁸ These facts argue that the effects of radon from operating UF_6 plants will be small compared with the effects of natural background radon.

^aThere is also a small long-term release of radon from the decay of ^{226}Ra in the wastes that are shipped off-site to an approved repository for burial. Releases from the burial ground are not addressed in this study; however, they are expected to be small in comparison with the long-term radon release from mill tailings, which contain much more ^{226}Ra .

^bThe natural radon flux in the United States appears to be about $1.7 \text{ atoms/cm}^2 \cdot \text{sec}$ ($3.0 \times 10^{-5} \text{ Ci/m}^2 \cdot \text{year}$).⁶ If this value is assumed to represent the average rate, it is estimated that the conterminous United States ($7.6 \times 10^{12} \text{ m}^2$ in area) releases $2.3 \times 10^{18} \text{ Ci}$ of ^{222}Rn annually.

8.6 References

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Table 1.1. Summary of radwaste treatment variables for the model fluorination-fractionation UF₆ conversion plant

	Case 1	Case 2	Case 3	Case 4
<u>Gaseous and Airborne Radwaste</u>				
Objective	Base case; control uranium losses and release of radium and noxious gases	Reduce uranium and radium releases by 2.5; reduce HF release by 70.	Reduce uranium and radium releases in building ventilation effluent by 14 (net overall reduction, 8); reduce ammonia release by 30	Reduce uranium and radium releases by 3000; reduce HF release by 700; reduce SO ₂ release by 50 compared with Cases 2 and 3
Treatment	Primary bag filters on dust-bearing air from materials handling processes; primary and secondary filters on chemical reactors; primary and secondary scrubbers on HF- and H ₂ S-bearing effluents	Same as Case 1 plus secondary bag filters; tertiary scrubbers on HF-bearing effluents; burn sulfide to SO ₂ and release	Same as Case 2 plus water baffle scrubbers on building ventilation effluent; exclude ammonium and sodium salts from the feed	Same as Case 3 plus HEPA filters on process effluents; more efficient HF condensers; F ₂ cleanup reactor; UF ₆ cleanup reactor; SO ₂ scrubber
<u>Liquid Radwaste</u>				
Objective	Release untreated waste	Reduce chemical releases; eliminate the release of sulfide and sulfur; reduce fluoride release by 300; reduce potassium salt release by 40; reduce sodium salt release by 2.5; reduce uranium release by 1.7	Reduce radium release by 275; reduce sodium salt release by 16; reduce ammonium salt release by 9; reduce uranium release by 10	Zero release to surface streams of liquid waste bearing radioactive materials and negligible release of chemicals from the process; decrease the amount of fluoride waste generated
Treatment	Settle in lined lagoon to recover uranium; supernate diluted with 10 parts water in equalization and released	Eliminate sulfide scrubbers on reduction off-gas; lime regeneration and recycle of KOH scrub liquors; CO ₂ regeneration and recycle of Na ₂ CO ₃ leach solution; precipitate fluoride from water scrub liquors with lime; settle solids in lined basin; combine supernate with waste from sodium removal and bleed stream from carbonate leach; adjust pH; dilute combined process wastes with 10 parts of water and release	Same as Case 2, plus precipitate radium in sodium removal waste with BaCl ₂ ; precipitate radium in carbonate leach bleed with ferrous sulfate; reduce salt and uranium releases by excluding sodium from the feed	Same as Case 2, plus evaporate liquid waste from sodium removal, carbonate leach liquid bleed, and water reduction scrubber; recycle purified water; reduce evaporator load by excluding sodium from the feed; make provisions for more efficient use of F ₂ and HF in plant to reduce fluoride load to waste treatment system; lime precipitate CaSO ₃ ·1/2H ₂ O and recycle KOH to caustic reduction scrubber; treat water scrub liquor from fluorine cell off-gas with lime, adjust pH, and release (no radioactive materials); condense hydrofluoric acid and release for industrial use (very low in radioactive materials)
<u>Solid Radwaste</u>				
Fluorination ash				
Objective	Recover uranium and dispose of residue	Same as Case 1	Same as Case 1	Reduce potential for long-term leaching and radon release
Treatment	Leach ash to recover uranium, dry, and drum ready for shipment off-site	Same as Case 1	Same as Case 1	Leach ash to recover uranium, and incorporate moist filter cake in cement; drum ready for shipment off-site
Distillation residues				
Objective	Store pending future processing	Same as Case 1	Same as Case 1	Same as Case 1
Treatment	Store in sealed containers	Same as Case 1	Same as Case 1	Same as Case 1
Solids generated by liquid waste treatment				
Objective	Not applicable	Store very-low-level chemical waste on-site	Store very-low-level chemical wastes on-site; prepare radium wastes for shipment off-site	Store very-low-level chemical wastes on-site; prepare evaporator residues for shipment off-site
Treatment	Not applicable	Settle CaF ₂ solids from treating water scrub liquors in lined basin; store CaF ₂ -CaCO ₃ filter cakes from KOH regeneration and carbonate leach circuit in lined basin	Same as Case 2, plus settle radium precipitation solids in lined basin; dry and drum radium precipitates ready for shipment	Dry and drum evaporator residues ready for shipment; store CaSO ₃ filter cake in lined sulfite basin; store slightly contaminated CaF ₂ -CaCO ₃ in lined fluoride pit; settle uncontaminated CaF ₂ from treating water scrub liquors from the fluorine cells in the lined fluoride basin (i.e., three lined storage basins in Case 4)

Table 4.1. Uranium refining and hexafluoride production

Plant	Location	Sampling	"Dry" purification - fractional distillation	"Wet" purification								UO ₃ re- duction to UO ₂	UO ₂ hydro- fluorination to UF ₄	Fluorin- ation to UF ₆	Enriched UF ₆ from enriched scrap or recycle	UF ₄ reduc- tion to U metal		Hydrolysis of enriched UF ₆ to UO ₂	Conversion of enriched UO ₂ to U metal
				Solvent extraction			Denitration									Magnesium	Calcium		
				TBP-hexane	TBP-kerosene	TBP-dodecane	Stirred pot (batch)	Stirred trough (continuous)	Fluidized bed	Rotary tube calciner	ADU (ammonium diuranate ppt and calcination)								
Allied Chemical	Metropolis, Ill.	a	a																
Kerr-McGee	Sequoyah County, Okla.	b		b	b			b											
ERDA-Fernald	Cincinnati, Ohio	c		c	c		d						d				d		
ERDA-Paducah	Kentucky	e									f		g						
ERDA-Portsmouth (20 metric ton/year)	Ohio	h								h				h					
AEC-Weldon Spring (closed)	Missouri	e		i	i		i				i			i			i		
Eldorado	Canada	e		j	j		k			j	j		j				j		j
Malvesi	France	l		l			l			l	m		m				l		
Springfields	Great Britain	n		n	n			o		p	o		o				p		p

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Table 4.2. Feed to the model yellow-cake-to-UF₆ conversion plant -
Cases 1 and 2^a

(Assumptions listed in Table 4.3)

Constituent of feed	Concentration (wt %)	Quantity fed (metric tons/year)
Uranium (U)	73.53	10,000
	(wt %, U basis)	
Impurities		
Ammonium (NH ₄ ⁺) ^a	3.09	420
Sodium (Na) ^a	2.41	329
Silica (SiO ₂)	1.2	163
Sulfate (SO ₄ ²⁻)	2.94	400
Arsenic (As)	0.06	8
Boron (B)	0.003	0.4
Calcium (Ca)	0.19	26
Carbonate (CO ₃ ²⁻)	0.31	42
Chloride, bromide, iodide (Cl ⁻ , Br ⁻ , I ⁻) calc. as Cl ⁻	0.07	10
Fluoride (F ⁻)	0.01	1
Iron (Fe)	0.38	52
Molybdenum (Mo)	0.10	14
Phosphate (PO ₄ ³⁻)	0.26	35
Potassium (K)	0.13	18
Vanadium (V)	0.12	16
Water (H ₂ O)	1.91	260
Extractable organics	0.05	7
Nitric acid-insoluble uranium	0.01	1

Principal radionuclides		(Ci/year)
U _{nat} ^b		3333
²³⁴ Th		3333
^{234m} Pa ^c		3333
²³⁰ Th		141.7
²²⁶ Ra		15.67
²²² Rn		15.67

^aSodium and ammonium ions are excluded from the feed in Cases 3 and 4 because they create difficulties in the advanced waste treatment systems.

^bThe "old" (prior to July 10, 1974) definition of a curie of natural uranium (U_{nat}) is used throughout this report to be consistent with the earlier report in this series on uranium mills. One curie of U_{nat} is the sum of 3.7×10^{10} dis/sec from ²³⁸U, plus 3.7×10^{10} dis/sec from ²³⁴U, plus 9×10^8 dis/sec from ²³⁵U. Under the "old" definition 1 kg of U_{nat} is equivalent to 333.3 μ Ci of U_{nat} or the sum of 333.3 μ Ci of ²³⁸U, 333.3 μ Ci of ²³⁴U, and 8.1 μ Ci of ²³⁵U. Under the current (July 10, 1974) definition 1 kg of U_{nat} is equivalent to 677.0 μ Ci of U_{nat}, or the sum of 330.9 μ Ci of ²³⁸U, 330.9 μ Ci of ²³⁴U, and 15.4 μ Ci of ²³⁵U. There is approximately a 1% difference between the "old" and the "new" curie in calculating source terms, except for ²³⁵U.

^cMetastable ^{234m}Pa, $t_{1/2} = 1.18$ min.

Table 4.3. Assumptions used in calculating feed to the model yellow-cake-to-UF₆ conversion plant

1. The feed is the composite product of the "model" uranium mills,^a i.e.:
 - 85% of the feed is acid-leached yellow cake which has been purified by amine solvent extraction, precipitated by addition of ammonia, and steam dried.
 - 15% of the feed is alkaline (carbonate)-leached yellow cake which has been precipitated with sodium hydroxide and dried.
 - The proportion of acid- vs alkaline-leached yellow cake was calculated from the relative ore processing rates, based on a survey of active mills made in the spring of 1973.^b
2. The acid-leached yellow cake is a partially cracked ammonium diuranate. Half the uranium is assumed to be present as (NH₄)₂U₂O₇ and the other half as UO₃. Its chemical composition is:
 - U = 74.20 wt % (av of ammonium diuranate received at the Kerr-McGee UF₆ plant in 1973)^c
 - Na = 0.85 wt % on a U basis (av of ammonium diuranate received at the Kerr-McGee UF₆ plant in 1973)^c
 - NH₄⁺ = 3.63 wt % on a U basis (calculated)
3. Alkaline (carbonate)-leached yellow cake is assumed to be Na₂U₂O₇ with a chemical composition of:
 - U = 69.80 wt % (av of Na₂U₂O₇ received at the Kerr-McGee UF₆ plant in 1973)^c
 - Na = 11.3 wt % on a U basis
4. Impurities other than radionuclides, sodium, ammonium, and silica are the average of the current feeds to the Allied Chemical UF₆ plant,^d the Kerr-McGee UF₆ plant,^c and the ERDA-Fernald refinery.^e
5. The silica content is the average of values for four currently or recently active mills (Anaconda, Uravan, Rifle, and Kerr-McGee).^f
6. The model UF₆ plant processes only virgin yellow cake (natural uranium) from United States mills (i.e., no recycle material from fuel reprocessing and no foreign ore concentrates).
7. The radioactive impurities in freshly milled yellow cake are the same as those used in the milling report^a (loc. cit., pp. 32, 34, and 164), i.e.:
 - Acid-leached yellow cake
 - ²³⁰Th = 5% of U_{nat} activity
 - ²²⁶Ra = 0.2% of U_{nat} activity
 - Alkaline (carbonate)-leached yellow cake
 - ²³⁰Th = negligible
 - ²²⁶Ra = 2% of U_{nat} activity
 - Composite yellow cake (calculated from above)
 - ²³⁰Th = 4.25% of U_{nat} activity
 - ²²⁶Ra = 0.47% of U_{nat} activity
8. The yellow cake feed has aged 6 months (minimum) to 10 years (maximum) since milling in a sealed drum so that:
 - (a) Thorium-234 (t_{1/2} = 24.1 days) and ^{234m}Pa (t_{1/2} = 1.18 min) daughters have grown back to secular equilibrium with ²³⁸U. Thorium-234 requires 168 days to grow back to 99% of secular equilibrium with ²³⁸U. Metastable ^{234m}Pa requires approximately 7 min to grow back to secular equilibrium with ²³⁴Th, so that it is in secular equilibrium with ²³⁴Th at all times.
 - (b) The radioactivity due to the decay, since milling, of ²³⁴U to ²³⁰Th (t_{1/2} = 8.3 x 10⁴ y and ²³⁸U (only 0.71% of natural uranium) is negligible.
 - (c) The radioactivity due to the decay, since milling, of the ²³⁰Th impurity to ²²⁶Ra (t_{1/2} = 1.62 x 10³ y) is negligible.

Table 4.3 (continued)

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- (d) The ^{222}Rn daughter ($t_{1/2} = 3.83$ days) has grown back to secular equilibrium with the ^{226}Ra impurity. While the amount of ^{222}Rn accumulating in the sealed drum is small, radon is an inert gas and potentially all of it might be released from the plant.
- (e) The daughter products of ^{222}Rn are not listed individually as source terms either because they have half-lives of less than 2 hr and do not accumulate in the bioenvironment (^{218}Po , ^{214}Pb , ^{214}Bi , and ^{214}Po) or because they individually contribute less than 0.02% of the total relative hazard (^{210}Pb , ^{210}Bi , and ^{210}Po). The daughters of ^{222}Rn are included when the dose from radon release is calculated. The relative hazard is estimated by dividing the curies present in the yellow cake feed by the Radiation Concentration Guide for that nuclide (presented in Code of Federal Regulations, Title 10, Part 20, Appendix B, Table 2, Column 1, soluble nuclide). It takes approximately 11.6 years for ^{210}Pb to grow back to a level where it contributes 0.02% of the total relative hazard.
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^aM. B. Sears, R. E. Blanco, R. C. Dahlman, G. S. Hill, A. D. Ryon, and J. P. Witherspoon, Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing "As Low As Practicable" Guides - Milling of Uranium Ores, ORNL-TM-4903, Vol. 1 (May 1975).

^bIbid., p. 224.

^cB. Brown (Plant Manager, Kerr-McGee Sequoyah UF_6 production facility) and J. Craig (Engineering Manager), personal communication to M. B. Sears, Oct. 15, 1974.

^dA. D. Riley (Plant Manager, Allied Chemical UF_6 plant) and J. H. Thomas (Technical Superintendent), personal communication to M. B. Sears, Nov. 13, 1974.

^eJ. Cavendish (Head, Production Technology Dept., National Lead Co. of Ohio), personal communication to M. B. Sears, Nov. 12, 1974.

^fG. P. Lang, E. N. Nelson, and C. W. Kuhlman, A Process for Controlling Insoluble Uranium in Ore Concentrates, MCW-1420, Mallinkrodt Chemical Works (Feb. 2, 1959), p. 13.

Table 4.4. Efficiency of noxious gas absorbers

Type of gas absorber	Gas absorbed	Scrubbing medium	Efficiency (%)
Baffle (orifice) with condensers	Denitrator off-gas	40% HNO ₃	~70 ^a
Spray tower	H ₂ S-S	Water	50 ^b
	UF ₆	KOH	80 ^b
	HF	KOH	80 ^{c,d}
	F ₂	KOH	80 ^{c,d}
Wetted packed tower	UF ₆	KOH	99 ^b
	HF	KOH	99 ^{c,d}
	F ₂	KOH	99 ^{c,d}
Medium-energy venturi	HF	Water	90 ^b
High-energy venturi	HF	Water	95 ^e
	HNO ₃	Water	97 ^e
	NO ₂	Water	30 ^e
	HF	KOH	99 ^f
	H ₂ S	KOH	85 ^{b,e}
	SO ₂	KOH	98 ^e
KOH coke box	UF ₆		90 ^{g,h}
	HF		90 ^{g,h}
	F ₂		90 ^{g,h}
NO _x absorber tower (20-plate bubble tower)	NO _x	Water	95 ⁱ

^aKerr-McGee Corporation, Applicants Environmental Report Sequoyah Uranium Hexafluoride Production Plant, DOCKET 40-8027 (June 1972), pp. 40-51.

^bA. D. Riley (Manager, Allied Chemical UF₆ plant), J. H. Thomas (Technical Superintendent), and R. W. Yates (Health Physicist), personal communication to M. B. Sears, Nov. 13, 1974.

^cBy analogy to UF₆.

^dBy analogy to HCl. (S. K. Kempner, E. N. Seiler, and D. H. Bowman, *J. Air Pollution Control Assoc.* 20(3), 139-43 (1970).

^eL. S. Harris, *Chem. Eng. Progr.* 62(4), 55-59 (April 1966).

^fBy analogy to caustic scrubbing of Cl₂ (footnote e).

^gEfficiency when used as tertiary scrubber in a train.

^hDowngraded efficiency of proprietary technology from 99.9% (footnote b) to 90% because it is not in the public domain.

ⁱB. J. Mayland and R. C. Heinze, *Chem. Eng. Progr.* 69(5), 75-76 (May 1973).

Table 4.5. Efficiency of wet dust collectors^{a,b}

Type of dust collector	Average pressure drop (in. H ₂ O)	Efficiency (%) on:		
		5- μ dust	2- μ dust	1- μ dust
Baffle (orifice)	6.1	93	75	40
Spray tower	1.4	94	87	55
Packed tower (fluidized bed)	2.4	95		58
Wet impingement	6.1	97	95	80
Venturi				
Medium energy	20.0	99.8	99	97
High energy	31.5	99.9		98

^aC. J. Stairmand, "Removal of Dust from Gases," pp. 364-402 in Processes for Air Pollution Control, 2nd ed., The Chemical Rubber Co., Cleveland, Ohio, 1972.

^bC. J. Stairmand, The Chemical Engineer 194, CE 310-26 (December 1965).

Table 4.6a. Airborne radwaste releases from the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant - Case 1

Type of release	U (kg/yr)	Principal radionuclides (Ci/yr)					
		U _{nat} ^a	²³⁴ Th	^{234m} Pa ^b	²³⁰ Th	²²⁶ Ra	²²² Rn ^c
<u>Crude uranium dusts -</u> (yellow cake, UO ₃ , UO ₂ , UF ₄)							
Materials handling	403.4	1.34E-1	1.34E-1	1.34E-1	5.71E-3	6.32E-4	
Reduction off-gas	0.05	1.66E-5	1.66E-5	1.66E-5	7.07E-7	7.83E-8	
Hydrofluorination off-gas	<0.10	<3.3 E-5	<3.3 E-5	<3.3 E-5	<1.4 E-6	<1.6 E-7	
Building ventilation	165.1	5.50E-2	5.50E-2	5.50E-2	2.32E-3	2.57E-4	
<u>Refined UF₆ hydrolysis products and fluorination off-gas dust</u>							
	93.6	3.12E-2	9.42E-4	9.42E-4	4.00E-5	4.44E-6	
<u>Ash dust</u>							
Before decay							
Materials handling	0.71	2.38E-4	1.32E-2	1.32E-2	5.61E-4	6.20E-5	
Building ventilation	0.29	9.65E-5	5.36E-3	5.36E-3	2.28E-4	2.52E-5	
After decay							
Materials handling							
Before leaching	0.71	2.38E-4	2.38E-4	2.38E-4	5.61E-4	6.20E-5	
After leaching	0.003	1.00E-6	7.12E-4	7.12E-4	1.68E-3	1.86E-4	
Building ventilation	0.39	1.29E-4	3.86E-4	3.86E-4	9.13E-4	1.10E-4	
<u>Radon gas</u>							
Sampling							1.63E+1
Yellow cake storage							8.1 E-6
Main UF ₆ conversion							2.95E+1
Ash storage							3.2 E-6
Ash leaching							2.60E+1
Total	664.2	2.21E-1	2.15E-1	2.15E-1	1.21E-2	1.35E-3	7.18E+1

^aOne curie of natural uranium is defined as the sum of 3.7 x 10¹⁰ dis/sec from ²³⁸U, 3.7 x 10¹⁰ dis/sec from ²³⁴U, and 9 x 10⁹ dis/sec from ²³⁵U; it is also equivalent to 3000 kg of natural uranium.

^bMetastable ^{234m}Pa, t_{1/2} = 1.18 min.

^cAs gas. Does not include ²²²Rn generated in dust particles by decay of ²²⁶Ra.

Table 4.6b. Airborne radwaste releases from the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant - Case 2

Type of release	U (kg/yr)	Principal radionuclides (Ci/yr)					²²² Rn ^c
		U _{nat} ^a	²³⁴ Th	^{234m} Pa ^b	²³⁰ Th	²²⁶ Ra	
<u>Crude uranium dusts -</u> (yellow cake, UO ₃ , UO ₂ , UF ₄)							
Materials handling	56.6	1.89E-2	1.89E-2	1.89E-2	8.02E-4	8.87E-5	
Reduction off-gas	0.28	9.33E-5	9.33E-5	9.33E-5	3.96E-6	4.37E-7	
Hydrofluorination off-gas	<0.10	<3.3 E-5	<3.3 E-5	<3.3 E-5	<1.4 E-6	<1.7 E-7	
Building ventilation	165.1	5.50E-2	5.50E-2	5.50E-2	2.32E-3	2.57E-4	
<u>Refined UF₆ hydrolysis products and fluorination off-gas dust</u>							
	27.4	9.13E-3	4.71E-4	4.71E-4	2.00E-5	2.22E-6	
<u>Ash dust</u>							
Before decay							
Materials handling	0.10	3.40E-5	1.89E-3	1.89E-3	8.01E-5	8.86E-6	
Building ventilation	0.29	9.65E-5	5.36E-3	5.36E-3	2.28E-4	2.52E-5	
After decay							
Materials handling							
Before leaching	0.10	3.40E-5	3.40E-5	3.40E-5	8.01E-5	8.86E-6	
After leaching	<0.01	1.43E-7	1.02E-4	1.02E-4	2.40E-4	2.66E-5	
Building ventilation	0.39	1.29E-4	3.86E-4	3.86E-4	9.13E-4	1.10E-4	
<u>Radon gas</u>							
Total	250.3	8.33E-2	8.22E-2	8.22E-2	4.69E-3	5.28E-4	7.18E+1

^aOne curie of natural uranium is defined as the sum of 3.7×10^{10} dis/sec from ²³⁸U, 3.7×10^{10} dis/sec from ²³⁴U, and 9×10^8 dis/sec from ²³⁵U; it is also equivalent to 3000 kg of natural uranium.

^bMetastable ^{234m}Pa, $t_{1/2} = 1.18$ min.

^cAs gas. Does not include ²²²Rn generated in dust particles by decay of ²²⁶Ra.

Table 4.6c. Airborne radwaste releases from the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant - Case 3

Type of release	U (kg/yr)	Principal radionuclides (Ci/yr)					
		U _{nat} ^a	²³⁴ Th	^{234m} Pa ^b	²³⁰ Th	²²⁶ Ra	²²² Rn ^c
<u>Crude uranium dusts -</u> (yellow cake, UO ₃ , UO ₂ , UF ₄)							
Materials handling	56.6	1.89E-2	1.89E-2	1.89E-2	8.02E-4	8.87E-5	
Reduction off-gas	0.28	9.33E-5	9.33E-5	9.33E-5	3.96E-6	4.37E-7	
Hydrofluorination off-gas	<0.10	<3.3 E-5	<3.3 E-5	<3.3 E-5	<1.4 E-6	<1.7 E-7	
Building ventilation	11.5	3.83E-3	3.83E-3	3.89E-3	1.63E-4	1.80E-5	
<u>Refined UF₆ hydrolysis products and fluorination off-gas dust</u>							
	8.3	2.77E-3	4.71E-4	4.71E-4	2.00E-5	2.22E-6	
<u>Ash dust</u>							
Before decay							
Materials handling	0.10	3.40E-5	1.89E-3	1.89E-3	8.01E-5	8.86E-6	
Building ventilation	0.02	6.76E-6	3.75E-4	3.75E-4	1.60E-5	1.76E-6	
After decay							
Materials handling							
Before leaching	0.10	3.40E-5	3.40E-5	3.40E-5	8.01E-5	8.86E-6	
After leaching	<0.01	1.43E-7	1.02E-4	1.02E-4	2.40E-4	2.66E-5	
Building ventilation	0.03	9.03E-6	2.70E-5	2.70E-5	6.39E-5	7.07E-6	
<u>Radon gas</u>							
Total	77.0	2.57E-2	2.57E-2	2.57E-2	1.47E-3	1.62E-4	7.18E+1

^aOne curie of natural uranium is defined as the sum of 3.7×10^{10} dis/sec from ²³⁸U, 3.7×10^{10} dis/sec from ²³⁵U, and 9×10^8 dis/sec from ²³⁴U; it is also equivalent to 3000 kg of natural uranium.

^bMetastable ^{234m}Pa, $t_{1/2} = 1.18$ min.

^cAs gas. Does not include ²²²Rn generated in dust particles by decay of ²²⁶Ra.

Table 4.6d. Airborne radwaste releases from the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant - Case 4

Type of release	U (kg/yr)	Principal radionuclides (Ci/yr)					²²² Rn ^c
		U _{nat} ^a	²³⁴ Th	^{234m} Pa ^b	²³⁰ Th	²²⁶ Ra	
<u>Crude uranium dusts -</u> (yellow cake, UO ₃ , UO ₂ , UF ₄)							
Materials handling	3.07E-2	1.02E-5	1.02E-5	1.02E-5	4.34E-7	4.79E-8	
Reduction off-gas	7.00E-5	2.33E-8	2.33E-8	2.33E-8	9.90E-10	1.10E-10	
Hydrofluorination off-gas	<5.0 E-5	<1.6 E-8	<1.6 E-8	<1.6 E-8	<7.0 E-10	<8.5 E-11	
Building ventilation	1.71E-1	5.70E-5	5.70E-5	5.70E-5	2.42E-6	2.68E-7	
<u>Refined UF₆ hydrolysis products and fluorination off-gas dust</u>							
	2.9 E-4	9.67E-8	2.36E-7	2.36E-7	1.00E-9	1.11E-10	
<u>Ash dust</u>							
Before decay							
Materials handling	5.0 E-5	1.70E-8	9.45E-7	9.45E-7	4.00E-8	4.43E-9	
Building ventilation	2.9 E-4	9.65E-8	5.36E-6	5.36E-6	2.28E-7	2.52E-8	
After decay							
Materials handling							
Before leaching	5.0E-5	1.70E-8	1.70E-8	1.70E-8	4.00E-8	4.43E-9	
After leaching	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
Building ventilation	3.9 E-4	1.29E-7	9.65E-8	9.65E-8	2.28E-7	2.52E-8	
<u>Radon gas</u>							
Total	2.0 E-1	6.76E-5	7.28E-5	7.28E-5	3.39E-6	3.75E-7	7.18E+1

^aOne curie of natural uranium is defined as the sum of 3.7×10^{10} dis/sec from ²³⁸U, 3.7×10^{10} dis/sec from ²³⁴U, and 9×10^9 dis/sec from ²³⁵U; it is also equivalent to 3000 kg of natural uranium.

^bMetastable ^{234m}Pa, $t_{1/2} = 1.18$ min.

^cAs gas. Does not include ²²²Rn generated in dust particles by decay of ²²⁶Ra.

n.a. = not applicable.

Table 4.7. Airborne chemwaste releases from the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant

Source	Code	Principal chemicals (lb/day)				
		NH ₃	H ₂ S	SO ₂	HF	H ₂
<u>Case 1</u>						
Feed preparation	2c	3.95E+3				
Reduction	3A		5.74E-1			4.41E+2
Hydrofluorination	4A				3.70E+1	
Fluorine cell H ₂ off-gas	7A				4.70E+1	
Fluorination	8A				4.17E00	
Sodium removal	11A	<u>9.64E+1</u>				
Total		3.96E+3	5.74E-1	-	8.82E+1	4.41E+2
<u>Case 2</u>						
Feed preparation	2c	3.95E+3				
Reduction	3A			1.30E+3		
Hydrofluorination	4A				3.70E-1	
Fluorine cell H ₂ off-gas	7A				4.70E-1	
Fluorination	8A				4.17E-1	
Sodium removal	11A	<u>9.64E+1</u>				
Total		3.96E+3	-	1.30E+3	1.26E00	-
<u>Case 3</u>						
Feed preparation	2c	1.19E+2				
Reduction	3A			1.30E+3		
Hydrofluorination	4A				3.70E-1	
Fluorine cell H ₂ off-gas	7A				4.70E-1	
Fluorination	8A				4.17E-1	
Sodium removal	11A	<u>1.21E+1</u>				
Total		1.31E+2	-	1.30E+3	1.26E00	-
<u>Case 4</u>						
Feed preparation	2c	9.70E+1				
Reduction	3A			2.59E+1		
Hydrofluorination	4A				3.70E-2	
Fluorine cell H ₂ off-gas	7A				1.88E-2	
Fluorination	8A				7.21E-2	
Sodium removal	11A	<u>1.01E+1</u>				
Total		1.07E+2	-	2.59E+1	1.28E-1	-

Table 4.8. Airborne radwaste treatment systems for the model fluorination-fractionation UF₆ plant^a
(Efficiencies given in parentheses)

Source	Principal contaminant removed	Case 1, base plant	Case 2	Case 3	Case 4
Sampling plant	Particulates	Bag filter (99.9%) ^b	Case 1 plus secondary bag filter (86%) ^c	Same as Case 2	Case 2 plus HEPA filter (99.95%) ^{d,e}
Feed preparation	Particulates	Bag filter (99.9%) ^b	Case 1 plus secondary bag filter (86%) ^c	Same as Case 2	Case 2 plus HEPA filter (99.95%) ^{d,e}
	NH ₃	None	None	None	None
Reduction	Particulates	Primary 10-μ sintered stainless steel filter; secondary 10-μ sintered stainless steel filter	Same as Case 1	Same as Case 1	Case 1 plus HEPA filter (99.95%) ^{d,e}
	H ₂ S, S	Water spray tower (H ₂ S, 50% ^f ; particulates, 90% ^g); KOH, high-energy venturi scrubber (H ₂ S, 85% ^h ; particulates, 96% ⁱ); KOH-packed tower (H ₂ S, 99% ^j ; particulates, 0% ^k)	H ₂ burner; water, high-energy venturi scrubber-condenser and demister (particulates, 99.0% ^l ; SO ₂ , 10% ^m)	Same as Case 2	Case 2 plus KOH high-energy venturi scrubber (SO ₂ , 98% ⁿ ; particulates, 50% ^o)
Hydrofluorination	Particulates	Primary porous carbon filter; secondary porous carbon filter	Same as Case 1	Same as Case 1	Case 1 plus HF-resistant HEPA filter (99.95%) ¹ after HF removal
	HF	Water, medium-energy venturi scrubber-condenser (HF, 90% ^m ; particulates, 90% ⁿ); KOH, medium-energy venturi scrubber (HF, 85% ^o ; particulates, 50% ^k)	Case 1 plus KOH packed tower (HF, 99% ^p ; particulates, 0% ⁿ)	Same as Case 2	Water-cooled and brine-cooled HF condenser (HF, 99% for system ^q ; particulates, 90% ^m); KOH packed tower (HF, 99% ^r ; particulates, 50% ⁿ); KOH coke box (HF, 90% ^s ; particulates, 0% ^k)
Fluorination	Particulates	Primary 10-μ sintered nickel filters; secondary 10-μ sintered nickel filters	Same as Case 1	Same as Case 1	Case 1 plus HF-resistant HEPA filter (99.95%) ¹ after UF ₆ , F ₂ , and HF removal
	UF ₆ product	Cold traps, 0°F and -50°F (effluent is 0.08 vol % UF ₆ ^s ; particulates, 95% ⁿ)	Same as Case 1	Same as Case 1	Same as Case 1
	UF ₆ , F ₂ , HF	Condenser, 0° to -15°F on F ₂ cells to reduce HF impurity fed to system (27% ^v); KOH spray tower (HF, 80% ^w ; particulates, 99% ^r); wet scrubbing system (particulates, 80% ⁿ)	Case 1 plus KOH coke box (HF, 90% ^t ; particulates, 50% ⁿ)	Same as Case 2	-120°F condenser on F ₂ cell to reduce HF impurity in F ₂ fed to system (65% ^u); F ₂ cleanup reactor followed by 10-μ sintered nickel filters and UF ₆ cold traps at 0°F and -50°F (95% for system ^v); UF ₆ cleanup reactor followed by filters (effluent contains 20 ppm of UF ₆); ^w KOH spray tower (HF, 80% ^r); ^x KOH packed tower (HF, 99% ^r ; particulates, 50% ⁿ); ^y KOH coke box (HF, 90% ^s); wet scrubbing system (particulates, 90% ⁿ)
Main plant solids handling-transfer points, screws, packing gland seals, ash handling, etc.	Particulates	Bag filters (99.9%) ^b	Case 1 plus secondary bag filter (86%) ^c	Same as Case 2	Case 2 plus HEPA filter (99.95%) ^{d,e}
Vacuum-cleaner system	Particulates	Cleaner bag; bag filter (99.9%) ^b	Case 1 plus secondary bag filter (86%) ^c	Same as Case 2	Case 2 plus HF-resistant HEPA filter (99.95%) ¹
UF ₆ sampling	UF ₆	None (vented through vacuum-cleaner system)	None	KOH high-energy venturi scrubber and demister (99%) ^x	Case 3 plus HF-resistant HEPA filter (99.95%) ¹
Carbonate leach (scrap recovery)	Particulates	Bag filter (99.9%) ^b	Case 1 plus secondary bag filter (86%) ^c	Same as Case 2	Case 2 plus HEPA filters (99.95%) ^{d,e}
F ₂ cell H ₂ off-gas	HF	Condenser, 0° to -15°F (27% ^v); H ₂ burner; water, medium-energy venturi scrubber-condenser and demister (90% ^m)	Case 1 plus KOH packed tower (99%) ^t	Same as Case 2	Fluorination process change - less HF to treat (8.6% ^z); condenser, -120°F (65% ^u); water, medium-energy venturi scrubber-condenser (90% ^w); KOH-packed tower (99% ^r ; particulates, 50% ⁿ); ^y KOH coke box (90% ^s)
Building ventilation effluent	Particulates	None	None	Baffle (orifice) water scrubbers (93%) ^b	Bag filter (99.9%) ^b

^aBag filter refers to pulse-jet type in all case studies.

^bAssumes that uranium dusts behave as typical industrial dusts; efficiency given by C. J. Stairmand, "Removal of Dust from Gases," pp. 398-99 in *Processes for Air Pollution Control*, ed. by G. Nonhebel, Chemical Rubber Co., Cleveland, Ohio, 1972.

^cAssumes that under industrial conditions a system of a primary bag filter backed by a second bag filter will achieve the efficiency of a single unit operation under optimum conditions (i.e., no leaky seals or holes in the bag) of 99.986% reported by K. J. Caplan and M. G. Mason, "Efficiency of Reverse-Jet Filters on Uranium Refining Operations," pp. 77-85 in *Air Cleaning Seminar, Ames Laboratory, September 15-17, 1952*, WASH-149 (March 1954). The second bag filter collects any dust which leaks through the first one; this ordinarily amounts to relatively little material.

^dC. A. Burchsted and A. B. Fuller, *Design, Construction and Testing of High Efficiency Air Filtration Systems for Nuclear Application*, ORNL-NSIC-65 (January 1970), p. 3.1.

^eTested periodically with dioctyl phthalate.

^fR. Yates (Health Physicist, Allied Chemical Corporation Metropolis Plant), personal communications to M. B. Sears, Nov. 13, 1974, and Dec. 10, 1974.

^gParticulates passing the 10-μ sintered metal filters were assumed to have an average particle size of 2 μ; efficiency of wet scrubbers on 2-μ particles was obtained from C. J. Stairmand, "Processes for Air Pollution Control," p. 365 in *Processes for Air Pollution Control*, ed. by G. Nonhebel, Chemical Rubber Co., Cleveland, Ohio, 1972, and C. J. Stairmand, *The Chemical Engineer* 194, CE 315 (December 1965).

^hL. S. Harris, *Chem. Eng. Progr.* 62(4), 55-59 (1966).

ⁱParticulates passing the spray tower and reaching the venturi are assumed to have an average particle size of 1 μ (C. J. Stairmand, p. 390 in *Processes for Air Pollution Control*, ed. by G. Nonhebel, Chemical Rubber Co., Cleveland, Ohio, 1972); efficiency of venturi on 1-μ particles was obtained from C. J. Stairmand, *The Chemical Engineer* 194, CE 315 (December 1965). A venturi followed by a packed tower was assumed to be equivalent to a venturi followed by a demister.

^jAssumptions discussed in Sect. 4.4.6.4.

^kParticulates passing the water venturi and reaching the KOH venturi are assumed to have an average particle size of 0.5 μ (C. J. Stairmand, "Removal of Dust from Gases," *loc. cit.*, p. 392); efficiency of KOH venturi on 0.5-μ particles is assumed to be 50% (*ibid.*).

^lTechnology not fully developed [W. L. Belvin, M. A. Krimmel, H. C. Schwalbe, and E. N. Gleaton, *Summary Report on Development of New Fluoride Resistant HEPA Filter Medium*, TID-26649, HERTY Foundation, Savannah, Georgia (in preparation)]. Assumes that ultimately HF-resistant HEPA filters with efficiencies comparable to regular HEPA filters will become available.

^mMedium-energy venturi; efficiencies up to 95% are possible with high-energy water venturi [L. S. Harris, *Chem. Eng. Progr.* 62(4), 55-59 (1966)].

ⁿArbitrary estimate.

^oMedium-energy venturi; by analogy to SO₂, efficiencies up to 98% should be possible with high-energy KOH venturi [L. S. Harris, *Chem. Eng. Progr.* 62(4), 55-59 (1966)].

^pBy analogy to HCl scrubbing; S. K. Kempner, E. N. Seiler, and D. H. Bowman, *J. Air Pollution Control Assoc.* 20(3), 139-43 (1970).

^qW. H. Pechin, R. E. Blanco, R. C. Dahlman, B. C. Finney, R. B. Lindauer, and J. P. Witherspoon, *Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing "As Low As Practicable" Guides - Fabrication of Light-Water Reactor Fuel from Enriched Uranium Dioxide*, ORNL-TM-4902 (May 1975), p. 38.

^rEfficiency of proprietary technology is reported as 99% (see footnote f). Efficiency downgraded to 90% because technology is not in the public domain.

^sS. H. Smiley, "Gas-Solids Reactors in Uranium Processing: A Critical Review," p. 260 in *Progress in Nuclear Energy, Series IV, Technology, Engineering, and Safety*, Vol. 4, ed. by C. M. Nicholls, Pergamon, New York, 1961.

^tCalculated by assuming as-produced F₂ has the composition given by A. P. Huber, J. Dykstra, and B. H. Thompson, "Multi-ton Production of Fluorine for Manufacture of Uranium Hexafluoride," Paper P/524, Proc. U. N. Intern. Conf. Peaceful Uses At. Energy, 2nd, Geneva, 1958, 4, 17-80 (1958), and that the F₂ feed to the model plant has the composition reported by C. A. Powell, "Current Manufacturing Processes Used in the United States for Mass Production of UF₆ from Purified UO₂," Paper P/1840, Proc. U. N. Intern. Conf. Peaceful Uses At. Energy, 2nd, Geneva, 1958, 4, 165-71 (1958).

^uERDA classified technology; efficiency is calculated from paper by Huber et al. (see footnote t).

^vERDA classified technology; efficiency as reported by W. R. Fedigo, C. R. King, L. A. Dean, J. E. Owen, and G. Bernstein, *Chem. Eng. Progr., Symp. Ser. Pt. 15*, 62, 12-19 (1966).

^wERDA classified technology; efficiency as reported by J. L. Powell, W. E. Forashee, and G. Bernstein, *Ind. Eng. Chem.* 51, 919-20 (1959).

^xBy analogy with caustic scrubbing of Cl₂ [L. S. Harris, *Chem. Eng. Progr.* 62(4), 55-59 (1966)].

^yBy analogy to the efficiency of the condenser on F₂ stream (see footnote t).

^zCalculated by assuming 90% F₂ efficiency in primary fluorination reactor and 95% efficiency in F₂ cleanup reactor system; ERDA classified technology.

Table 4.9. Liquid radwaste releases from the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant

Source	Liquid flow (gal/day)	Code	Principal radionuclides				
			U _{nat} ^a	²³⁴ Th	^{234m} Pa ^b	²³⁰ Th	²²⁶ Ra
Maximum Permissible Conc., μCi/ml 10 CFR 20, Table II (General population)			3E-5	2E-5	3E-6	2E-6	3E-8
Case 1, Ci/yr							
Reduction water scrubber		3L	9.43E-3	9.43E-3	9.43E-3	4.01E-4	4.43E-5
Reduction KOH scrubber		3K					
Hydrofluorination water scrubber		4L					
Hydrofluorination KOH scrubber		4K	8.50E-4	8.50E-4	8.50E-4	3.60E-5	4.00E-6
Water scrubber on fluorine cell							
H ₂ off-gas		7L	-	-	-	-	-
KOH waste from fluorination scrubber after uranium recovery		8K	1.04E-1	4.01E-2 ^c	4.01E-2 ^c	8.00E-5	8.87E-6
Carbonate leaching		9L	8.42E-2	2.79E-2 ^c	2.79E-2 ^c	1.64E-4	8.42E-4
Sodium removal		11L	2.39E-1	7.93E-2 ^c	7.93E-2 ^c	7.14E-4	1.78E-2
Total	1.23E+5		4.38E-1	1.58E-1	1.58E-1	1.40E-3	1.88E-2 ^d
Avg μCi/ml (before dilution)			3.13E-6	1.13E-6	1.13E-6	1.20E-8	1.35E-7
Case 2, Ci/yr							
Reduction water scrubber		3IF	7.21E-3	7.21E-3	7.21E-3	3.06E-4	3.39E-5
Hydrofluorination water scrubber		4IF	8.00E-5	8.00E-5	8.00E-5	3.40E-6	3.76E-7
Water scrubber on fluorine cell							
H ₂ off-gas		7IF	-	-	-	-	-
KOH bleed stream with moist fluorination CaF ₂ filter cake		8IF	2.44E-4	1.41E-4 ^c	1.41E-4 ^c	2.12E-7	2.36E-8
Carbonate leach bleed		9L	8.60E-3	4.97E-3 ^c	4.97E-3 ^c	1.72E-5	8.60E-5
Sodium removal		11L	2.39E-1	7.93E-2 ^c	7.93E-2 ^c	7.14E-4	1.78E-2
Total	7.48E+4		2.55E-1	9.17E-2	9.17E-2	1.03E-3	1.80E-2 ^d
Avg μCi/ml (before dilution)			3.00E-6	1.08E-6	1.08E-7	1.22E-8	2.12E-7
Case 3, Ci/yr							
Reduction water scrubber		3IF	7.21E-3	7.21E-3	7.21E-3	3.06E-4	3.39E-5
Hydrofluorination water scrubber		4IF	8.00E-5	8.00E-5	8.00E-5	3.40E-6	3.76E-7
Water scrubber on fluorine cell							
H ₂ off-gas		7IF	-	-	-	-	-
KOH bleed stream with moist fluorination CaF ₂ filter cake		8IF	2.44E-4	1.41E-4 ^e	1.41E-4 ^e	2.12E-7	2.36E-8
Carbonate leach bleed		9IF	8.60E-3	4.95E-3 ^e	4.95E-3 ^e	1.72E-5	2.15E-5
Sodium removal		11IF	2.75E-2	2.37E-2 ^e	2.37E-2 ^e	8.20E-5	1.22E-5
Total	4.70E+4		4.36E-2	3.61E-2	3.61E-2	4.08E-4	6.82E-5
Avg μCi/ml (before dilution)			8.13E-7	6.76E-7	6.76E-7	7.64E-9	1.28E-9
Case 4, Ci/yr							
Water scrubber on fluorine cell							
H ₂ off-gas		7IF	-	-	-	-	-
Total	1.44E+4		d	d	d	d	d

^aOne curie of natural uranium is defined as the sum of 3.7×10^{10} dis/sec from ²³⁸U, 3.7×10^{10} dis/sec from ²³⁴U, and 9×10^8 dis/sec from ²³⁵U; it is also equivalent to 3000 kg of natural uranium.

^bMetastable ^{234m}Pa, $t_{1/2} = 1.18$ min.

^cProcess chemically separates uranium from other radionuclides. Holdup time after separation is assumed to be 14 days so that ²³⁴Th and ^{234m}Pa have grown back to 40% of secular equilibrium with uranium.

^dRequires dilution by a factor of ~10 to meet the maximum permissible concentration for release to the general population shown in 10 CFR 20, Appendix B, Table II.

^eHoldup time of 30 days. ^{234m}Th and ^{234m}Pa have grown back to 60% of secular equilibrium.

^fIn addition, 25 wt % hydrofluoric acid may be released for industrial use (see Table 4.20). Environmental effects from this acid will depend on its end use, but the radiological effects are expected to be low because the acid contains only small amounts of radioactive materials.

Table 4.10. Liquid chemwaste releases from the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant

Source	Code	Liquid flow (gal/day)	Principal chemicals ^a (lb/day)							
			Anions			Sulfide or sulfur	Cations or uranium			
			Carbonate, CO ₃ ²⁻	Fluoride, F ⁻	Sulfate, SO ₄ ²⁻		Ammonium, NH ₄ ⁺	Sodium, Na ⁺	Potassium, K ⁺	Uranium, U
<u>Case 1</u>										
Reduction water scrubber	3L	2.88E+4				3.61E+2				1.95E-1
Reduction KOH scrubber	3K	1.89E+3				3.61E+2			1.10E+3	1.21E-2
Hydrofluorination water scrubber	4L	2.88E+4		2.11E+3						1.76E-2
Hydrofluorination KOH scrubber	4K	1.04E+3		2.34E+2					6.02E+2	1.02E-3
Water scrubber on fluorine cell H ₂ off-gas	7L	1.44E+4		4.03E+2						
KOH waste from fluorination scrubber after uranium recovery	8K	9.14E+3	4.12E+2	1.98E+3					5.23E+3	2.28E00
Carbonate leaching	9L	7.41E+3	2.22E+3	3.52E+2				2.29E+3		1.85E00
Sodium removal	11L	3.14E+4			1.91E+4		6.10E+3	1.29E+3	4.8 E+1	5.26E00
Total		1.23E+5	2.63E+3	5.08E+3	1.91E+4	7.22E+2	6.10E+3	3.58E+3	6.98E+3	9.62E00
<u>Case 2</u>										
Reduction water scrubber	3LT	9.46E+2			1.80E+2 ^b					1.58E-1
Hydrofluorination water scrubber	4LT	2.88E+4		6.00E00						1.95E-3
Water scrubber on fluorine cell H ₂ off-gas	7LT	1.44E+4		3.00E00						
KOH bleed stream with moist fluorination filter cake	8LT	2.15E+2		4.47E-2					1.23E+2	
Carbonate leach bleed	9L	7.56E+2	1.15E+2	1.20E+1				1.12E+2		1.89E-1
Sodium removal	11L	3.14E+4			1.91E+4		6.10E+3	1.29E+3	4.81E+1	5.26E00
Total		7.48E+4	1.15E+2	2.10E+1	1.93E+4	-	6.10E+3	1.40E+3	1.71E+2	5.61E00
<u>Case 3</u>										
Reduction water scrubber	3LT	9.46E+2			1.80E+2 ^b					1.58E-1
Hydrofluorination water scrubber	4LT	2.88E+4		6.00E00						1.95E-3
Water scrubber on fluorine cell H ₂ off-gas	7LT	1.44E+4		3.00E00						
KOH bleed stream with moist fluorination filter cake	8LT	2.15E+2		4.47E-2					1.23E+2	
Carbonate leach bleed	11LT	7.56E+2	1.11E+2	1.20E+1				1.06E+2		1.89E-1
Sodium removal	9LT	3.61E+3			2.19E+3		7.00E+2	1.20E+2	4.8 E+1	6.04E-1
Total		4.70E+4	1.11E+2	2.10E+1	2.37E+3	-	7.00E+2	2.26E+2	1.71E+2	9.53E-1
<u>Case 4</u>										
Water scrubber on fluorine cell H ₂ off-gas	7LT	1.44E+4	-	3.00E00	-	-	-	-	-	-
Total		1.44E+4	-	3.00E00	-	-	-	-	-	-

^aHydronium (H₃O⁺, acid) and hydroxide (OH⁻, base) ions not shown. In Case 1, both acidic and basic streams are released; in Cases 2 to 4 wastes are neutralized before release.

^bPresent as sulfite (SO₃²⁻) rather than sulfate (SO₄²⁻).

Table 4.11. Solid chemwaste-radwaste generated by the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant^{a,b}

Source	Code	Quantity (lb/yr)	Principal radionuclides							
			Total (Ci/yr)				Average concentration (uCi/g)			
			U _{nat} ^c	²³⁴ Th, ^{234m} Pa ^d each	²³⁰ Th	²²⁶ Ra, ²²² Rn, ²¹⁸ Po, ²¹⁴ Pb, ²¹⁴ Bi, ²¹⁴ Po, each	U _{nat} ^c	²³⁴ Th, ^{234m} Pa ^d each	²³⁰ Th	²²⁶ Ra, ²²² Rn, ²¹⁸ Po, ²¹⁴ Pb, ²¹⁴ Bi, ²¹⁴ Po, each
Avg. composition of earth's crust ^e			1. E-6	1. E-6	1. E-6	1. E-6	1. E-6	1. E-6	1. E-6	
Case 1										
Carbonate-leached ash from fluorination, principally CaF ₂ , dried and drummed for disposal	10W	2.21E+6	1.17E-1	1.17E-1	1.42E+2	1.57E+1	1.2 E-4	1.2 E-4	1.4 E-1	1.6 E-2
Still tops and bottoms, stored in gas-tight containers	8Uc + 8Ud	8.87E+4	1.67E00	1.67E00	3.79E-3	4.22E-4	4.2 E-2	4.2 E-2	9.3 E-5	1.0 E-5
Total		2.30E+6	1.79E00	1.79E00	1.42E+2	1.57E+1				
Case 2										
Carbonate-leached ash from fluorination, principally CaF ₂ , dried and drummed for disposal	10W	2.45E+6	1.17E-1	1.17E-1	1.42E+2	1.57E+1	1.0 E-4	1.0 E-4	1.3 E-1	1.4 E-2
Still tops and bottoms, stored in gas-tight containers	8Uc + 8Ud	8.87E+4	1.67E00	1.67E00	3.79E-3	4.22E-4	4.2 E-2	4.2 E-2	9.3 E-5	1.0 E-5
CaF ₂ -CaCO ₃ stored in the fluoride settling basins	4X + 4Y + 7X + 7Y + 8Y + 9X	3.56E+6	1.21E-1	1.21E-1	1.25E-4	9.24E-5	7.5 E-5	7.5 E-5	7.8 E-8	5.7 E-8
Total		6.10E+6	1.89E00	1.89E00	1.42E+2	1.57E+1				
Case 3										
Carbonate-leached ash from fluorination, principally CaF ₂ , dried and drummed for disposal	10W	2.45E+6	1.17E-1	1.17E-1	1.42E+2	1.57E+1	1.0 E-4	1.0 E-4	1.3 E-1	1.4 E-2
Still tops and bottoms, stored in gas-tight containers	8Uc + 8Ud	8.87E+4	1.67E00	1.67E00	3.79E-3	4.22E-4	4.2 E-2	4.2 E-2	9.3 E-5	1.0 E-5
CaF ₂ -CaCO ₃ stored in fluoride settling basin	4X + 4Y + 7X + 7Y + 8Y + 9X	3.56E+6	1.21E-1	1.21E-1	1.25E-4	9.24E-5	7.5 E-5	7.5 E-5	7.8 E-8	5.7 E-8
Fe ₂ SO ₄ ·7H ₂ O and BaSO ₄ , dried and drummed for disposal	9Y + 11Z	1.80E+3	3.25E-6	3.25E-6	8.79E-9	2.11E-3	4.0 E-6	4.0 E-6	1.1 E-8	2.6 E-3
Total		6.10E+6	1.89E00	1.89E00	1.42E+2	1.57E+1				
Case 4										
Carbonate-leached ash from fluorination, principally CaF ₂ , cemented and drummed for disposal	10W	1.63E+7	1.17E-1	1.17E-1	1.42E+2	1.57E+1	1.6 E-5	1.6 E-5	1.9 E-2	2.1 E-3
Still tops and bottoms, stored in gas-tight containers	8Uc + 8Ud	8.87E+4	1.67E00	1.67E00	3.79E-3	4.22E-4	4.2 E-2	4.2 E-2	9.3 E-5	1.0 E-5
CaF ₂ -CaCO ₃ stored in lined fluoride pit	4Y + 7Y + 8Y + 9X	4.04E+5	3.54E-2	3.54E-2	9.16E-5	8.87E-5	1.9 E-4	1.9 E-4	5.0 E-7	4.8 E-7
CaF ₂ stored in lined fluoride settling basin	7X	1.13E+5	-	-	-	-	-	-	-	-
CaSO ₃ ·1/2H ₂ O stored in lined sulfite settling basin	3Y	9.39E+5	4.72E-5	4.72E-5	2.01E-6	2.21E-7	1.1 E-8	1.1 E-8	4.7 E-10	5.2 E-11
(NH ₄) ₂ SO ₄ , Na ₂ SO ₄ evaporator residues dried and drummed for disposal	3Z, 9Z, 11Z	8.40E+5	4.03E-2	4.03E-2	4.85E-4	1.79E-3	9.3 E-5	9.3 E-5	1.1 E-6	4.1 E-6
Total		1.88E+7	1.83E00	1.83E00	1.42E+2	1.57E+1				

^aOnly radioactive materials in the yellow cake feed to the plant are considered; possible radioactive impurities in the chemical feed to the plant are not included.

^bStored 6 months so that ²³⁴Th and ^{234m}Pa are in secular equilibrium with ²³⁸U, and radium daughters through ²¹⁴Po are in secular equilibrium with ²²⁶Ra; assumes negligible loss of ²²²Rn gas during storage.

^cOne curie of U_{nat} is defined as the sum of 1 Ci of ²³⁸U, 1 Ci of ²³⁴U, and 2.43 x 10⁻² Ci of ²³⁵U; 1 Ci of U_{nat} is also equivalent to 3000 kg of U_{nat}.

^dMetastable ^{234m}Pa, t_{1/2} = 1.18 min.

^eEstimated by assuming the presence of 3 ppm of uranium in the earth's crust and secular equilibrium.

Table 4.12. Dust-bearing airflows at the model 10,000-metric ton/yr
 fluorination-fractionation UF₆ plant
 (Codes shown on Figs. 4.1-4.5)

Source	Code	Airflow (cfm)
Materials handling		
Sampling		
Process	1a }	10,000
Vacuum cleaner system	1b }	
Feed preparation		
Drum dumping	2a	4,000
Drum cleaning	2b	6,000
Calciner	2c	5,000
Air classifier	2d	2,500
Oxide vacuum cleaner system	2e	500
Conversion		
UF ₄ handling	5a	3,000
UF ₄ vacuum cleaner system	5b	1,000
Ash handling	6a }	2,000
Ash vacuum cleaner system	6b }	
Carbonate leach (uranium recycle)		
Drum dumping	9a	3,000
Vacuum cleaner system	9b	500
Waste calciner	10a	3,000
Waste packaging	10b	3,000
Waste vacuum cleaner system	10c	500
Building air		
Process cooling fans		
6 at 1000 cfm each }	12A	6,000
2 at 6500 cfm each }		
Building ventilation effluent		
18 fans at 25,000 cfm each }	13A	450,000
2 hoods at 14,000 cfm each }		

Table 4.13. Airborne uranium releases from model 10,000-metric ton/yr fluorination-fractionation UF₆ plant
(Codes shown in Figs. 4.1-4.5)

Source	Code	Quantity of U _{nat} released (kg/yr) ^{a,b}			
		Case 1, ^c (Base plant)	Case 2	Case 3	Case 4
Sampling ^d	1A	31.4	4.4	4.4	0.22E-2
Feed preparation					
Drum dumping	2a	31.4	4.4	4.4	} 2.10E-2
Drum cleaning	2b	30.7	4.3	4.3	
Wet calciner	2c	142.1	19.9	19.9	
Air classifier	2d	72.1	10.1	10.1	
Oxide vacuum cleaner	2e	24.3	3.4	3.4	
Sodium removal	11A	<0.5	<0.07	<0.07	
Reduction ^e	3A	0.05	0.28	0.28	0.007E-2
Hydrofluorination					
Process	4A	<0.10	<0.10	<0.10	} 0.75E-2 ^f
UF ₄ handling	5a	37.8	5.3	5.3	
UF ₄ vacuum cleaner	5b	33.6	4.7	4.7	
Fluorination					
Process ^g	8A	73.6	7.4	7.4	0.01E-2
UF ₆ sampling and ash degassing ^h		20.0	20.0	0.2	0.01E-2
Ash handling (dust)					
Collecting and drumming ⁱ	6A	0.71	0.10	0.10	5.0E-5
Carbonate leach (ash dust)					
Drum dumping ⁱ	9A	0.71	0.10	0.10	5.0E-5
Drying and packaging ⁱ	10A	0.003	<0.01	<0.01	n.a.
Building ventilation					
20 exhaust fans	12A	150.7	150.7	10.5	15.73E-2 ^f
8 process cooling fans	13A	15.1	15.1	1.1	1.58E-2 ^f
Total		664.2	250.2	76.3	2.04E-1

^aCase 2 is based primarily on stack sampling data obtained through the courtesy of the Allied Chemical Corporation. These data were extrapolated to a processing rate of 10,000 metric tons/yr, assuming that releases are directly proportional to the processing rate. Maximum efficiency of dust collectors and scrubbers is obtained when the plant operates continuously near the design capacity. Actual releases from a 10,000-metric ton/yr plant operating under optimum conditions will probably be lower than these projections. The data represent the continuous monitoring and daily analyses of all major process stacks and building exhaust vents summarized over an operational period of 1 yr. The source terms are based on a 1-year (1971) summary of the individual stack data adjusted to the average total annual uranium release (1b/ton of uranium processed) for the period 1969-1974.

^bCase studies 1, 3, and 4 are calculated from Case 2 by using the efficiencies listed in Table 4.8.

^cCase 1, the base plant, contains off-gas treatment required for operation of the process. Treatment consists of uranium recovery, where the value of the uranium recovered exceeds the treatment cost, or in the reduction of noxious fumes such as HF (highly corrosive) or H₂S (odor of rotten eggs) whose release would be unacceptable within the plant area.

^dEstimated from drum dumping.

^eCalculated from the uranium contents of Allied Chemical Corporation scrubber liquors and from treatment efficiencies as given in Table 4.8. It was necessary to use calculated values in order to design the advanced treatment systems.

^fIncludes estimated UF₄ dust release from solids handling for the F₂ and UF₆ cleanup reactors, assuming that 50% of the UF₄ passes through the cleanup reactors before the primary fluorinator and that conventional solids handling techniques (screw conveyors, hoppers, etc.) are used.

^gFluorination losses were calculated by assuming a 355-scfm gas flow containing 0.08 vol % UF₆ from the UF₆ cold traps and treatment efficiencies as given in Table 4.8.

^hEstimated by difference between data for Case 2 on ash handling plus UF₆ sampling, and the ash handling estimate; assumes no hydrolysis or treatment in Cases 1 and 2 of UF₆ drawn into the vacuum off-gas system.

ⁱEstimated by comparison with similar operations in feed preparation steps at the UF₆ plant and yellow cake drying and packaging at a uranium mill.

n.a. = not applicable; ash cemented rather than dried.

Table 4.14. Airborne ash dust releases from the model
 fluorination-fractionation UF₆ plant^a
 (Codes shown on Figs. 4.2, 4.4, and 4.5)

Source	Code	Release (% of ash handled)			
		Case 1	Case 2	Case 3	Case 4
Ash handling, before decay (removing ash from fluorination fluid bed and filters)	6A	4.0E-4	5.6E-5	5.6E-5	2.8E-8
Ash drum dumping after decay	9A	4.0E-4	5.6E-5	5.6E-5	2.8E-8
Ash drying and drumming after decay and carbonate leach	10A	<u>1.2E-3</u>	<u>1.7E-4</u>	<u>1.7E-4</u>	<u>b</u>
Total		2.0E-3	2.8E-4	2.8E-4	5.6E-8

^aEstimated by analogy to similar operations in UF₆ feed preparation (Table 4.14) and yellow cake drying and packaging at a uranium mill (Sears et al., Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Establishing "As Low As Practicable" Guides - Milling of Uranium Ores, ORNL-TM-4903, Vol. 1 (May 1973), p. 236.

^bWastes cemented; no release of airborne particulates from drying and drumming.

Table 4.15. Radionuclide content of the fluorination ash at the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant

(Codes shown on Figs. 4.2, 4.4, and 4.5)

Radionuclide	Total ash processed (Ci/year)			
	Stream 8Ua ash before decay	Stream 9Ua ash after 6 months decay	Stream 10W carbonate- leached ash before decay	Carbonate- leached ash after decay
U ^a _{nat}	6.00E+1 ^b	6.00E+1 ^b	9.47E-2 ^c	9.47E-2 ^c
²³⁴ Th	3.33E+3 ^d	6.00E+1	6.00E+1	9.47E-2
^{234m} Pa	3.33E+3 ^d	6.00E+1	6.00E+1	9.47E-2
²³⁰ Th	1.42E+2 ^d	1.42E+2 ^d	1.42E+2 ^d	1.42E+2 ^d
²²⁶ Ra	1.57E+1 ^d	1.57E+1 ^d	1.57E+1 ^d	1.57E+1 ^d

^a One curie of natural uranium is defined as the sum of 3.7×10^{10} dis/sec from ²³⁸U, 3.7×10^{10} dis/sec from ²³⁴U, and 9×10^8 dis/sec from ²³⁵U; it is also equivalent to 3000 kg of natural uranium.

^b Assumes that fluorination ash contains 1.8% of total uranium processed by the model plant; taken from S. Lawroski, A. A. Jonke, N. Levitz, E. J. Petkus, A. H. F. Litty, W. A. Rodger, G. J. Vogel, R. K. Steunenber, O. Sandus, W. J. Mecham, R. C. Leimatainen, R. W. Kessie, L. Trevorow, and R. C. Vogel, "Production of Refined UF₆ from Ore Concentrates by Fluidization and Fractional Distillation Techniques," P/1552, Proc. U. N. Intern. Conf. Peaceful Uses At. Energy, 2nd, Geneva, 1958, 4, 52 (1958).

^c Assumptions are discussed in Sect. 4.4.10 on carbonate leach.

^d Assumes that essentially all the radioactive impurities in the feed leave the process in the fluorination ash.

Table 4.16. Impurity removal effected by reduction and hydrofluorination of ore concentrates

Impurity	Removed as	Removal (% of original present)						
		a	Bluewater, ^b N. M., acid-leached feed	Bluewater, ^b N. M., carbonate- leached feed	Durango, ^b Colo., acid-leached feed	Uravan, ^b Colo., acid-leached feed	Rifle, ^b Colo., acid-leached feed	South African feed
As	AsH ₃	100	-	-	-	-	-	>98
B	BF ₃	100	-	-	-	99	92	>90
Mo	MoF ₆ , MoOF ₄	40	73	88	-	-	83	79
P	PH ₃	33	>93	66	0	33	25	-
Si	SiF ₄	90	99	-	-	-	-	99
V	-	-	>96	77	-	46	25	-
SO ₄ ²⁻	H ₂ S, S	95	91	94	92	99	92	65
CO ₃ ²⁻	CO ₂	100	-	-	-	-	-	-

^aA. H. Sutton, J. C. Bishop, M. H. Cohen, and K. J. Stahman, "Reduction and Hydrofluorination of Uranium Concentrates by Fluid Bed Techniques," Chem. Eng. Progr., Symp. Ser. Pt. 15, 62, 27 (1966).

^bCalculated from data presented by S. Lawroski, A. A. Jonke, N. Levitz, E. J. Petkus, A. H. F. Litty, W. A. Rodger, G. J. Vogel, R. K. Steunenber, O. Sandus, W. J. Mecham, R. C. Liimatainen, R. W. Kessie, L. Trevorow, and R. C. Vogel, "Production of Refined UF₆ from Ore Concentrates by Fluidization and Fractional Distillation Techniques," Paper P/1552, Proc. U. N. Intern. Conf. Peaceful Uses At. Energy, 2nd, Geneva, 4, 50 (1958).

Table 4.17. Reduction waste streams and material flows for the model 10,000-metric ton/yr fluorination-fractionation UF_6 plant^a
(Codes shown in Figs. 4.2, 4.10-4.12; discussion in Sect. 4.4.6)

Code	Stream		Case study	Gas flow (scfm)			Liquid flow (gal/day)	Flow rate (lb/day)								
	Type	Description		Total	N ₂	O ₂		U	S ²⁻	H ⁺	H ₂	H ₂ O vapor or H ₂ O condensed from vapor phase	SO ₂ or SO ₃ ²⁻ calc. as SO ₂	CO ₂ or CO ₃ ²⁻ , calc. as CO ₂	K ⁺	OH ⁻
3	Gaseous	Feed to reduction off-gas waste treatment system	1-4	205	51		2.08E-1	7.20E+2	4.53E+1	4.41E+2	6.77E+3					
3A	Gaseous	Effluent released to atmosphere from reduction	1	114	51		3.74E-4	5.40E-1	3.42E-2	4.41E+2	2.51E+2					
			2,3	536	455	36	2.06E-4				3.22E+3	1.30E+3	2.71E+1			
			4	520	455	36	5.14E-7				2.13E+3	2.59E+1	1.71E+0			
3B	Gaseous	Feed to reduction KOH scrubber	1	114	51		2.08E-2	3.61E+2	2.26E+1	4.41E+2	2.51E+2					
			2,3	n.a.			n.a.				n.a.	n.a.	n.a.			
			4	536	455	36	2.06E-3				3.22E+3	1.30E+3	2.71E+1			
3C	Gaseous	Feed to reduction water scrubber	1	Same as stream 3												
			2-4	651	455	36	2.08E-1				1.11E+4	1.44E+3	2.71E+1			
3D	Gaseous	Air feed to H ₂ , H ₂ S burner	2-4	511	404	107										
3K	Liquid	Waste stream from reduction KOH scrubber	1				1.89E+3	2.06E-2	3.61E+2		Nil			1.10E+3	9.54E+1	
			2,3				n.a.	n.a.			n.a.	n.a.	n.a.	n.a.	n.a.	
			4				4.01E+3	1.03E-3			1.09E+3	1.27E+3	2.71E+1	2.25E+3	1.97E+2	
3L	Liquid	Waste stream from reduction water scrubber	1				2.88E+4	1.87E-1	3.61E+2	2.26E+1	6.52E+3					
			2,3				9.46E+2	2.08E-1			7.89E+3	1.44E+2				
			4				9.46E+2	2.08E-1			7.89E+3	1.44E+2				
3M	Liquid	10% KOH feed to reduction scrubbers	1				1.89E+3							1.10E+3	4.77E+2	
			2,3				n.a.							n.a.	n.a.	
			4				3.88E+3							2.25E+3	9.84E+2	

^aAssumptions:

- (1) 50% excess H₂ used in reduction.
- (2) 200% excess air used to burn H₂ and H₂S in Cases 2-4.
- (3) Sulfur in reduction off-gas assumed to be H₂S.
- (4) Efficiencies of off-gas scrubbers are listed in Table 4.8.
- (5) KOH scrubbers are recirculating system. Initial KOH concentration, 10 wt %; final concentration, 2 wt %.
- (6) Case 1 water scrubber is single pass, 20 gpm; Cases 2-4 water scrubbers are recirculating systems operating on water condensed from process off-gas.
- (7) Water balances in Cases 2-4 were estimated by assuming that the water scrubber operates at 40°C and the Case 4 KOH scrubber operates at 37°C.

n.a. = not applicable.

Table 4.18. Radionuclide composition of solid wastes generated by liquid waste treatment systems at the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant^{a,b}

Source of radioactive materials	Code	Quantity of solids (lb/yr)	Principal radionuclides								
			Total (Ci/yr)				Concentration (μCi/g)				
			U _{nat} ^c	²³⁴ Th, ^{234m} Pa, d each	²³⁰ Th	²²⁶ Ra, ²²² Rn, ²¹⁸ Po, ²¹⁴ Pb, ²¹⁴ Bi, ²¹⁴ Po, each	U _{nat} ^c	²³⁴ Th, ^{234m} Pa, d each	²³⁰ Th	²²⁶ Ra, ²²² Rn, ²¹⁸ Po, ²¹⁴ Pb, ²¹⁴ Bi, ²¹⁴ Po, each	
Average composition of earth's crust ^e								1 E-6	1 E-6	1 E-6	1 E-6
Cases 2 and 3: CaF ₂ -CaCO ₃ stored in fluoride settling basin											
Hydrofluorination water scrub	4X	1.43E+6	8.00E-4	8.00E-4	3.40E-5	3.76E-6	1.2E-6	1.2E-6	5.3E-8	5.8E-9	
Hydrofluorination KOH scrub	4Y	1.58E+5	3.33E-5	3.33E-5	1.42E-6	1.57E-7	4.6E-7	4.6E-7	1.9E-8	2.2E-9	
Fluorine cell H ₂ water scrub	7X	2.72E+5	-	-	-	-	-	-	-	-	
Fluorine cell H ₂ KOH scrub	7Y	3.02E+4	-	-	-	-	-	-	-	-	
Fluorination KOH scrub	8Y	1.54E+6	1.04E-1	1.04E-1	9.02E-5	9.98E-6	1.5E-4	1.5E-4	1.0E-7	1.4E-8	
Carbonate leach recycle circuit	9X	1.32E+5	1.67E-2	1.67E-2	3.23E-8	7.85E-5	2.8E-4	2.8E-4	5.4E-10	1.3E-6	
Total		3.56E+6	1.21E-1	1.21E-4	1.25E-4	9.24E-5	Avg. 7.5E-5	7.5E-5	7.8E-8	5.7E-8	
Case 3: BaSO ₄ -FeSO ₄ ·7H ₂ O from radium settling basin, dried and drummed for disposal											
Carbonate leach liquid bleed	9Y	3.79E+2	9.26E-7	9.26E-7	1.85E-9	6.45E-5	5.4E-6	5.4E-6	1.1E-8	3.8E-6	
Sodium removal process waste	11Y	1.42E+3	2.32E-6	2.32E-6	6.94E-9	2.05E-3	3.6E-6	3.6E-6	1.1E-8	3.7E-3	
Total		1.80E+3	3.25E-6	3.25E-6	8.79E-9	2.11E-3	Avg. 4.0E-6	4.0E-6	1.1E-8	2.6E-3	
Case 4: CaF ₂ -CaCO ₃ stored in fluoride-lined pit											
Hydrofluorination KOH scrub	4Y	2.37E+4	3.33E-5	3.33E-5	1.42E-6	1.57E-7	3.1E-6	3.1E-6	1.3E-7	1.5E-8	
Fluorine cell H ₂ KOH scrub	7Y	1.26E+4	-	-	-	-	-	-	-	-	
Fluorination KOH scrub	8Y	2.36E+5	1.87E-2	1.87E-2	9.02E-5	9.98E-6	1.7E-4	1.7E-4	8.4E-7	9.3E-8	
Carbonate leach recycle circuit	9X	1.32E+5	1.67E-2	1.67E-2	3.23E-8	7.85E-5	2.8E-4	2.8E-4	5.4E-10	1.3E-6	
Total		4.04E+5	3.54E-2	3.54E-2	9.16E-5	8.87E-5	Avg. 1.9E-4	1.9E-4	5.0E-7	4.8E-7	
Case 4: CaF ₂ stored in fluoride settling basin											
Fluorine cell H ₂ water scrub	7X	1.13E+5	-	-	-	-	-	-	-	-	
Total		1.13E+5	-	-	-	-	-	-	-	-	
Case 4: CaSO ₃ ·1/2H ₂ O stored in sulfite settling basin											
Reduction KOH scrub	3Y	9.39E+5	4.72E-5	4.72E-5	2.01E-6	2.21E-7	Avg. 1.1E-8	1.1E-8	4.7E-10	5.2E-11	
Case 4: (NH ₄) ₂ SO ₄ -Na ₂ SO ₄ evaporator residues, dried and drummed for disposal											
Reduction water scrub	3L	6.24E+1	9.43E-3	9.43E-3	4.01E-4	4.43E-5					
Carbonate leach liquid bleed	9L	9.73E+4	8.60E-3	8.60E-3	1.72E-5	8.60E-5					
Sodium removal	11L	7.41E+5	2.23E-2	2.23E-2	6.66E-5	1.66E-3					
Total		8.40E+5	4.03E-2	4.03E-2	4.85E-4	1.79E-3	Avg. 1.1E-4	1.1E-4	1.3E-6	4.7E-6	

^aOnly radioactive materials in the yellow cake feed to the plant are considered; possible radioactive impurities in the chemical feed to the plant are not included.

^bStored 6 months so that ²³⁴Th and ^{234m}Pa are in secular equilibrium with ²³⁸U, and radium daughters through ²¹⁴Po are in secular equilibrium with ²²⁶Ra; assumes negligible ²²²Rn loss in storage.

^cOne curie of U_{nat} is defined as the sum of 1 Ci of ²³⁸U, 1 Ci of ²³⁵U, and 2.43 x 10⁻² Ci of ²³³U; 1 Ci of U_{nat} is also equivalent to 3000 kg of U_{nat}.

^dMetastable ²³⁴Pa, t_{1/2} = 1.18 min.

^eEstimated by assuming 3 ppm of uranium in the earth's crust and secular equilibrium.

Table 4.19. Solubilities of solid wastes generated by the model fluorination-fractionation UF₆ plants

Chemical compound	Solubility in water at 25°C (g/liter of saturated solution)	Reference
<u>Chemwaste</u>		
CaF ₂	0.015 to 0.018 (15° to 40°C)	a, page 601
CaCO ₃	0.05 ^b	a, page 537
Ca(OH) ₂	1.2	a, page 631
CaSO ₃	0.043 (18°C)	a, page 659
CaSO ₄	2.1 to 7.1 ^c	a, pages 660-61
(NH ₄) ₂ SO ₄	433	d, page 755
Na ₂ SO ₄	217	d, pages 1130-39
<u>Radioactive materials</u> (short-lived daughters not shown)		
UF ₄	0.10	e
UO ₂	0.0008	d, page 1621
UO ₃	0.011	d, page 1621
ThF ₄	0.17	d, page 1538
ThO ₂	<0.00002	d, page 1545
RaF ₂	f	
Ra(OH) ₂	f	
PbF ₂	0.68	d, page 1298
PbO	0.05 to 0.11 ^g	d, page 1316

^aW. F. Linke, Solubilities, Vol. I, 4th ed., Van Nostrand, Princeton, N. J., 1958.

^bSolubility in water in contact with ordinary air; solubility dependent upon partial pressure of CO₂.

^cSolubility varies with the method of preparation of CaSO₄.

^dW. F. Linke, Solubilities, Vol. II, 4th ed., Van Nostrand, Princeton, N. J., 1965.

^eR. J. Allen, H. G. Petrow, and A. Whitman, "Preparation of Dense, Metal Grade Uranium Tetrafluoride from Uniferous Ores," P/503, Proc. Second Geneva Conf., 4, 121 (1958).

^fSolubility of RaF₂ and Ra(OH)₂ is not known but is expected to be less than the solubility of the corresponding barium compounds (J. M. Mellor, Inorganic and Theoretical Chemistry, Vol. IV, p. 93, Longmans, Green, and Co., London, 1952.); solubility of BaF₂ in water at 25°C is 1.6 g/liter (ref. a, page 359); solubility of Ba(OH)₂ in water at 25°C is 46.8 g/liter (ref. a, page 378).

^gSolubility depends on the crystalline form of the PbO.

Table 4.20. Hydrofluorination waste streams and material flows for the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant^a
(Codes shown in Figs. 4.2 and 4.13-4.16; discussion in Sect. 4.5.7)

Code	Stream		Case study	Gas flow (scfm)	Liquid flow (gal/day)	Flow rate (lb/day)					
	Type	Description				U	F ⁻	H ⁺	H ₂ O vapor or H ₂ O condensed from vapor phase	K ⁺	OH ⁻
4	Gaseous	Feed to hydrofluorination off-gas waste treatment system	1-3	245 ^b		1.91E-2	2.34E+3	1.24E+2	1.11E+4		
			4	260 ^c		1.91E-2	3.51E+3	1.86E+2	1.11E+4		
4A	Gaseous	Effluent released to atmosphere from hydrofluorination	1	63		<7.34E-4	3.51E+1	1.86E00	2.10E+2		
			2, 3	63		<7.34E-4	3.51E-1	1.86E-2	2.10E+2		
			4	62		<2.57E-7	3.51E-2	1.86E-3	1.50E+2		
4B	Gaseous	Feed to hydrofluorination KOH scrubbers	1-3	68		1.54E-3	2.34E+2	1.24E+1	3.57E+2		
			4	62		1.54E-3	3.51E+1	1.86E00	1.11E+2		
4K	Liquid	Waste stream from hydrofluorination KOH scrubber	1-3		1.08E+3	7.34E-4	2.34E+2		1.48E+2	6.02E+2	5.22E+1
			4		1.54E+2	7.34E-4	3.51E+1		nil	9.03E+1	7.83E+0
4L	Liquid	Waste stream from hydrofluorination water scrubbers	1-3		2.88E+4	1.76E-2	2.11E+3	1.12E+2	1.07E+4		
			4		n.a.	n.a.	n.a.	n.a.	n.a.		
4M	Liquid	10% KOH feed to hydrofluorination scrubbers	1-3		1.04E+3					6.02E+2	2.62E+2
			4		1.56E+2					9.03E+1	3.93E+1
4N	Liquid	Water feed to hydrofluorination scrubber	1-3		2.73E+4						
			4		n.a.						
4O	Liquid	25% aqueous HF recovered by condensers for use in industry	1-3		n.a.	n.a.	n.a.	n.a.	n.a.		
			4		1.63E+3	1.76E-2	3.48E+3	1.84E+2	1.10E+4		

^aAssumptions:

- (1) 60 scfm of N₂ (inert gas) used to fluidize the beds (i.e., 30 scfm per conversion line).
- (2) Cases 1-3: 10% excess HF used in hydrofluorination.
- (3) Case 4: 15% excess HF used in hydrofluorination.
- (4) Efficiencies of off-gas scrubbers and condensers are listed in Table 4.8.
- (5) Water scrubbers are single pass, 20 gpm.
- (6) KOH scrubbers are recirculating systems. Initial KOH concentration, 10 wt %; final concentration, 2 wt %.
- (7) Water balances for Cases 1-3 estimated by assuming that the water scrubber operates at ~40°C and KOH scrubbers at ~32°C; Case 4 KOH scrubbers are assumed to be at 25°C.

^b154 scfm of water vapor (product of hydrofluorination reaction), 60 scfm of nitrogen (to fluidize the beds), 31 scfm of HF (excess over stoichiometric).

^c154 scfm of water vapor, 60 scfm of nitrogen, and 46 scfm of HF (excess over stoichiometric).

n.a. = not applicable.

Table 4.21. Radionuclide composition of recovered 25 wt % hydrofluoric acid in F-F Case 4, Stream 40^{a,b}

Radionuclide	Recovered 25 wt % HF		10 CFR 20 MPC (μ Ci/ml)
	Ci/year	μ Ci/ml	
U_{nat}^c	7.2E-4	4.3E-7	2E-5
^{234}Th	7.2E-4	4.3E-7	2E-5
^{234m}Pa	7.2E-4	4.3E-7	-
^{230}Th	3.1E-5	1.8E-8	2E-6
^{226}Ra	3.4E-6	2.0E-9	3E-8

^aAssumptions:

- (1) 15% excess HF to hydrofluorination.
- (2) 99% efficient HF condensers on off-gas.
- (3) 90% efficient particulate removal by condensers.

^bValues represent probable upper limit; estimated from analytical limit of detection for uranium passing the porous carbon filters. Data obtained through the courtesy of the Allied Chemical Corporation.

^cOne curie of natural uranium is defined as the sum of 3.7×10^{10} dis/sec from ^{238}U , 3.7×10^{10} dis/sec from ^{234}U , and 9×10^8 dis/sec from ^{235}U ; it is also equivalent to 3000 kg of natural uranium.

Table 4.22. Typical impurity content of UF₆ produced by the fluorination-fractionation process^a

Minimum wt % UF₆ in product, 99.98%

Vapor pressure of filled container at 200°F, 65 psi(abs)

Impurity	Concentration (ppm, U basis)	Impurity	Concentration (ppm, U basis)
A. Metals Forming Volatile Metal Fluorides		C. Metals Forming Nonvolatile Metal Fluorides	
Sb	<0.7	Al	<3.0
B	<0.9	Ba	<1.0
Mo	<0.1	Bi	1.2
Nb	<0.1	Cd	<1.0
P	<11.8	Ca	7.4
Ru	<0.7	Cr	<8.9
Si	<7.4	Cu	8.9
Ta	<0.7	Fe	3
Ti	0.3	Pb	<1.0
W	<0.7	Li	<1.0
V	<0.1	Mg	1.5
B. Others		Mn	<0.4
Br ₂	<5	Ni	<5.9
Cl ₂	<5	K	<10.4
HF	28	Ag	0.4
Hydrocarbons	Nil	Na	3
		Sr	<8.9
		Th	<1.5
		Sn	<1.0
		Zn	<29.6
		Zr	<0.1
		Total	<99

^aData obtained through the courtesy of the Allied Chemical Corporation.

Table 4.23. Fluorination waste and recycle streams and material flows for the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant^a
(Codes shown on Figs. 4.2, 4.17-4.19; discussion in Sect. 4.5.8)

Code	Type	Stream Description	Case study	Gas flow (scfm)				Liquid flow (gal/day)	Solid flow (lb/day)	Flow rate (lb/day)				
				Total	"Inert"	O ₂	H ₂ O vapor			U	Total F	K ⁺	OH ⁻	CO ₃ ²⁻
8	Gaseous	Feed to fluorination off-gas KOH scrubbing system	1-3	362	346					2.70E+2	1.98E+3			
			4	358	346				6.75E00	3.42E+2				
8A	Gaseous	Effluent released to atmosphere from fluorination	1	364	346	7	11			5.40E-1	3.96E00			
			2,3	364	346	7	11			5.40E-2	3.96E-1			
			4	361	346	0.4	11			6.75E-7	6.85E-2			
8B	Gaseous	CO ₂ feed to uranium recovery	1-3	1.71										
			4	0.04										
8K	Liquid	Fluorination KOH waste stream after uranium recovery	1-3					9.14E+3		2.28E00	1.98E+3	5.23E+3	2.88E+2	4.11E+2
			4					1.65E+3		4.14E-1	3.42E+2	8.71E+2	7.59E+1	7.59E00
8L	Liquid	Fluorination KOH scrubber liquid before uranium recovery	1-3					9.14E+3		2.70E+2	1.98E+3	5.32E+3	4.64E+2	
			4					1.65E+3		6.75E00	3.42E+2	8.90E+2	7.72E+1	
8M	Liquid	10% KOH feed to fluorination scrubbers	1-3					9.14E+3				5.32E+3	2.32E+3	
			4					1.65E+3				8.90E+2	3.88E+2	
8Ua	Solid	Fluorination ash	1-4							9.00E+3	1.32E+3			
8Ub	Solid	Uranium recovered from fluorination scrubber liquor	1-3							5.16E+2	2.68E+2		8.91E+1	
			4						1.29E+1	6.34E00		2.48E00		
8Uc + 8Ud	Solid	Still tops and bottoms	1-4							2.96E+2 ^b	3.68E+1 ^b	1.62E+2 ^b		
8Ue	Solid	Uranium fluoride solids from F ₂ cleanup reactor	1-3							n.a.				
			4							2.98E+4				
8Uf	Solid	Uranium fluoride solids from UF ₆ cleanup reactor	1-3							n.a.				
			4							9.46E+2				

^aAssumptions:

(1) Cases 1-3 -

Feed to fluorination:

Solids are 97% UF₄ and 3% UO₂, the average reported by Brater et al. for single-stage fluid-bed hydrofluorination ["Development and Production Experience with Mechanically Agitated Fluid Beds as Applied to the Hydrofluorination of Fine Uranium Oxide Powders," Chem. Eng. Progr., Symp. Ser. Pt. 15, 62, 1-11 (1966)].F₂ contains 8 vol % HF and 2 vol % "inert" components, [C. A. Powell, "Current Manufacturing Processes Used in the United States for Mass Production of UF₆ from Purified UO₃," Paper P/1840, Proc. U. N. Intern. Conf. Peaceful Uses At. Energy, 2nd, Geneva, 1958, 4, 165-71 (1958)].90% F₂ utilization in fluorination [maximum utilization reported by Ruch et al., "Production of Pure Uranium Hexafluoride from Ore Concentrates," Chem. Eng. Progr., Symp. Ser. Pt. 15, 56, 35-41 (1960)].346 scfm of "inert" gases (N₂ to fluidize beds, seal leakage, oxygen from fluorination of oxide or oxyfluoride impurities).0.08 vol % UF₆ in effluent from UF₆ cold traps (average reported by Smiley, "Gas-Solid Reactors in Uranium Processing: A Critical Review," pp. 241-62 in Progress in Nuclear Energy, Series IV, Technology, Engineering and Safety, Vol. 4, edited by C. M. Nicholls, Pergamon Press, 1961).

(2) Case 4 -

Feed to fluorination:

Solids are 97% UF₄ and 3% UO₂.F₂ contains 4 vol % HF [Huber et al., "Multi-ton Production of Fluorine for Manufacture of Uranium Hexafluoride," Paper P/524, Proc. U. N. Intern. Conf. Peaceful Uses At. Energy, 2nd, Geneva, 1958, 4, 172-80 (1958)] and 2 vol % inert components.99.5% F₂ utilization in fluorination [90% F₂ utilization in primary fluorinator (Ruch et al., Ibid.) and 95% in F₂ cleanup reactor (Pedigo et al., "Fluidized Bed Recovery of Fluorine in the Manufacture of UF₆," Chem. Eng. Progr., Symp. Ser. Pt. 15, 62, 12-19 (1966))].

346 scfm of "inert" gases.

20 ppm of UF₆ in effluent from UF₆ cleanup reactor (Pedigo et al., Ibid.).

(3) Efficiencies of wet scrubbers are listed in Table 4.8.

(4) KOH scrubbers are recirculating systems operating at 25°C. Initial KOH concentration, 10 wt %; final concentration, 2 wt %.

Chemistry of scrubbers is described in Sect. 4.5.8.3.

(5) 100% excess CO₂ is added in uranium recovery assuming that all the uranium is present as soluble K₄UO₆.^bAssumptions discussed in Sect. 4.4.13.

n.a. = not applicable.

Table 4.24. Operating characteristics of fluorine cell^a

Amperage, A	6000
Anode current density, A/ft ²	143
Voltage, V	8-12
Inlet water temperature, °F	165-175
Outlet water temperature, °F	170-180
Hydrogen fluoride concentration, %	40-42
lb fluorine/thousands of A-hr	1.40
Life, millions of A-hr	15 to 30

^aData obtained from A. P. Huber, J. Dykstra, and B. H. Thompson, "Multi-ton Production of Fluorine for Manufacture of Uranium Hexafluoride," Paper P/524, Proc. U. N. Intern. Conf. Peaceful Uses At. Energy, 2nd, Geneva, 1958, 4, 172-80 (1958).

Table 4.25. Fluorine cell waste and recycle streams and material flows for the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant^a
(Codes shown in Figs. 4.3, 4.19, and 4.20; discussion in Sect. 4.5.9)

Stream		Case study	Gas flow (scfm)			Liquid flow (gal/day)	Flow rate (lb/day)								
Code	Type		Description	Total	N ₂		O ₂	F ⁻	H ⁺	H ₂ vapor or water condensed from gas phase	CO ₂	K ⁺	OH ⁻	H ₂	F ₂
7	Gaseous	Feed to fluorine cell H ₂ off-gas scrubbing system	1-3	372	256	22	4.46E+2	2.37E+1	6.47E+3	1.69E+1					
			4	368	234	20	1.87E+2	9.94E+0	5.91E+3	1.55E+1					
7A	Gaseous	Effluent released to atmosphere from fluorine cell H ₂ off-gas system	1	289	256	22	4.46E+1	2.37E+0	8.96E+2	1.69E+1					
			2,3	288	256	22	4.46E-1	2.37E-2	8.96E+2	1.69E-1					
			4	288	234	20	1.87E-2	9.94E-4	8.96E+2	1.55E-3					
7B	Gaseous	Feed to KOH scrubbers on H ₂ off-gas	1	n.a.			n.a.	n.a.	n.a.	n.a.					
			2,3	289	256	22	4.46E+1	2.37E+0	8.96E+2	1.69E+1					
			4	288	234	20	1.87E+1	9.94E-1	8.96E+2	1.55E+1					
7C	Gaseous	H ₂ effluent from HF condenser	1-3	98	2		4.46E+2	2.37E+1					7.24E+2		
			4	86	2		1.87E+2	9.94E+0					6.61E+2		
7D	Gaseous	H ₂ feed to HF condenser	1-3	100	2		6.14E+2	3.26E+1					7.24E+2		
			4	91	2		5.61E+2	2.98E+1					6.61E+2		
7E	Gaseous	F ₂ feed to HF condenser	1-3	164	2		8.33E+2	4.43E+1						1.365E+4	
			4	150	2		7.61E+2	4.04E+1						1.247E+4	
7F	Gaseous	F ₂ effluent from HF condenser - feed to fluorination	1-3	159	2		6.08E+2	3.23E+1						1.365E+4	
			4	140	2		2.78E+2	1.48E+1						1.247E+4	
7G	Gaseous	Air feed to H ₂ burner	1-3	321	254	67						1.69E+1			
			4	293	232	61						1.55E+1			
7K	Liquid	Waste stream from KOH scrubber on H ₂ off-gas	1				n.a.	n.a.	n.a.	n.a.	n.a.	n.a.			
			2,3				2.62E+2	4.46E+1	Nil	1.68E+1	1.52E+2	1.32E+1			
			4				1.41E+1	1.87E+1	Nil	1.55E+1	8.16E+1	7.12E+0			
7L	Liquid	Waste stream from water scrubber-condenser on H ₂ off-gas	1-3				1.44E+4	4.03E+2	2.14E+1	5.58E+3	-				
			4				1.44E+4	1.68E+2	8.95E+0	5.02E+3	-				
7M	Liquid	10% KOH feed to scrubber on H ₂ off-gas	1				n.a.								
			2,3				2.62E+2				1.52E+2	6.64E+1			
			4				1.41E+1				8.16E+1	3.56E+1			
7N	Liquid	Water feed to scrubber - condenser on H ₂ off-gas	1				1.44E+4								
			2,3				1.37E+3								
			4				1.38E+3								
7O	Liquid	HF recovered from H ₂ stream for recycle	1-3				1.68E+2	8.9 E+0							
			4				3.74E+2	1.99E+1							
7P	Liquid	HF recovered from F ₂ stream for recycle	1-3				2.25E+2	1.20E+1							
			4				4.83E+2	2.56E+1							

^aAssumptions:

- (1) As-produced H₂ (i.e., Stream 7D) contains 9 vol % HF and 2 vol % "inert" components; as-produced fluorine (i.e., Stream 7E) contains 11 vol % HF and 2 vol % "inert" components [A. P. Huber, J. Dykstra, and B. H. Thompson, "Multi-ton Production of Fluorine for Manufacture of Uranium Hexafluoride," Paper P/524, Proc. U. N. Intern. Conf. Peaceful Uses At. Energy, 2nd, Geneva, 1958, 4, 172-80 (1958)].
- (2) Fluorine utilization is 90% in Cases 1-3, 99.5% in Case 4.
- (3) Efficiencies of off-gas scrubbers and condensers are listed in Table 4.8.
- (4) 50% excess air is used in the H₂ burner.
- (5) Water scrubbers are single pass, 10 gpm, operating at 30°C.
- (6) KOH scrubbers are recirculating systems operating at 30°C. Initial KOH concentration, 10 wt %; final concentration, 2 wt %.

Table 4.26. Carbonate leach (uranium recycle) material flows for the model 10,000-metric ton/yr fluorination-fractionation UF_6 plant
(Codes shown in Fig. 4.4 and 4.5; discussion in Sect. 4.5.10)

Code	Stream		Case study	Liquid flow (gal/day)	Solid flow (lb/day)	Flow rate (lb/day)						
	Type	Description				U	F	Na	CO_3^{2-}	OH^-	Ca	CO_2
9Ua	Solid	Fluorination ash ^a	1-4		8998	1320	3914				3684	
9C	Gas	Recarbonation	1 2-4									n.a. 135 ^b
9L	Liquid	Waste stream from carbonate leach	1 2-4	7414 756	4978 244	2 0.2	352 12	2288 112	2218 115	118 5		
9La	Liquid	Bleed from carbonate circuit	1 2-4	n.a. 220	n.a. 202	n.a. 0.05	n.a. 10	n.a. 96	n.a. 96	n.a. 4		
9Ib	Liquid	Bleed from yellow cake wash	1 2-4	n.a. 536	n.a. 40	n.a. 0.15	n.a. 2	n.a. 18	n.a. 19	n.a. 1		
9M	Liquid	Carbonate leach feed	1 2-4	3676 3676	3674 3674 ^c	Traces	c	1594 1594 ^c	2080 2080			
9N	Liquid	Ash filter cake wash	1 2-4	1898 1898	332 1575 ^c	Traces	c	144 683 ^c	188 892			
9O	Liquid	Caustic precipitation feed	1 2-4	1108 784	1387 981	Traces	Traces	797 564		590 417		
9P	Liquid	Yellow cake wash	1-4	1320								
9Q	Slurry	Lime precipitation feed	1 2-4	n.a. 53	n.a. 354					n.a. 162	n.a. 192	
9R	Liquid	$CaCO_3$ - CaF_2 cake wash	1 2-4	n.a. 114	n.a. 93 ^c	n.a. Traces	n.a. c	n.a. 40 ^c	n.a. 53			
9S	Liquid	Recycle solution to recarbonation	1 2-4	n.a. 5680	n.a. 4822 ^c	n.a. Traces	n.a. c	n.a. 2048 ^c	n.a. 2670	n.a. 104		
9U	Solid	Recovered yellow cake	1 2-4	132 132	1446 1448	1317 1319	0.1 0.1	128 128	0.7 1.0	0.1 0.1		
9M' + 9N'	Solid	Makeup Na_2CO_3	1		4005			1738	2268			
9V	Solid	Makeup Na_2CO_3	2-4		700			270	352			
9W	Solid	Leached ash filter cake	1 2-4	474 474	7413 8326	1 1	3562 3835	120 584	46 222		3684 3684	
9X	Solid	$CaCO_3$ - CaF_2 filter cake from lime precipitation	1 2-4	n.a. 28	n.a. 440	n.a. 0.4	n.a. 67	n.a. 10	n.a. 196		n.a. 192	
10W	Solid	Dried waste containing most of the long-lived radioactive materials other than the UF_6 product	1 2-4		7380 8164	1 1	3562 3834	121 578			3684 3684	

^aDecayed 6 months.

^bIdealized stoichiometry is shown assuming that all the caustic is converted to Na_2CO_3 during recarbonation; cost estimates are based on 100% excess CO_2 as flue gas containing 12% CO_2 entering and 6% CO_2 exiting the recarbonation tower.

^cSolution contains 16.8 g of NaF per liter in addition to the chemicals listed.

n.a. = not available.

Table 4.27. Sodium removal material flows for the model 10,000-metric ton/yr fluorination-fractionation UF_6 plant^{a,b}
 (Codes shown in Figs. 4.1, 4.2, 4.4, and 4.5; discussion in Sect. 4.5.11)

Code	Stream		Case study	Liquid flow (gal/day)	Flow rate (lb/day)				
	Type	Description			U	Na ⁺	K ⁺	NH ₄ ⁺	SO ₄ ²⁻
2U	Solid	Na ₂ U ₂ O ₇ from carbonate leach uranium mills	1,2 3,4		11,020 None	1250 None			
9U	Solid	Na ₂ U ₂ O ₇ recovered by carbonate leach of fluorination ash	1-4		1,320	128			
8Ub	Solid	K ₂ U ₂ O ₇ recovered from fluorination off-gas scrubbers	1-3 4		268 6		51 2		
2U	Solid	Composite uranium feed to sodium removal	1,2 3 4		12,610 1,580 1,320	1370 128 128	51 51 2		
11L	Liquid	Waste stream from sodium removal	1,2 3 4	31,430 3,610 2,930	5 0.6 0.5	1290 120 120	48 48 2	6120 700 570	19,060 2,190 1,780
11M	Liquid	Liquid feed to (NH ₄) ₂ SO ₄ wash	1,2 3 4	31,430 3,610 2,930				7160 820 670	19,060 2,190 1,780
11U	Solid	(NH ₄) ₂ U ₂ O ₇ product of sodium removal	1,2 3 4		12,600 1,580 1,320	82 8 8	3 3 -	1040 120 120	

^aNot shown are the carbonate and caustic anions in the yellow cake feed and liquid waste or the sulfate anions in the (NH₄)₂U₂O₇ product.

^bAssumptions:

- (1) Stream 2U contains 11.3 wt % sodium on a uranium basis (average of Na₂U₂O₇ received at Kerr-McGee UF₆ plant in 1973).
- (2) Stream 9U contains 10 wt % sodium on a uranium basis (Table 4.26).
- (3) Stream 8Ub contains 19.2 wt % potassium on a uranium basis (equivalent to sodium on a mole basis).
- (4) (NH₄)₂U₂O₇ product (Stream 11U) contains 0.5 wt % sodium on a uranium basis (R. C. Merritt, The Extractive Metallurgy of Uranium, Colorado School of Mines Research Institute, 1971, p. 234).
- (5) Initial (NH₄)₂SO₄ concentration in Stream 11M is 10 wt %; final sodium concentration waste 11L is 0.5 wt %.

Table 4.28. Evaporation of liquid wastes at the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant - Case 4

(For liquid wastes unsuited to chemical treatment; discussion given in Sect. 4.4.12; chemical compositions of liquid feeds to the evaporator in Tables 4.18, 4.25, and 4.26; the radionuclide composition of the solids generated in Table 4.11; codes shown on Figs. 4.1, 4.5, 4.12, and 4.27.)

Liquid waste treated		Volume treated (gal/day)	Chemical usage H ₂ SO ₄ (lb/day)	Solid waste generated (lb/day)					
Source	Code			Code	Total	(NH ₄) ₂ SO ₄	Na ₂ SO ₄	NaF	U
<u>Case 4</u>									
Reduction water scrub liquor	3L	9.46E+2	-	3Z	2.07E-1	-	-	-	2.08E-1
Carbonate leach liquid bleed	9L	7.56E+2	2.04E+2	9Z	3.25E+2	-	2.96E+2	2.87E+1	1.90E-1
Sodium removal process waste	11L	<u>2.93E+3</u>	-	11Z	<u>2.47E+3</u>	<u>2.09E+3</u>	<u>3.81E+2</u>	-	<u>4.91E-1</u>
Total		4.63E+3			2.80E+3	2.09E+3	6.77E+2	2.87E+1	8.89E-1

Table 4.29. Chemical treatment of liquid wastes at the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant^a
 (Chemical compositions of liquid wastes given in Tables 4.18-4.26; composition of liquid effluents from waste treatment given in Tables 4.9 and 4.10)

Liquid waste treated	Volume treated (gal/day)	Chemical usage (lb/day)			Solid waste generated (lb/day)								Liquid ^d bleed retained with solids (gal/day)	Liquid effluent from waste treatment			
		Source	Code	CaO ^b	Copperas (FeSO ₄ ·7H ₂ O)	BaCl ₂	Code	Total	CaF ₂	CaCO ₃ ^c	Ca(OH) ₂ ^c	CaSO ₃ ·1/2H ₂ O		FeSO ₄ ·7H ₂ O	BaSO ₄	U	Code
Case 2																	
Fluoride treatment system for water scrub liquors																	
Hydrofluorination	4L	2.88E+4	2.80E+3		4X	4.75E+3	4.34E+3		4.12E+2					1.76E-2 ^e	1.99E+2	4LT	Release
Fluorine cell H ₂	7L	1.44E+4	5.35E+2		7X	9.08E+2	8.29E+2		7.87E+1					-	3.80E+1	7LT	Release
KOH regeneration by fluoride precipitation (scrub liquors)																	
Hydrofluorination	4K	1.04E+3	3.13E+2		4Y	5.28E+2	4.82E+2		4.58E+1					7.34E-4 ^e	2.22E+1		Recycle
Fluorine cell H ₂	7K	2.62E+2	5.92E+1		7Y	1.00E+2	9.18E+1		8.71E00					-	4.19E00		Recycle
Fluorination	8K	9.14E+3	3.49E+3		8Y	5.12E+3	4.07E+3	6.79E+2	4.43E+2					2.28E00 ^e	2.15E+2		Recycle
Carbonate leach recycle circuit (internal process)	9M + 9N + 9W	5.10E+3	2.68E+2 ^f		9X	4.40E+2	1.36E+2	3.05E+2	f					7.36E-2	2.84E+1		Recycle
Case 3																	
Fluoride treatment system for water scrub liquors																	
Hydrofluorination	4L	2.88E+4	2.80E+3		4X	4.75E+3	4.34E+3		4.12E+2					1.76E-2 ^e	1.99E+2	4LT	Release
Fluorine cell H ₂	7L	1.44E+4	5.35E+2		7X	9.08E+2	8.29E+2		7.87E+1					-	3.80E+1	7LT	Release
KOH regeneration by fluoride precipitation (scrub liquors)																	
Hydrofluorination	4K	1.04E+3	3.13E+2		4Y	5.28E+2	4.82E+2		4.58E+1					7.34E-4 ^e	2.22E+1		Recycle
Fluorine cell H ₂	7K	2.62E+2	5.92E+1		7Y	1.00E+2	9.18E+1		8.71E00					-	4.19E00		Recycle
Fluorination	8K	9.14E+3	3.49E+3		8Y	5.12E+3	4.07E+3	6.79E+2	4.43E+2					2.28E00 ^e	2.15E+2		Recycle
Carbonate leach recycle circuit (internal process)	9M + 9N + 9W	5.10E+3	2.68E+2 ^f		9X	4.40E+2	1.36E+2	3.05E+2	f					7.36E-2	2.84E+1		Recycle
Radium precipitation system for process effluents																	
Carbonate leach liquid bleed	9L	7.56E+2		1.26E00	9Y	1.26E00					1.26E00			2.04E-5	8.15E-2	9LT	Release
Sodium removal process waste	11L	3.61E+3			11Y	4.73E00					4.73E00			5.12E-5	3.06E-1	11LT	Release
Case 4																	
Fluoride treatment system for water scrub liquor																	
Fluorine cell H ₂	7L	1.44E+4	2.23E+2		7X	3.78E+2	3.46E+2		3.28E+1					-	1.58E+1	7LT	Release
KOH regeneration by fluoride precipitation (scrub liquors)																	
Hydrofluorination	4K	1.56E+2	4.70E+1		4Y	7.92E+1	7.24E+1		6.87E00					7.34E-4 ^e	3.32E00		Recycle
Fluorine cell H ₂	7K	1.41E+1	2.48E+1		7Y	4.21E+1	3.85E+1		3.65E00					-	1.76E-1		Recycle
Fluorination	8K	1.65E+3	6.10E+2		8Y	7.87E+2	7.02E+2	1.02E+1	7.43E+1					4.14E-1 ^e	3.30E+1		Recycle
KOH regeneration by sulfite precipitation (scrub liquors)																	
Reduction	3K	4.01E+3	1.42E+3		3Y	3.13E+3		6.1E+1	1.71E+2	2.90E+3				1.03E-3 ^e	2.02E+2		Recycle
Carbonate leach recycle circuit (internal process)	9M + 9N + 9W	5.10E+3	2.68E+2 ^f		9X	4.40E+2	1.36E+2	3.05E+2	f					7.36E-2	2.84E+1		Recycle

^aDoes not include internal process changes to reduce the load to liquid waste treatment unless they generate additional solid waste (i.e., carbonate leach recycle circuit).

^bIncludes 10% excess.

^cWith time, excess Ca(OH)₂ will tend to react with CO₂ in the environment to form CaCO₃.

^dAssumes that settled solids or filter cakes retain 35 wt % moisture.

^eMaximizing assumptions: 100% of uranium in solution precipitates; 10% remains in solution (i.e., sum does not balance - purpose is to avoid underestimating either waste).

^fNo excess CaO.

Table 6.1. Estimated capital and annual costs and contribution to power cost for the 10,000-metric ton/yr model fluorination-fractionation process UF₆ conversion plant

Radwaste case	Building ventilation (\$1000)			Dust control (\$1000)			Process off-gas (\$1000)			Liquid and solid chemwaste-radwaste (\$1000)			Total waste treatment (\$1000)			Contribution to power cost ^b (mills/kWhr)					
	Capital cost ^a	Annual fixed charge	Annual operating cost	Total annual cost	Capital cost ^a	Annual fixed charge	Annual operating cost	Total annual cost	Capital cost ^a	Annual fixed charge	Annual operating cost	Total annual cost	Capital cost ^a	Annual fixed charge	Annual operating cost		Total annual cost				
1	(BASE CASE)																				
2	N.A.	N.A.	N.A.	N.A.	867.9	225.7	26.2	251.9	98.4 ^c	25.6	12.5	38.1	1051	273.3	119.4 ^d	392.7	2017	524.6	158.1	682.7	0.00126
3	1363 ^e	354.4	57.9	412.3	867.9	225.7	26.2	251.9	131.5	34.2	15.5	49.7	1158	301.2	127.6 ^d	428.8	3520	915.5	227.2	1143	0.00211
4	4569 ^e	1188	248	1436	1092	284.1	35.3	319.4	474.2 ^f	123.3	54.4	177.7	1215 ^g	315.7	659.6 ^h	975.3	7350	1911	997.2	2908	0.00536

^aIncludes direct cost (installed equipment but not structure cost) and indirect cost. The interest during construction is included as an indirect cost.

^bThe contribution to power cost is calculated on the basis of a 10,000-ton/yr UF₆ conversion plant servicing a nuclear economy of about seventy-seven 1000-MW(e) LWRs (irradiated level, 33,000 MWd/metric ton; load factor, 80%; thermal efficiency, 32.5%). The costs include the direct charges but do not include the effect of carrying charges on fuel working capital.

^cIncludes a capital cost credit of \$74,500 for replacement of Case 1 reduction off-gas equipment.

^dIncludes an annual expense for lime of \$31,500 as an additional operating cost.

^eIncludes a capital cost credit of \$178,100 for Case 1 building exhaust fans.

^fIncludes a capital cost credit of \$146,300 for replacement of Case 1 reduction, hydrofluorination, and fluorination and fluorine cell off-gas equipment.

^gIncludes a capital cost credit of \$149,800 for Case 1 leached fluorination ash dryer.

^hIncludes the following annual expenses as additional annual operating costs: lime - \$9700; drums for packaging dried solids - \$41,800; cement for leached and filtered fluorination ash - \$128,600; and drums for packaging cemented fluorination ash - \$374,000. The cost of storing the drums on-site or shipping off-site for storage or burial is not included.

Table 6.2. Installed costs^a of equipment for the 10,000-metric ton/yr model fluorination-fractionation process UF₆ conversion plant

WASTE TREATMENT CASE 2

Item	Costs without structure (\$1000)	
	Direct ^b	Capital ^c
Pulse jet bag filter, 10,000 cfm	124.0	298.0
Pulse jet bag filter, 10,000 cfm	84.0	202.0
Pulse jet bag filter, 6400 cfm	65.0	156.0
Pulse jet bag filter, 4000 cfm	49.0	118.0
Pulse jet bag filter, 2600 cfm	38.0	91.0
Natural gas air heater, 2661 Btu/min	0.7	1.7
Natural gas air heater, 1584 Btu/min	0.5	1.2
Off-gas burner, 328 scfm	5.1	12.2
H ₂ O venturi scrubber, condenser, and demister, 850 scfm	11.6	27.8
KOH packed tower, 12 in. diam x 15 ft high, SS	12.8	30.7
Pump, 1 gpm, centrifugal (2)	2.6	6.2
Mixing tank, 250 gallon, C.S. (2)	8.6	20.6
KOH coke box, 8 ft diam x 8 ft high	14.1	34.6
KOH packed tower, 1.6 ft diam x 15 ft high, SS	17.0	40.8
Centrifuge, 20 in., vertical basket	13.0	31.2
Mixing tank, 3700 gallon, CS (2)	33.2	79.7
Filter, rotary drum vacuum, 15 ft ²	16.5	39.6
Pump, 20 gpm, centrifugal (6)	10.4	25.0
Lime storage tank, 4000 gallon, CS (2)	11.0	26.4
Lime conveyor, screw, 6 in. diam x 20 ft (2)	15.2	36.4
Filter cake conveyor, screw, 6 in. diam x 25 ft	9.6	23.0
Slurry mix tank, 850 gallon, CS (2)	20.4	49.0
Slurry pump, 5 gpm, centrifugal (2)	3.0	7.2
Pipeline, 1000 ft, 3 in. ABS, 150 pipe (2)	2.6	6.2
Mixing tank, lead lined, 10,000 gallon (2)	86.0	206.4
Pump, 50 gpm, centrifugal	2.2	5.3
Mixing tank, 7000 gallon, CS (2)	47.0	112.8
Mixing tank, 250 gallon, CS (2)	8.9	21.4
Filter, rotary drum vacuum, 3 ft ²	6.3	15.1
Packed tower, 1.7 ft diam x 44 ft high	17.0	40.8
Surge tank, 7500 gallon, CS (2)	20.5	49.2
Lagoon, lined, 4.38 x 10 ³ gallon	83.3	200.0
TOTAL	839.1	2014

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

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

^cCapital costs are calculated by multiplying the direct cost by 2.4. Capital costs include direct costs and indirect costs.

Table 6.3. Installed costs^a of equipment for the 10,000-metric ton/yr model fluorination-fractionation process UF₆ conversion plant

WASTE TREATMENT CASE 3

Item	Costs without structure (\$1000)	
	Direct ^b	Capital ^c
Baffle orifice scrubber, 60,000 cfm (8)	642.0	1541.0
Pulse jet bag filter, 19,000 cfm	124.0	298.0
Pulse jet bag filter, 10,000 cfm	84.0	202.0
Pulse jet bag filter, 6400 cfm	65.0	156.0
Pulse jet bag filter, 4000 cfm	49.0	118.0
Pulse jet bag filter, 2600 cfm	38.0	91.0
Natural gas air heater, 2661 Btu/min	0.7	1.7
Natural gas air heater, 1584 Btu/min	0.5	1.2
Off-gas burner, 328 scfm	5.1	12.2
H ₂ O venturi scrubber, condenser and demister, 850 scfm	11.6	27.8
KOH packed tower, 12 in. diam x 15 ft high, SS	12.8	30.7
Pump, 1 gpm, centrifugal (2)	2.6	6.2
Mixing tank, 250 gallon, CS (4)	17.5	42.0
KOH coked box, 8 ft diam x 8 ft high	14.1	34.6
KOH packed tower, 1.6 ft diam x 15 ft high, SS	17.0	40.8
KOH venturi scrubber and demister, 1200 cfm	13.8	33.1
Centrifuge, 20 in., vertical basket	13.0	31.2
Mixing tank, 3700 gallon, CS (2)	33.2	79.7
Filter, rotary drum vacuum, 15 ft ²	16.5	39.6
Pump, 20 gpm, centrifugal (6)	10.4	25.0
Lime storage tank, 4000 gallon, CS (2)	11.0	26.4
Lime conveyor, screw, 6 in. diam x 20 ft (2)	15.2	36.4
Filter cake conveyor, screw, 6 in. diam x 25 ft	9.6	23.0
Slurry mix tank, 850 gallon, CS (2)	20.4	49.0
Slurry pump, 5 gpm, centrifugal (2)	3.0	7.2
Pipeline, 1000 ft, 3 in. ABS, 150 pipe (3)	3.9	9.3
Mixing tank, lead lined, 10,000 gallon (2)	86.0	206.0
Pump, 50 gpm, centrifugal	2.2	5.3
Mixing tank, 7000 gallon, CS (2)	47.0	112.8
Filter, rotary drum vacuum, 3 ft ²	6.3	15.1
Packed tower, 1.7 ft diam x 44 ft high	17.0	40.8
Surge tank, 7500 gallon, CS (2)	20.5	49.2
Mixing tank, 1000 gallon, CS	8.9	21.4
Mixing tank, 5000 gallon, CS	19.4	46.6
Pump, 10 gpm, centrifugal (3)	4.9	11.8
H ₂ SO ₄ tank, lead lined, 500 gallon (2)	18.9	45.4
Pump, 1 gpm, metering (2)	4.8	11.5
pH control equipment	8.0	19.2
Lagoon, lined, 4.38 x 10 ⁶ gallon	83.3	200.0
Lagoon, lined, 1.31 x 10 ⁶ gallon	10.1	24.2
TOTAL	1571	3771

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

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

^cCapital costs are calculated by multiplying the direct cost by 2.4. Capital costs include direct costs and indirect costs.

Table 6.4. Installed costs^a of equipment for the 10,000-metric ton/yr model fluorination-fractionation process UF₆ conversion plant

WASTE TREATMENT CASE 4

Item	Costs without structure (\$1000)	
	Direct ^b	Capital ^c
Pulse jet bag filter, 60,000 cfm (8)	1978.0	4747.0
Pulse jet bag filter, 19,000 cfm	124.0	298.0
Pulse jet bag filter, 10,000 cfm	84.0	202.0
Pulse jet bag filter, 6400 cfm	65.0	156.0
Pulse jet bag filter, 4000 cfm	49.0	118.0
Pulse jet bag filter, 2600 cfm	38.0	91.0
Natural gas air heater, 2661 Btu/min	0.7	1.7
Natural gas air heater, 1584 Btu/min (2)	1.0	2.4
HEPA filters, 20,000 cfm	30.0	72.0
HEPA filters, 10,000 cfm	15.0	36.0
HEPA filters, 7000 cfm	10.5	25.2
HEPA filters, 4000 cfm	6.0	14.4
HEPA filters, 3000 cfm	4.5	10.8
HEPA filters, 1000 cfm	1.5	3.6
Blowers	15.9	38.2
Duct	13.1	31.4
Off-gas burner, 328 scfm	5.1	12.2
H ₂ O venturi scrubber, condenser and demister, 850 scfm	11.6	27.8
KOH venturi scrubber, 730 scfm	8.7	20.9
Condenser, Karbate, 10 ⁶ Btu/hr (2)	12.0	28.8
HF tanks, lead lined, 500 gallon (2)	10.0	24.0
Refrigeration unit, 2 ton with brine tank and pump	12.0	28.8
KOH packed tower, 12 in. diam x 15 ft high, SS	12.8	30.7
Pump, 1 gpm, centrifugal (2)	2.6	6.2
Mixing tank, 250 gallon, CS (4)	17.2	41.2
Condenser, Karbate, 17.7 ft ² (2)	4.5	10.8
Refrigeration system, 7 ton, -120°F	136.0	326.4
KOH packed tower, 1.6 ft diam x 15 ft high, SS	17.0	40.8
KOH coke box, 8 ft diam x 8 ft high	14.1	34.6
Natural gas air heater, 1584 Btu/min	0.5	1.2
Mixing tank, 1800 gallon, CS (4)	44.3	106.3
Pump, 5 gpm, centrifugal (6)	9.0	21.6
Filter, rotary drum vacuum, 8 ft ²	11.0	26.4
Filter cake conveyor, screw, 6 in. diam x 25 ft	9.6	23.0
Slurry pump, 5 gpm, centrifugal (2)	2.7	6.5
Mixing tank, 7000 gallon, CS (2)	47.0	112.8
Packed tower, 1.7 ft diam x 44 ft high	17.0	40.8
Surge tank, 7500 gallon, CS (2)	20.5	49.2
Pipeline, 2000 ft, 2 in. ABS, 150 pipe	1.6	3.8
Lime storage tank, 1400 gallon, CS	2.7	6.5
Lime conveyor, screw, 6 in. diam x 20 ft	3.0	7.2
Mixing tank, 2000 gallon, CS (2)	23.5	56.4
H ₂ SO ₄ tank, lead lined, 500 gal. (4)	37.8	90.8
Pump, 1 gpm, centrifugal (4)	5.2	12.5
pH control equipment (2)	16.0	38.4
Evaporator, 60 ft ²	26.7	64.1
Condenser, 114 ft ²	6.3	15.1
Surge tank, 2000 gallon, CS	4.0	9.6
Calciner, direct rotary, 20 ft ³	20.6	49.4
Mixing tank, 6400 gallon, CS (2)	44.3	106.3
Pump, 20 gpm, centrifugal (4)	6.8	16.3
Pipeline, 1000 ft, 3 in. ABS, 150 pipe	1.9	4.6
Centrifuge, 12 in. vertical basket	7.8	18.7
Mixing tank, 2500 gallon, CS (2)	27.7	66.5
Filter, rotary drum vacuum, 3 ft ² (2)	12.6	30.2
Pump, 1 gpm, metering (2)	4.8	11.5
Lagoon, lined, 1.41 x 10 ⁶ gallon	10.6	25.4
Lagoon, lined, 8.45 x 10 ⁶ gallon	31.0	74.4
Cement plant	75.6	181.4
TOTAL	3232	7757

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

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

^cCapital costs are calculated by multiplying the direct cost by 2.4. Capital costs include direct costs and indirect costs.

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

	<u>Latitude (N)</u>	<u>Longitude (W)</u>
Midwestern site	35° 52' 50"	97° 35' 00"
	38° 12' 18"	90° 28' 28"
	41° 22' 43"	88° 16' 36"
Western (milling) site	35° 15' 50"	107° 55' 50"
	35° 24' 30"	107° 50' 00"
	43° 04' 00"	105° 30' 00"
	42° 49' 00"	107° 37' 00"
	38° 19' 30"	108° 45' 00"

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	1197	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	6,200	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	2460 ±1453	4157 ±4280	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	3331	7488	30,129	70,627	237,996	1,086,821	2,411,517	3,562,135
Density (ind./mile ²)												

^aStandard deviation of the mean (total).

Table 7.3. Representative population distribution at successive distances for western (milling) sites in the United States

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	0	38	0	0	5	306	2,330
NNE	0	0	0	0	146	0	0	0	0	67	259	6,053
NE	0	0	0	0	0	0	0	0	0	80	194	1,197
ENE	0	0	0	0	0	0	0	0	105	91	909	2,232
E	0	0	0	0	0	0	0	71	0	58	39	755
ESE	0	0	0	0	0	0	0	426	0	483	193	328
SE	0	0	0	0	0	0	995	164	0	411	295	7
SSE	0	0	0	0	0	0	1196	0	722	365	268	353
S	0	0	0	0	0	0	0	0	1931	0	225	0
SSW	0	0	0	0	0	0	0	327	580	280	206	0
SW	0	0	0	0	0	0	0	0	303	179	466	92
WSW	0	0	191	0	0	0	0	0	168	181	5,578	5,226
W	0	0	0	0	0	0	97	197	0	79	69	4,185
WNW	0	0	0	0	0	0	0	102	135	338	2,954	4,881
NW	0	0	0	0	0	0	0	0	0	643	858	365
NNW	0	0	0	0	0	0	0	197	91	410	197	181
Mean (by distance)	0	0	12 ±106 ^a	0	9 ±81	0	145 ±865	93 ±275	255 ±1063	229 ±458	813 ±3,271	1,761 ±4,828
Cumulative	0	0	191	191	337	337	2663	4147	8182	11,852	24,868	53,053
Density (ind./mile ²)			← 4.3 →				9.9	← 3.0 →			← 7.1 →	

^aStandard deviation of the mean.

Table 7.4. Maximum annual doses^a to individuals^{b,c} from airborne effluents from a model F-F UF₆ plant^d

ALL AIRBORNE EFFLUENTS

Airborne radwaste treatment case	Individual total-body dose (mrem)	Adult organ doses (mrem)									
		GI tract	Bone	Thyroid	Lung	Muscle	Kidney	Liver	Spleen	Testes	Ovaries
<u>Midwestern site</u>											
1	9.9E00	5.8E00	1.3E+2	1.0E+1	3.8E+1	9.5E00	2.7E+1	1.0E+1	8.7E00	9.8E00	8.1E00
2	3.8E00	2.2E00	5.1E+1	4.0E00	1.5E+1	3.6E00	1.0E+1	3.9E00	3.4E00	3.8E00	3.1E00
3	1.2E00	7.0E-1	1.6E+1	1.2E00	5.0E00	1.1E00	3.4E00	1.2E00	1.1E00	1.2E00	9.7E-1
4	1.9E-2	1.5E-2	1.2E-1	1.9E-2	6.3E-1	1.8E-2	1.9E-1	5.4E-2	9.5E-2	2.0E-2	1.4E-2
<u>New Mexico site</u>											
1	1.3E+1	7.4E00	1.8E+2	1.4E+1	5.3E+1	1.2E+1	3.7E+1	1.3E+1	1.2E+1	1.3E+1	1.1E+1
2	5.0E00	2.8E00	6.9E+1	5.2E00	2.1E+1	4.8E00	1.4E+1	5.2E00	4.5E00	4.9E00	4.1E00
3	1.6E00	8.9E-1	2.2E+1	1.6E00	7.1E00	1.5E00	4.6E00	1.7E00	1.5E00	1.5E00	1.3E00
4	2.6E-2	2.0E-2	1.7E-1	2.6E-2	9.2E-1	2.4E-2	2.8E-1	7.7E-2	1.4E-1	2.8E-2	2.0E-2

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

^bMaximum dose to individual at 0.5 mile (800 m) and downwind of the prevailing wind direction. Release height: 5 m. Average dose is 47% of the maximum.

^cAll food is produced and consumed at the location of the dose calculation. Daily intakes are 1.0 liter of milk, 0.25 kg of vegetables, and 0.3 kg of beef.

^d10,000-metric ton/yr fluorination-fractionation plant.

Table 7.4a. Doses^a to individuals and to population from airborne effluents from a model F-F UF₆ plant^b

DUST CONTROL EFFLUENT

Airborne radwaste treatment case	Maximum annual individual doses at 0.5 mile (800 m)				Annual doses to population within 55 miles	
	Total-body dose (mrem)	Adult organ doses (mrem)			Total-body (person-rem)	Bone (person-organ-rem)
		Bone	Lung	Kidney		
<u>Midwestern site</u>						
1	6.4E00	8.9E+1	2.4E+1	1.8E+1	6.0E00	7.4E+1
2	8.8E-1	1.2E+1	3.3E00	2.4E00	8.2E-1	1.0E+1
3	8.8E-1	1.2E+1	3.3E00	2.4E00	8.2E-1	1.0E+1
4	4.9E-4	6.6E-3	1.8E-3	1.3E-3	4.5E-4	6.1E-3
<u>New Mexico site</u>						
1	8.5E00	1.2E+2	3.3E+1	2.5E+1	1.3E-1	1.8E00
2	1.1E00	1.6E+1	4.6E00	3.3E00	1.8E-2	2.5E-1
3	1.1E00	1.6E+1	4.6E00	3.3E00	1.8E-2	2.5E-1
4	6.4E-4	9.9E-3	2.5E-3	1.8E-3	1.1E-5	1.3E-4

^a50-yr dose commitment from exposure to effluents from one year's operation of the model plant. Release height: 5 m.

^b10,000-metric ton/yr fluorination-fractionation plant.

Table 7.4b. Doses to individuals^a and to population from airborne effluents from a model F-F UF₆ plant^b

PROCESS OFF-GAS

Airborne radwaste treatment case	Maximum annual individual doses at 0.5 mile (800 m) ^a				Annual doses to population within 55 miles ^a	
	Total-body dose (mrem)	Adult organ doses (mrem)			Total-body (person-rem)	Bone (person-organ-rem)
		Bone	Lung	Kidney		
<u>Midwestern site</u>						
1	8.0E-1	6.9E00	3.9E00	1.7E00	7.5E-1	9.2E00
2	2.5E-1	2.4E00	1.2E00	5.6E-1	2.4E-1	3.0E00
3	1.1E-1	1.2E00	4.4E00	2.7E-1	9.8E-2	1.2E00
4	2.3E-5	4.3E-4	5.8E-5	2.3E-5	2.1E-5	2.9E-4
<u>New Mexico site</u>						
1	1.0E00	9.2E00	5.5E00	2.2E00	1.6E-2	2.3E-1
2	3.3E-1	3.2E00	1.7E00	5.8E00	5.2E-3	7.3E-2
3	1.3E-1	1.7E00	6.0E-1	3.5E-1	2.1E-3	3.0E-2
4	3.1E-5	6.0E-4	8.0E-5	1.1E-4	5.5E-7	6.4E-6

^a50-year dose commitment from exposure to effluents from one year's operation of the model plant. Release height: 5 m.

^b10,000-metric ton/yr fluorination-fractionation plant.

Table 7.4c. Doses to individuals^a and to population from airborne effluents from a model F-F UF₆ plant^b

BUILDING VENTILATION EFFLUENT

Airborne radwaste treatment case	Maximum annual individual doses at 0.5 mile (800 m)				Annual doses to population within 55 miles	
	Total-body dose (mrem)	Adult organ doses (mrem)			Total-body (person-rem)	Bone (person-organ-rem)
		Bone	Lung	Kidney		
<u>Midwestern site</u>						
1	2.7E00	3.6E+1	9.7E00	7.4E00	2.5E00	3.0E+1
2	2.7E00	3.6E+1	9.7E00	7.4E00	2.5E00	3.0E+1
3	1.8E-1	2.6E00	6.9E-1	5.2E-1	1.7E-1	2.1E00
4	2.7E-3	3.8E-2	1.0E-2	7.6E-3	2.5E-3	3.4E-2
<u>New Mexico site</u>						
1	3.5E00	4.9E+1	1.4E+1	1.0E+1	5.5E-2	7.7E-1
2	3.5E00	4.9E+1	1.4E+1	1.0E+1	5.5E-2	7.7E-1
3	2.4E-1	3.4E00	9.6E-1	7.1E-1	3.8E-3	5.3E-2
4	3.5E-3	5.1E-2	1.4E-2	1.0E-2	6.2E-5	7.3E-4

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

Release height: 5 m.

^b10,000-metric ton/yr fluorination-fractionation plant.

Table 7.5. Annual doses^a to the population^b from airborne effluents from a model F-F UF₆ plant^c
ALL AIRBORNE EFFLUENTS

Airborne radwaste treatment case	Population total-body dose (person-rems)	Population organ dose (person-organ-rems)									
		GI tract	Bone	Thyroid	Lung	Muscle	Kidney	Liver	Spleen	Testes	Ovaries
<u>Midwestern site</u>											
1	9.3E00	6.6E00	1.1E+2	9.9E00	3.4E+1	8.8E00	2.5E+1	9.2E00	8.0E00	9.3E00	7.2E00
2	3.6E00	2.6E00	4.4E+1	3.8E00	1.5E+1	3.4E00	1.0E+1	3.7E00	3.2E00	3.6E00	2.8E00
3	1.2E00	8.5E-1	1.4E+1	1.3E00	6.5E00	1.1E00	3.9E00	1.3E00	1.1E00	1.2E00	9.2E-1
4	1.2E-1	8.9E-2	5.8E-1	1.2E-1	2.8E00	1.1E-1	1.1E00	2.0E-1	2.0E-1	1.4E-1	7.6E-2
<u>New Mexico site</u>											
1	2.1E-1	1.3E-1	2.8E00	2.2E-1	9.5E-1	2.0E-1	6.3E-1	2.1E-1	1.8E-1	2.0E-1	1.6E-1
2	8.0E-2	5.1E-2	1.1E00	8.4E-2	4.2E-1	7.6E-2	2.6E-1	8.5E-2	7.2E-2	8.0E-2	6.3E-2
3	2.7E-2	1.7E-2	3.5E-1	2.8E-2	1.9E-1	2.5E-2	1.0E-1	3.0E-2	2.6E-2	2.7E-2	2.1E-2
4	3.0E-3	2.2E-3	1.6E-2	3.0E-3	8.6E-2	2.7E-3	3.1E-2	5.5E-3	5.4E-3	3.3E-3	1.9E-3

^a50-year dose commitment from exposure to effluents from one year's operation of the model plant. Release height: 5 m.

^bEntire population within 55 miles of the model plant; daily food intakes are 300 mL of milk, 0.25 kg of vegetables, and 0.3 kg of meat. All food is produced and consumed at the reference location.

^c10,000-metric ton/yr fluorination-fractionation plant.

Table 7.6. Exposure modes contributing to total-body dose from airborne effluents of a model F-F UF₆ plant^a

Terrestrial exposure mode	Maximum annual individual total-body dose ^b (mrem)	Percent of total-body dose
Submersion in air ^c	0.002	0.019
Contaminated ground ^c	3.2	31.8
Inhalation ^d	2.2	22.6
Ingestion ^e	4.5	45.6

^a10,000-metric ton/yr fluorination-fractionation plant.

^bCase 1 at 0.5 mile (800 m) downwind from the plant; midwestern site.

^cExposure for 100% of the time; no shielding.

^dInhalation rate of 20 m³ of air per day.

^eAll food is produced and consumed at the location of the dose calculation. Daily intakes are 1.0 liter of milk, 0.25 kg of vegetables, 0.3 kg of beef.

Table 7.7. Major radionuclides contributing to doses from airborne effluents from a model F-F UF₆ plant^a

Radionuclide	Percent of total-body or organ dose ^b					
	Total body	GI tract	Bone	Thyroid	Lung	Kidney
²²⁶ Ra	29.5	0.7	21.4	28.3	8.1	10.7
²³⁰ Th	17.8	1.0	48.6	17.1	20.4	51.3
²³⁴ Th	<0.1	13.9	<0.1	<0.1	0.1	0.2
²³⁴ U	13.9	19.2	13.6	12.0	33.6	15.9
²³⁵ U	7.1	6.7	1.1	8.5	2.3	2.2
²³⁸ U	31.6	58.2	15.2	34.2	33.9	19.3
²²² Rn (as gaseous release) ^c	0.2	0.2	0.1	0.2	1.6	0.7

^aFluorination-fractionation plant.

^bMaximum 50-yr dose commitment to individual at 0.5 mile (800 m) from exposure to Case 1 effluents from one year's operation of the model plant at the midwestern site.

^cIncludes daughters ²¹⁸Po and ²¹⁴Pb from assuming 7-min decay of ²²²Rn gas after it leaves the plant.

Table 7.8. Major radionuclides contributing to exposure modes for airborne effluents from a model F-F UF₆ plant^{a,b}

Radionuclide	Percent of total-body exposure mode ^c				Percent of organ exposure mode					
	Submersion ^d in air	Contaminated ^d ground	Inhalation ^e	Ingestion ^f	Bone		Lung		Kidney	
					Inhalation ^e	Ingestion ^f	Inhalation ^e	Ingestion ^f	Inhalation ^e	Ingestion ^f
²²⁶ Ra	<0.1	0.1	0.4	64.8	0.1	51.2	0.5	64.8	<0.1	31.4
²³⁰ Th	<0.1	0.6	74.6	1.0	87.4	2.8	24.8	1.0	85.6	4.6
²³⁴ Th	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	0.1	<0.1	0.3	<0.1
²³⁴ U	<0.1	8.5	12.8	18.0	6.4	23.7	38.2	18.0	7.0	33.7
²³⁵ U	<0.1	21.7	0.3	0.4	0.1	0.5	0.9	0.4	0.2	0.8
²³⁸ U	<0.1	68.9	11.3	15.8	5.9	21.7	33.3	15.8	6.1	29.5
²²² Rn (as gaseous release) ^g	99.8	0.2	0.3	<0.1	0.1	<0.1	2.1	<0.1	0.9	<0.1

^aFluorination-fractionation plant.

^bCase 1 at 0.5 mile (800 m) downwind from the plant, midwestern site.

^cContributions of exposure modes to total-body dose given in Table 7.6.

^dExposure for 100% of the time; no shielding.

^eInhalation rate of 20 m³ of air per day.

^fAll food is produced and consumed at the location of the dose calculation. Daily intakes are 1.0 liter of milk, 0.25 kg of vegetables, and 0.3 kg of beef.

^gIncludes daughters ²¹⁸Po and ²¹⁴Pb, assuming 7-min decay of ²²²Rn gas after it leaves the plant.

Table 7.9a. Effect of food source on doses
from a model F-F UF₆ plant

Case 1					
Maximum annual individual doses (mrem/yr) per percent of food produced locally ^{a,b}					
	0	10	30	50	100
Midwestern site					
Total body	5	6	7	8	10
Bone	75	81	92	103	130
Lungs	33	34	35	36	38
Kidneys	18	19	20	22	27
New Mexico site					
Total body	7	8	9	10	13
Bone	110	117	131	145	180
Lungs	47	48	49	50	53
Kidneys	25	26	29	31	37

^aMaximum 50-yr dose commitment to individual at 0.5 mile (800 m) from exposure to airborne effluents from one year's operation of a model 10,000-metric ton/yr fluorination-fractionation plant. Release height, 5 m. The average dose is 47% of the maximum.

^bLocal food is produced 0.5 mile downwind of the plant in the prevailing wind direction. Other food is imported from outside the area.

Table 7.9b. Effect of food source on doses
from a model F-F UF₆ plant

Case 2

	Maximum annual individual doses (mrem/yr) per percent of food produced locally ^{a,b}				
	0	10	30	50	100
Midwestern site					
Total body	2.1	2.2	2.6	2.9	3.8
Bone	29	32	36	40	51
Lungs	13	13	14	14	15
Kidneys	7	7	7	8	10
New Mexico site					
Total body	2.8	3.0	3.5	3.9	5.0
Bone	42	45	50	56	69
Lungs	19	19	19	20	21
Kidneys	9	10	11	12	14

^aMaximum 50-yr dose commitment to individual at 0.5 mile (800 m) from exposure to airborne effluents from one year's operation of a model 10,000-metric ton/yr fluorination-fractionation plant. Release height, 5 m. The average dose is 47% of the maximum.

^bLocal food is produced 0.5 mile downwind of the plant in the prevailing wind direction. Other food is imported from outside the area.

Table 7.9c. Effect of food source on doses
from a model F-F UF₆ plant

Case 3

	Maximum annual individual doses (mrem/yr) per percent of food produced locally ^{a,b}				
	0	10	30	50	100
Midwestern site					
Total body	0.6	0.7	0.8	0.9	1.2
Bone	9	10	11	13	16
Lungs	4.5	4.5	4.6	4.7	5.0
Kidneys	2.3	2.4	2.6	2.8	3.4
New Mexico site					
Total body	0.9	0.9	1.1	1.2	1.6
Bone	13	14	15	17	22
Lungs	6.4	6.5	6.6	6.7	7.1
Kidneys	3.3	3.4	3.7	3.9	4.6

^aMaximum 50-yr dose commitment to individual at 0.5 mile (800 m) from exposure to airborne effluents from one year's operation of a model 10,000-metric ton/yr fluorination-fractionation plant. Release height, 5 m. The average dose is 47% of the maximum.

^bLocal food is produced 0.5 mile downwind of the plant in the prevailing wind direction. Other food is imported from outside the area.

Table 7.9d. Effect of food source on doses
from a model F-F UF₆ plant

Case 4

	Maximum annual individual doses (mrem/yr) per percent of food produced locally ^{a,b}				
	0	10	30	50	100
Midwestern site					
Total body	0.017	0.018	0.018	0.018	0.019
Bone	0.11	0.11	0.11	0.11	0.12
Lungs	0.63	0.63	0.63	0.63	0.63
Kidneys	0.19	0.19	0.19	0.19	0.19
New Mexico site					
Total body	0.024	0.024	0.024	0.025	0.026
Bone	0.15	0.15	0.16	0.16	0.17
Lungs	0.91	0.91	0.92	0.92	0.92
Kidneys	0.27	0.27	0.27	0.27	0.28

^aMaximum 50-yr dose commitment to individual at 0.5 mile (800 m) from exposure to airborne effluents from one year's operation of a model 10,000-metric ton/yr fluorination-fractionation plant. Release height, 5 m. The average dose is 47% of the maximum.

^bLocal food is produced 0.5 mile downwind of the plant in the prevailing wind direction. Other food is imported from outside the area.

Table 7.10. Effect of release height on dose
from a model F-F UF₆ plant

Release height (meters)	Fraction of total-body dose relative to that for a 5-meter release height ^{a,b}	
	Midwestern site	New Mexico site
1	0.63	0.70
5	1.00	1.00
10	0.96	0.95
20	0.53	0.48
30	0.32	0.25

^aMaximum 50-yr dose commitment to individual at 0.5 mile (800 m) from exposure to airborne effluents from one year's operation of the model plant.

^bThese fractions also apply approximately to organ doses.

Table 7.11. Reduction of dose as a function of distance from a model F-F UF₆ plant

Distance (miles)	Fraction of total-body dose relative to that at 0.5 mile ^{a, b}	
	Midwestern site	New Mexico site
0.5 ^c	1.00	1.00
1.0	0.26	0.26
2.5	0.05	0.04
5.0	0.01	0.01

^aMaximum 50-yr dose commitment to individual from exposure to airborne effluents from one year's operation of the model plant; 5-m release height.

^bThese fractions also apply approximately to organ doses.

^cThe site boundary is assumed to be 0.5 mile.

Table 7.12. Annual doses to individuals from liquid effluents from a model F-F UF₆ plant^a

(Case 4 has no liquid radioactive releases.)

Aquatic exposure mode	Annual individual doses ^b (mrem)					
	Liquid Case 1		Liquid Case 2		Liquid Case 3	
	Total body	Bone	Total body	Bone	Total body	Bone
	<u>15-cfs stream</u>					
Submersion in water ^c	3.4E-5	-	2.2E-5	-	5.7E-6	-
Ingestion of water ^d	3.3E00	3.6E+1	3.1E00	3.2E+1	7.9E-2	1.3E00
Eating fish ^e	2.3E00	2.3E+1	2.3E00	2.3E+1	2.0E-2	2.8E-1
Totals	5.6E00	5.9E+1	5.4E00	5.5E+1	9.9E-2	1.6E00
	<u>1300-cfs river</u>					
Submersion in water ^c	4.3E-7	-	2.6E-7	-	6.6E-8	-
Ingestion of water ^d	4.2E-2	4.5E-1	3.7E-2	3.8E-1	9.1E-4	1.5E-2
Eating fish ^e	2.9E-2	2.9E-1	2.8E-2	2.8E-1	2.3E-4	3.2E-3
Totals	7.1E-2	7.4E-1	6.5E-2	6.6E-1	1.1E-3	1.8E-2

^a10,000-metric ton/yr fluorination-fractionation plant.

^b50-yr dose commitment from one year's use of the stream or river that receives the liquid effluents.

^cSwimming in water; 1% of year.

^dDaily intake of 1.2 liters of water.

^eDaily intake of 20 g of fish.

Table 7.13. Major radionuclides contributing to total-body exposure modes for liquid effluents from a model F-F UF₆ plant^a

(Case 4 has no liquid radioactive releases.)

Radionuclide	Liquid Case 1			Liquid Case 2			Liquid Case 3		
	Drinking water ^b	Eating fish ^c	Swimming ^d	Drinking water ^b	Eating fish ^c	Swimming ^d	Drinking water ^b	Eating fish ^c	Swimming ^d
²²⁶ Ra	80.6	95.2	4.7	87.3	97.4	7.5	13.2	42.6	0.1
²³⁰ Th	0.1	0.1	0.1	0.1	<0.1	0.1	0.1	1.9	0.1
^{234m} Pa	<0.1	<0.1	1.9	<0.1	<0.1	1.8	<0.1	<0.1	2.6
²³⁴ Th	<0.1	<0.1	50.8	<0.1	<0.1	49.3	<0.1	<0.1	69.8
²³⁴ U	10.1	2.4	12.2	6.6	1.5	11.8	45.2	29.2	7.9
²³⁵ U	0.2	<0.1	30.2	0.2	<0.1	29.2	1.0	0.7	19.3
²³⁸ U	8.9	2.1	0.1	5.8	1.3	0.1	39.7	25.6	0.1

^aFluorination-fractionation plant.

^bDaily intake of 1.2 liters of water.

^cDaily intake of 20 g of fish.

^dSwimming in water; 1% of year.

Table 7.14. Annual doses to aquatic biota from liquid effluents from a model F-F UF₆ plant^a

Liquid radwaste treatment case	Annual biota doses (mrem)			
	Algae	Invertebrates	Fish	Muskrat and/or waterfowl
<u>15-cfs stream</u>				
1	3.3E+4	3.4E+3	4.0E+2	2.8E+4
2	2.3E+4	2.3E+3	3.0E+2	2.9E+4
3	3.0E+3	3.2E+2	3.1E+1	1.2E+2
4 ^b	-	-	-	-
<u>1300-cfs river</u>				
1	4.2E+2	4.3E+1	5.0E00	3.5E+2
2	2.8E+2	2.8E+1	3.6E00	3.5E+2
3	3.5E+1	3.7E00	3.6E-1	1.4E00
4 ^b	-	-	-	-

^a10,000-metric ton/yr fluorination-fractionation plant.

^bNo radioactive releases in liquid Case 4.

Table 7.15. Major radionuclides contributing to aquatic biota doses from liquid effluents from a model F-F UF₆ plant^{a,b}

Radionuclide	Percent of total dose			
	Plants	Invertebrates	Fish	Muskrat or waterfowl
²²⁶ Ra	19.7	19.1	32.5	99.9
²³⁰ Th	0.5	1.5	0.7	<0.1
²³⁴ Th	0.9	2.9	1.6	<0.1
^{234m} Pa	0.9	0.8	0.7	<0.1
²³⁴ U	39.4	38.2	32.5	<0.1
²³⁵ U	1.0	0.9	0.8	<0.1
²³⁸ U	36.4	35.3	30.0	<0.1

^aLiquid Case 1.

^bFluorination-fractionation plant.

Table 7.16. Long-lived radionuclides dispersed via terrestrial pathways during the 30-yr life of a model F-F UF₆ plant - Case 1^{a,b}

Radionuclide	Total airborne release during 30-yr plant life (Ci)	Terrestrial activity concentration ^c (Ci/m ²)
²²⁶ Ra	4.1E-2	1.7E-12
²³⁰ Th	3.6E-1	1.5E-11
²³⁴ U	3.3E00	1.3E-10
²³⁵ U	8.0E-2	3.3E-12
²³⁸ U	3.3E00	1.3E-10

^a10,000-metric ton/yr fluorination-fractionation plant.

^bAquatic releases not included.

^cActivity dispersed uniformly over an area of 2.461E+10 m² (i.e., dispersed within a 55-mile radius of the plant).

Table 7.17. Annual doses^{a,b} to average individual after the model F-F UF₆ plant^c closes until significant decay of radionuclides occurs - Case 1

Radionuclide	Individual total-body doses (mrem) per exposure mode				Adult organ doses (mrem) per exposure mode					
	Contaminated ground	Inhalation	Ingestion	Total	Bone		Lung		Kidney	
					Inhalation	Ingestion	Inhalation	Ingestion	Inhalation	Ingestion
²²⁶ Ra	1.9E-6	4.9E-7	5.0E-5	5.2E-5	4.7E-6	5.0E-4	4.2E-6	5.0E-5	4.9E-7	5.0E-5
²³⁰ Th	3.2E-5	1.5E-5	1.7E-6	4.9E-5	5.7E-4	6.1E-5	7.0E-5	1.7E-6	8.2E-5	1.7E-5
²³⁴ U	3.7E-4	1.4E-6	1.1E-5	3.8E-4	2.2E-5	1.7E-4	5.4E-5	1.1E-5	5.0E-6	4.2E-5
²³⁵ U	2.0E-4	2.8E-8	2.5E-7	2.0E-4	4.7E-7	3.9E-6	1.2E-6	2.5E-7	1.2E-7	9.1E-7
²³⁸ U	5.9E-4	1.2E-6	9.1E-6	6.0E-4	2.0E-5	1.7E-4	4.7E-5	9.1E-6	4.4E-6	3.7E-5
Total	1.2E-3	1.8E-5	7.2E-5	1.3E-3	6.2E-4	9.0E-4	1.8E-4	7.2E-5	9.2E-5	1.5E-4

^aDose after plant closes from radioactive materials which were dispersed in the terrestrial environment during 30-year operation of a model 10,000-metric ton/yr fluorination-fractionation UF₆ plant, assuming a uniform distribution of the radioactive dusts within a 55-mile radius from the plant.

^bIn addition to these doses, there will be a long-term radon dose to individuals living near the repository where the fluorination ash is buried.

^c10,000-metric ton/yr fluorination-fractionation plant.

Table 7.18. Annual doses^{a,b} to the population^c after the model F-F UF₆ plant^d closes until significant decay of radionuclides occurs - Case 1, midwestern site^e

Radionuclide	Population total-body dose (person-rem)	Population organ doses (person-organ-rem)		
		Bone	Lung	Kidney
²²⁶ Ra	1.9E-1	1.8E00	2.0E-1	1.9E-1
²³⁰ Th	1.8E-1	2.4E00	3.7E-1	4.7E-1
²³⁴ U	1.4E00	2.0E00	1.3E00	1.5E00
²³⁵ U	7.2E-1	7.4E-1	7.3E-1	7.2E-1
²³⁸ U	2.2E00	2.8E00	2.3E00	2.3E00
Total	4.7E00	9.7E00	4.9E00	5.2E00

^aDose after plant closes from radioactive materials which were dispersed in the terrestrial environment during 30-year operation of a model 10,000-metric ton/yr fluorination-fractionation UF₆ plant, assuming uniform distribution of the radioactive dusts within a 55-mile radius of the plant.

^bIn addition to these doses, there will be a long-term radon dose to the population living near the repository where the fluorination ash is buried.

^cEntire population within 55 miles of the model plant.

^d10,000-metric ton/yr fluorination-fractionation plant.

^ePopulation total-body dose for New Mexico site is about 2% of dose at midwestern site.

Table 8.1. Total annual cost increase for reduction of the environmental impact of the model 10,000-metric ton/yr fluorination-fractionation UF₆ production plant^a

MIDWESTERN SITE

	Case 1	Case 2	Case 3	Case 4
Annual cost increase over base	Base	\$6.83E+5	\$1.14E+6 ^b	\$2.91E+6 ^b
Environmental impact				
Maximum annual individual dose at 0.5 mile from airborne effluents, mrem ^c				
Total body	9.9E00	3.8E00	1.2E00	1.9E-2
Bone	1.3E+2	5.1E+1	1.6E+1	1.2E-1
Lung	3.8E+1	1.5E+1	5.0E00	6.3E-1
Kidney	2.7E+1	1.0E+1	3.4E00	1.9E-1
Annual total population dose out to 55 miles from airborne effluents, person-rem ^c				
Total body	9.3E00	3.6E00	1.2E00	1.2E-1
Bone	1.1E+2	4.4E+1	1.4E+1	5.8E-1
Lung	3.4E+1	1.5E+1	6.5E00	2.8E00
Kidney	2.5E+1	1.0E+1	3.9E00	1.1E00
Annual individual dose from liquid effluents, mrem				
15-cfs stream				
Total body	5.6E00	5.4E00	9.9E-2	-
Bone	5.9E+1	5.5E+1	1.6E00	-
1300-cfs river				
Total body	7.1E-2	6.5E-2	1.1E-3	-
Bone	7.4E-1	6.6E-1	1.8E-2	-
Chemical releases, lb/day ^d				
Gaseous effluents				
HF	8.8E+1	1.2E00	1.2E00	1.2E-1
H ₂ S	5.7E-1	-	-	-
SO ₂	-	1.3E+3	1.3E+3	2.6E+1
NH ₃	4.0E+3	4.0E+3	1.3E+2	1.1E+2
Liquid effluents				
F ⁻	5.1E+3	2.1E+1	2.1E+1	3.0E00
S ²⁻ or S	7.2E+2	-	-	-
CO ₃ ²⁻	2.6E+3	1.5E+2	1.1E+2	-
SO ₄ ²⁻	1.9E+4	1.9E+4	2.3E+3	-
NH ₄ ⁺	6.1E+3	6.1E+3	7.0E+2	-
Na ⁺	3.6E+3	1.4E+3	2.3E+2	-
K ⁺	7.0E+3	1.7E+2	1.7E+2	-
Solid waste generated, lb/yr ^e				
Containing 10 ⁻¹ to 10 ⁻² μCi of ²³⁰ Th/g and only slightly soluble				
	2.2E+6	2.5E+6	2.5E+6	1.6E+7
Containing <10 ⁻³ μCi of ²³⁰ Th/g and only slightly soluble				
	8.9E+4	3.6E+6	3.6E+6	1.5E+6
Containing <10 ⁻⁴ μCi of ²³⁰ Th/g but soluble				
	-	-	-	9.6E+5

^aMid-1973 dollars.^bDoes not include cost to the mill of changing the plant feed.^cFive-meter release height; 100% local food.^dProcess effluents only; does not include combustion products from heating the plant or operating vehicles, or sanitary and laundry wastes.^eLong-term hazard defined by ²³⁰Th parent since ²²⁶Ra will gradually grow to secular equilibrium with ²³⁰Th.

Table 8.2. Total annual cost increase for reduction of the environmental impact^a of the model 10,000-metric ton/yr fluorination-fractionation UF₆ production plant^a

NEW MEXICO SITE

	Case 1	Case 2	Case 3	Case 4
Annual cost increase over base	Base	\$6.83E+5	\$1.14E+6 ^b	\$2.91E+6 ^b
Environmental impact				
Maximum annual individual dose at 0.5 mile from airborne effluents, mrem ^c				
Total body	1.3E+1	5.0E00	1.6E00	2.6E-2
Bone	1.8E+2	6.9E+1	2.2E+1	1.7E-1
Lung	5.3E+1	2.1E+1	7.1E00	9.2E-1
Kidney	3.7E+1	1.4E+1	4.6E00	2.8E-1
Annual total population dose out to 55 miles from airborne effluents, person-rem ^c				
Total body	2.1E-1	8.0E-2	2.7E-2	3.0E-3
Bone	2.8E00	1.1E00	3.5E-1	1.6E-2
Lung	9.5E-1	4.2E-1	1.9E-1	8.6E-2
Kidney	6.3E-1	2.6E-1	1.0E-1	3.1E-2
Annual individual dose from liquid effluents, mrem				
15-cfs stream				
Total body	5.6E00	5.4E00	9.9E-2	-
Bone	5.9E+1	5.5E+1	1.6E00	-
1300-cfs river				
Total body	7.1E-2	6.5E-2	1.1E-3	-
Bone	7.4E-1	6.6E-1	1.8E-2	-
Chemical releases, lb/day ^d				
Gaseous effluents				
HF	8.8E+1	1.2E00	1.2E00	1.2E-1
H ₂ S	5.7E-1	-	-	-
SO ₂	-	1.3E+3	1.3E+3	2.6E+1
NH ₃	4.0E+3	4.0E+3	1.3E+2	1.1E+2
Liquid effluents				
F ⁻	5.1E+3	2.1E+1	2.1E+1	3.0E00
S ²⁻ or S	7.2E+2	-	-	-
CO ₃ ²⁻	2.6E+3	1.5E+2	1.1E+2	-
SO ₄ ²⁻	1.9E+4	1.9E+4	2.3E+3	-
NH ₄ ⁺	6.1E+3	6.1E+3	7.0E+2	-
Na ⁺	3.6E+3	1.4E+3	2.3E+2	-
K ⁺	7.0E+3	1.7E+2	1.7E+2	-
Solid waste generated, lb/yr ^e				
Containing 10 ⁻¹ to 10 ⁻² μCi of ²³⁰ Th/g and only slightly soluble				
	2.2E+6	2.5E+6	2.5E+6	1.6E+7
Containing <10 ⁻³ μCi of ²³⁰ Th/g and only slightly soluble				
	8.9E+4	3.6E+6	3.6E+6	1.5E+6
Containing <10 ⁻⁴ μCi of ²³⁰ Th/g but soluble				
	-	-	-	9.6E+5

^aMid-1973 dollars.^bDoes not include cost to the mill of changing the plant feed.^cFive-meter release height; 100% local food.^dProcess effluents only; does not include combustion products from heating the plant or operating vehicles, or sanitary and laundry wastes.^eLong-term hazard defined by ²³⁰Th parent since ²²⁶Ra will gradually grow to secular equilibrium with ²³⁰Th.

Table 8.3. Annual cost for reduction of dose from airborne effluents at the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant

COMBINED AIRBORNE EFFLUENTS

Case No.	Total annual cost increase over base (\$1000) ^a	Maximum annual individual dose at 0.5 mile (mrem) ^b				Annual total population dose out to 55 miles (person-rem) ^b			
		Total body	Bone	Lungs	Kidneys	Total body	Bone	Lungs	Kidneys
<u>Midwestern site</u>									
1	Base	9.9E00	1.3E+2	3.8E+1	2.7E+1	9.3E00	1.1E+2	3.4E+1	2.5E+1
2	290	3.8E00	5.1E+1	1.5E+1	1.0E+1	3.6E00	4.4E+1	1.5E+1	1.0E+1
3	714	1.2E00	1.6E+1	5.0E00	3.4E00	1.2E00	1.4E+1	6.5E00	3.9E00
4	1933	1.9E-2	1.2E-1	6.3E-1	1.9E-1	1.2E-1	5.8E-1	2.8E00	1.1E00
<u>New Mexico site</u>									
1	Base	1.3E+1	1.8E+2	5.3E+1	3.7E+1	2.1E-1	2.8E00	9.5E-1	6.3E-1
2	290	5.0E00	6.9E+1	2.1E+1	1.4E+1	8.0E-2	1.1E00	4.2E-1	2.6E-1
3	714	1.6E00	2.2E+1	7.1E00	4.6E00	2.7E-2	3.5E-1	1.9E-1	1.0E-1
4	1933	2.6E-2	1.7E-1	9.2E-1	2.8E-1	3.0E-3	1.6E-2	8.6E-2	3.1E-2

^aMid-1973 dollars.

^bFive-meter release height; 100% local food.

Table 8.3a. Annual cost for reduction of dose from airborne effluents at the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant

DUST CONTROL EFFLUENT

Case No.	Total annual cost increase over base (\$1000) ^a	Maximum annual individual dose at 0.5 mile (mrem) ^b				Annual total population dose out to 55 miles (person-rem) ^b	
		Total body	Bone	Lung	Kidney	Total body	Bone
<u>Midwestern site</u>							
1	Base	6.4E00	8.9E+1	2.4E+1	1.8E+1	6.0E00	7.4E+1
2	252	8.8E-1	1.2E+1	3.3E00	2.4E00	8.2E-1	1.0E+1
3	252	8.8E-1	1.2E+1	3.3E00	2.4E00	8.2E-1	1.0E+1
4	320	4.9E-4	6.6E-3	1.8E-3	1.3E-3	4.5E-4	6.1E-3
<u>New Mexico site</u>							
1	Base	8.5E00	1.2E+2	3.3E+1	2.5E+1	1.3E-1	1.8E00
2	252	1.1E00	1.6E+1	4.6E00	3.3E00	1.8E-2	2.5E-1
3	252	1.1E00	1.6E+1	4.6E00	3.3E00	1.8E-2	2.5E-1
4	320	6.4E-4	9.0E-3	2.5E-3	1.8E-3	1.1E-5	1.3E-4

^aMid-1973 dollars.

^bFive-meter release height; 100% local food.

Table 8.3b. Annual cost for reduction of dose from airborne effluents at the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant

PROCESS OFF-GAS

Case No.	Total annual cost increase over base (\$1000) ^a	Maximum annual individual dose at 0.5 mile (mrem) ^b				Annual total population dose out to 55 miles (person-rem) ^b	
		Total body	Bone	Lung	Kidney	Total body	Bone
<u>Midwestern site</u>							
1	Base	8.0E-1	6.9E00	3.9E00	1.7E00	7.5E-1	9.2E00
2	38	2.5E-1	2.4E00	1.2E00	5.6E-1	2.4E-1	3.0E00
3	50	1.1E-1	1.2E00	4.4E-1	2.7E-1	9.8E-2	1.2E00
4	178	2.3E-5	4.3E-4	5.8E-5	2.3E-5	2.1E-5	2.8E-4
<u>New Mexico site</u>							
1	Base	1.0E00	9.2E00	5.5E00	2.2E00	1.6E-2	2.2E-1
2	38	3.3E-1	3.2E00	1.7E00	5.8E-1	5.2E-3	7.3E-2
3	50	1.3E-1	1.7E00	6.0E-1	3.5E-1	2.1E-3	3.0E-2
4	178	3.1E-5	6.0E-4	8.0E-5	1.1E-4	5.2E-7	6.4E-6

^aMid-1973 dollars.

^bFive-meter release height; 100% local food.

Table 8.3c. Annual cost for reduction of dose from airborne effluents at the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant

BUILDING VENTILATION EFFLUENT

Case No.	Total annual cost increase over base (\$1000) ^a	Maximum annual individual dose at 0.5 mile (mrem) ^b				Annual total population dose out to 55 miles (person-rem) ^b	
		Total body	Bone	Lung	Kidney	Total body	Bone
<u>Midwestern site</u>							
1	Base	2.6E00	3.6E+1	9.7E00	7.4E00	2.4E00	3.0E+1
2	Base	2.6E00	3.6E+1	9.7E00	7.4E00	2.4E00	3.0E+1
3	412	1.8E-1	2.6E00	6.9E-1	5.2E-1	1.7E-1	2.1E00
4	1436	2.7E-3	3.8E-2	1.0E-2	7.6E-3	2.5E-3	3.4E-2
<u>New Mexico site</u>							
1	Base	3.5E00	4.9E+1	1.4E+1	1.0E+1	5.5E-2	7.7E-1
2	Base	3.5E00	4.9E+1	1.4E+1	1.0E+1	5.5E-2	7.7E-1
3	412	2.4E-1	3.4E00	9.6E-1	7.1E-1	3.8E-3	5.3E-2
4	1436	3.5E-3	5.1E-2	1.4E-2	1.0E-2	6.2E-5	7.3E-4

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^aMid-1973 dollars.

^bFive-meter release height; 100% local food.

Table 8.4. Incremental cost increase - dose reduction between case studies at the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant^a

COMBINED AIRBORNE EFFLUENTS

Case increment	Increase in annual cost (\$1000)	Decrease in maximum annual individual dose at 0.5 mile (mrem)		Decrease in annual dose to population out to 55 miles (person-rem)		Cost/benefit				
		Total body	Bone	Total body	Bone	Individual at 0.5 mile (\$1000/mrem)		Total population within 55 miles (\$1000/person-rem)		
						Total body	Bone	Total body	Bone	
<u>Midwestern site</u>										
1/2	290	6.09E00	8.10E+1	5.71E00	7.00E+1	4.8E+1	3.6E00	5.1E+1	4.1E00	
2/3	424	2.61E00	3.51E+1	2.42E00	3.00E+1	1.6E+2	1.2E+1	1.8E+2	1.4E+1	
3/4	1219	1.16E00	1.57E+1	1.09E00	1.34E+1	1.0E+3	7.8E+1	1.1E+3	9.1E+1	
<u>New Mexico site</u>										
1/2	290	7.95E00	1.11E+2	1.25E-1	1.74E00	3.6E+1	2.6E00	2.3E+3	1.7E+2	
2/3	424	3.40E00	4.77E+1	5.33E-2	7.49E-1	1.2E+2	8.9E00	8.0E+3	5.7E+2	
3/4	1219	1.52E00	2.13E+1	2.38E-2	3.35E-1	8.0E+2	5.7E+1	5.1E+4	3.6E+3	

^a1973 dollars; 5-m release height; 100% local food.

Table 8.4a. Incremental cost increase - dose reduction between case studies
at the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant ^a

DUST CONTROL EFFLUENT

Case increment	Increase in annual cost (\$1000)	Decrease in maximum annual individual dose at 0.5 mile (mrem)		Decrease in annual dose to population out to 55 miles (person-rem)		Cost/benefit				
		Total body	Bone	Total body	Bone	Individual at 0.5 mile (\$1000/mrem)		Total population within 55 miles (\$1000/person-rem)		
						Total body	Bone	Total body	Bone	
<u>Midwestern site</u>										
1/2	252	5.49E00	7.70E+1	5.19E00	6.35E+1	4.6E+1	3.3E00	4.9E+1	4.0E00	229
2/3	-	-	-	-	-	-	-	-	-	
3/4	67.5	8.80E-1	1.19E+1	8.21E-1	1.02E+1	7.7E+1	5.7E00	8.2E+1	6.6E00	
<u>New Mexico site</u>										
1/2	252	7.33E00	1.04E+2	1.14E-1	1.59E00	3.4E+1	2.4E00	2.2E+3	1.6E+2	
2/3	-	-	-	-	-	-	-	-	-	
3/4	67.5	1.12E00	1.62E+1	1.78E-2	2.53E-1	6.0E+1	4.2E00	3.8E+3	2.7E+2	

^a1973 dollars; 5-m release height; 100% local food.

Table 8.4b. Incremental cost increase - dose reduction between case studies
at the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant ^a

PROCESS OFF-GAS

Case increment	Increase in annual cost (\$1000)	Decrease in maximum annual individual dose at 0.5 mile (mrem)		Decrease in annual dose to population out to 55 miles (person-rem)		Cost/benefit				
		Total body	Bone	Total body	Bone	Individual at 0.5 mile (\$1000/mrem)		Total population within 55 miles (\$1000/person-rem)		
						Total body	Bone	Total body	Bone	
<u>Midwestern site</u>										
1/2	38.1	5.46E-1	4.52E00	5.16E-1	6.29E00	6.7E+1	8.4E00	7.4E+1	6.1E00	
2/3	11.6	1.48E-1	1.14E00	1.40E-1	1.75E00	7.8E+1	1.0E+1	8.3E+1	6.6E00	
3/4	128.0	1.05E-1	1.23E00	9.77E-2	1.20E00	1.2E+3	1.0E+2	1.1E+3	1.1E+2	
<u>New Mexico site</u>										
1/2	38.1	6.98E-1	6.04E00	1.08E-2	1.52E-1	5.5E+1	6.3E00	3.5E+3	2.5E+2	
2/3	11.6	1.98E-1	1.48E00	3.05E-3	4.31E-2	5.6E+1	7.8E00	3.8E+3	2.7E+2	
3/4	128.0	1.34E-1	1.68E00	2.12E-3	2.98E-2	9.6E+2	7.6E+1	6.0E+5	4.3E+5	

^a 1973 dollars; 5-m release height; 100% local food.

Table 8.4c. Incremental cost increase - dose reduction between case studies
at the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant^a

BUILDING VENTILATION EFFLUENT

Case increment	Increase in annual cost (\$1000)	Decrease in maximum annual individual dose at 0.5 mile (mrem)		Decrease in annual dose to population out to 55 miles (person-rem)		Cost/benefit				
		Total body	Bone	Total body	Bone	Individual at 0.5 mile (\$1000/mrem)		Total population within 55 miles (\$1000/person-rem)		
						Total body	Bone	Total body	Bone	
<u>Midwestern site</u>										
1/2	-	-	-	-	-	-	-	-	-	-
2/3	412	2.47E00	3.35E+1	2.28E00	2.82E+1	1.7E+2	1.2E+1	1.8E+2	1.5E+1	
3/4	1024	1.81E-1	2.53E00	1.68E-1	2.08E00	5.7E+3	4.0E+2	6.1E+3	4.9E+2	
<u>New Mexico site</u>										
1/2	-	-	-	-	-	-	-	-	-	-
2/3	412	3.25E00	4.55E+1	5.08E-2	7.16E-1	1.3E+2	9.1E00	8.1E+3	5.8E+2	
3/4	1024	2.35E-1	3.37E00	3.72E-3	5.24E-2	4.4E+3	3.0E+2	2.8E+5	2.0E+4	

^a1973 dollars; 5-m release height; 100% local food.

Table 8.5. Annual cost increase for reduction of dose from liquid effluents at the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant

COMBINED LIQUID EFFLUENTS

Case No.	Total annual cost increase over base (\$1000) ^{a,b}	Annual individual dose from 15-cfs stream (mrem)		Annual individual dose from 1300-cfs river (mrem)	
		Total body	Bone	Total body	Bone
1	Base	5.6E00	5.9E+1	7.1E-2	7.4E-1
2	393	5.4E00	5.5E+1	6.5E-2	6.6E-1
3 ^c	429	9.9E-2	1.6E00	1.1E-3	1.8E-2
4 ^{c,d}	461	-	-	-	-

^aMid-1973 dollars.

^bIncludes cost of treating solids generated by liquid waste treatment systems.

^cChanges in the plant feed reduce the radium load to the liquid waste treatment system.

^dIncludes ERDA proprietary technology for internal process changes which reduce the fluoride load to the liquid waste treatment system.

Table 8.6. Cost/effectiveness of treating individual dust control streams at the model 10,000-metric ton/yr fluorination-fractionation UF₆ production plant^a

Case No.	Total annual cost (\$1000)	Major contributors to the radiological dose ^b		Case increment	Increase in annual cost (\$1000)	Decrease in U _{nat} ^c release (Ci/yr)	Decrease in ²²⁶ Ra release (Ci/yr)	Cost/effectiveness		
		U _{nat} ^c (Ci/yr)	²²⁶ Ra (Ci/yr)					\$1000 per 10 ⁻² Ci of U _{nat} ^c per year	\$1000 per 10 ⁻⁶ Ci of ²²⁶ Ra per year	
<u>Dust control effluent</u>										
<u>From dry materials handling</u>										
<u>Sampling (Stream 1A)</u>										
1	Base	1.0 E-2	4.9 E-5							
2, 3	58.6	1.5 E-3	6.9 E-6	1/2	58.6	8.5E-3	4.2E-5	6.9E+1	1.4E+1	
4	74.7	7.3 E-7	3.4 E-9	2/4	16.1	1.5E-3	6.9E-6	1.1E+2	2.3E+1	
<u>Feed preparation (Stream 2A)</u>										
1	Base	1.0 E-1	4.7 E-4							
2, 3	87.0	1.4 E-2	6.6 E-5	1/2	87.0	8.6E-1	4.0E-4	1.0E00	2.2E00	
4	117.5	7.0 E-6	3.3 E-8	2/4	30.5	1.4E-2	6.6E-5	2.1E+1	4.6E00	
<u>UF₄ handling (Stream 5A)</u>										
1	Base	2.4 E-2	1.1 E-4							
2, 3	34.2	3.3 E-3	1.6 E-5	1/2	34.2	2.1E-2	9.4E-5	1.6E+1	3.6E00	
4	40.6	2.5 E-6	1.2 E-8	2/4	6.4	3.3E-3	1.6E-5	1.9E+1	4.0E00	
<u>Ash handling (Stream 6A; removing ash from fluorination fluid bed)</u>										
1	Base	2.4 E-4	6.2 E-5							
2, 3	26.4	3.4 E-5	8.9 E-6	1/2	26.4	2.1E-4	5.3E-5	1.3E+3	5.0E00	
4	30.6	1.7 E-8	4.4 E-9	2/4	4.2	3.4E-5	8.9E-6	1.2E+3	4.7E00	
<u>Ash handling (Streams 9A + 10A; carbonate leach)</u>										
1	Base	2.4 E-4	2.5 E-4							
2, 3	45.7 ^d	3.4 E-5	3.6 E-5	1/2	45.7	2.1E-4	2.1E-4	2.2E+3	2.2E00	
4	56.0 ^d	1.7 E-8	4.4 E-9	2/4	10.3	3.4E-5	3.6E-5	2.9E+3	2.9E00	
<u>Building ventilation effluent (Streams 12A + 13A)</u>										
1, 2	Base	5.5 E-2	3.9 E-4							
3	412.3	3.8 E-3	2.7 E-5	1/3	412.3	5.1E-2	3.7E-4	8.1E+1	1.1E+1	
4	1436	5.7 E-5	3.2 E-7	3/4	1024	3.8E-3	2.7E-5	2.7E+3	3.8E+2	

^aCost/benefit (dollars/mrem) for combined streams is presented in Tables 8.4a and 8.4c.

^b²³⁰Th is also a major contributor to dose; Ci of ²³⁰Th = 9.04 x Ci of ²²⁶Ra.

^cOne curie of U_{nat} is defined as the sum of 1 Ci of ²³⁸U, 1 Ci of ²³⁵U, and 2.43 x 10⁻² Ci of ²³⁵U; 1 Ci of U_{nat} is also equivalent to 3000 kg of U_{nat}.

^dCosts assume that streams 9a + 9b alternate with streams 10b + 10c, so that a smaller dust collector may be used (see Fig. 4.6 for stream codes).

Table 8.7. Cost/effectiveness of treating individual process off-gas streams at the model 10,000-metric ton/yr. fluorination-fractionation UF₆ production plant ^a

Case No.	Total annual cost (\$1000)	Major contributors to the radiological dose ^b		Chemicals released		Case increment	Increase in annual cost (\$1000)	Decrease in U _{nat} release (Ci/yr)	Decrease in ²²⁶ Ra release (Ci/yr)	Decrease in chemical release (lb/day)	Cost/effectiveness			
		U _{nat} ^c (Ci/yr)	²²⁶ Ra (Ci/yr)	Chemical	Quantity (lb/day)						\$1000 per 10 ⁻² Ci of U _{nat} per yr	\$1000 per 10 ⁻⁵ Ci of ²²⁶ Ra per yr	\$1000 per lb of chemical per day	
<u>Reduction (Stream 3A)</u>														
1	Base	1.7E-5	7.8E-8	H ₂ S	5.7E-1									
2, 3 ^d	-10.3 ^e	9.3E-5	4.4E-7	SO ₂	1.3E+3									
4 ^d	-3.2 ^e	2.3E-8	1.1E-10	SO ₂	2.6E+1	2/4	7.1	9.3E-5	4.4E-7	1.3E+3	7.6E+2	1.6E+2	5.5E-3	
<u>Hydrofluorination (Stream 4A)</u>														
1	Base	<3.3E-5	<1.6E-7	HF	3.7E+1									
2, 3	16.1	<3.3E-5	<1.6E-7	HF	3.7E-1	1/2	16.1	f	f	3.7E+1	-	-	4.4E-1	
4	37.1	<1.6E-8	<8.5E-11	HF	3.7E-2	2/4	21.0	<3.3E-5	<1.6E-7	3.3E-1	<6.4E+3	<1.3E+3	6.3E00	
<u>Fluorination (Stream 8A)</u>														
1	Base	2.5E-2	4.4E-6	HF	4.2E00									
2, 3	12.6	2.5E-3	2.2E-6	HF	4.2E-1	1/2	12.6	2.2E-2	2.2E-6	3.8E00	5.7E00	5.7E+1	3.3E00	
4	62.0 ^g	1.2E-6	1.1E-10	HF	7.2E-2	2/4	49.4	2.5E-3	2.2E-6	3.5E-1	2.0E+2	2.2E+2	1.4E+2	
<u>Fluorine cell (Stream 7A)</u>														
1	Base	-	-	HF	4.7E+1									
2, 3	19.7	-	-	HF	4.7E-1	1/2	19.7	-	-	4.7E+1	-	-	4.2E-1	
4	81.7	-	-	HF	1.9E-2	2/4	62.0	-	-	4.5E-1	-	-	1.4E+2	
<u>UF₆ sampling and ash degassing</u>														
1, 2	Base	6.7E-3	-	HF	f									
3	11.6	6.7E-4	-	HF	f	1/3	11.6	6.0E-3	-	f	1.9E+1	-	f	
4	f	3.3E-7	-	HF	f									
<u>Feed preparation plus sodium removal (Streams 2C + 11A)</u>														
1, 2	Base	i	i	NH ₃	4.0E+3									
3, 4	(1700) ^h	i	i	NH ₃	1.3E+2	1/3	(1700) ^h	i	i	3.8E+3	-	-	(4.5E-1) ^h	

^aCost/benefit (dollars/mrem) for combined streams is presented in Table 8.4b.

^b²³⁰Th is also a major contributor to dose; Ci of ²³⁰Th = 9.04 x Ci of ²²⁶Ra.

^cOne curie of U_{nat} is defined as the sum of 1 Ci of ²³⁸U, 1 Ci of ²³⁴U, and 2.43 x 10⁻² Ci of ²³⁵U; 1 Ci of U_{nat} is also equivalent to 3000 kg of U_{nat}.

^dOff-gas treatment system changed to eliminate sulfide and sulfur from liquid waste.

^eIncludes a cost credit of \$26,000 for replacement of Case 1 reduction off-gas equipment.

^fNegligible.

^gCost of fluorine and UF₆ cleanup reactors is not included since the value of the recovered materials justifies their installation.

^hVery rough estimate of cost to mills of eliminating ammonium and sodium ions from the model UF₆ plant feed; cost is not included in summary tables.

ⁱIncluded under treatment of dust control streams (Table 8.6).

Table 8.8. Cost/effectiveness of treating individual liquid waste streams at the model 10,000-metric ton/yr fluorination-fractionation (FF) plant

Case No.	Total annual cost ^a (\$1000)	Solid radwaste generated (lb/day)	Major contributors to the radiological dose		Chemicals released						Case increment	Increase in annual cost (\$1000)	Decrease in ²²⁶ Ra release (Ci/yr)	Decrease in release of asterisked chemical (lb/day)	Cost/effectiveness		
			^U nat (Ci/yr)	²²⁶ Ra (Ci/yr)	Chemical	Quantity (lb/day)	Chemical	Quantity (lb/day)	Chemical	Quantity (lb/day)					- \$1000 per 10 ⁻⁵ Ci or ²²⁶ Ra per yr	\$1000 per lb of asterisked chemical per day	
<u>Fluoride scrub liquors</u>																	
KOH scrub liquors (Streams 4K, 7K, 8K)	b	0	0	1.0E-1	4.0E-5	F ^{-*}	2.3E+3	K ⁺	6.0E+3	CO ₃ ²⁻	4.3E+2						
	2, 3	142	5.7E+3	-	-	F ^{-*}	-	K ⁺	1.2E+2	CO ₃ ²⁻	-	b/2	142	4.0E-5	2.3E+3	3.6E+1	6.0E-2
	4	57 ^c +57 ^d	9.1E+2	-	-	F ^{-*}	-	K ⁺	-	CO ₃ ²⁻	-	b/2	114	4.0E-5	2.3E+3	3.9E+1	5.0E-2
Water scrub liquors (Streams 4L, 7L)	1	Base	0	8.0E-4	3.8E-6	F ^{-*}	2.5E+3	-	-	-	-						
	2, 3	156	5.7E+3	8.0E-5	3.8E-7	F ^{-*}	9.0E00	-	-	-	-	1/2	156	3.4E-6	2.5E+3	4.6E+2	6.2E-2
	4	68 ^c +16 ^e +57 ^f	3.8E+2	-	-	F ^{-*}	3.0E00	-	-	-	-	1/4	142	3.8E-6	2.5E+3	4.7E+2	5.7E-2
<u>Carbonate leach bleed (Stream 9L)</u>																	
	1	Base	0	8.4E-2	8.4E-4	F ⁻	3.5E+2	Na ⁺	2.3E+3	CO ₃ ^{2-*}	2.3E+3						
	2	94 ^g	4.4E+2	8.6E-3	8.6E-5	F ⁻	1.2E+1	Na ⁺	1.1E+2	CO ₃ ^{2-*}	1.2E+2	1/2	94	7.5E-4	2.2E+3	1.2E00	4.3E-2
	3	94 ^g +10 ^c	4.4E+2	8.6E-3	2.2E-5	F ⁻	1.2E+1	Na ⁺	1.1E+2	CO ₃ ^{2-*}	1.2E+2	2/3	10	6.4E-5	0	1.6E00	-
	4	94 ^g +38 ^h	7.7E+2	-	-	F	-	Na ⁺	-	CO ₃ ^{2-*}	-	2/4	38	8.6E-5	1.2E+2	4.4E00	3.2E-1
<u>Sodium removal waste (Stream 11 L)</u>																	
	1, 2	Base	0	2.4E-1	1.8E-2	NH ₄ ⁺ *	6.1E+3	Na ⁺	1.3E+3	SO ₄ ²⁻	1.9E+4						
	i	(550) ⁱ	0	2.8E-2	2.0E-3	NH ₄ ⁺ *	7.0E+2	Na ⁺	1.2E+2	SO ₄ ²⁻	2.2E+3	1/i	(550)	1.6E-2	5.4E+3	1.0E-1	1.0E-1
	3	(550) ⁱ +26	4.7E00	2.8E-2	1.2E-5	NH ₄ ⁺ *	7.0E+2	Na ⁺	1.2E+2	SO ₄ ²⁻	2.2E+3	1/3	26	2.0E-3	0	1.3E-1	-
	4	(550) ⁱ +87 ^h	2.9E+3	-	-	NH ₄ ⁺ *	-	Na ⁺	-	SO ₄ ²⁻	-	i/4	87	2.0E-3	8.3E+3	4.4E-1	1.2E-1
<u>Reduction scrub liquors (Streams 3L + 3K)</u>																	
	1	Base	0	9.4E-3	4.4E-5	S ^{2-*}	7.2E+2	K ⁺	1.1E+3	-	-						
	2, 3	SO ₂ gas release	0	7.2E-3	3.4E-5	SO ₃ ^{2-*}	2.5E00	-	-	-	-	1/2	SO ₂ gas release	1.0E-5	7.2E+2	SO ₂ gas release	SO ₂ gas release
	4 (3L)	15.9 ^l	2.1E-1	-	-	-	-	-	-	-	-	2/4(3L)	15.9	3.4E-5	2.5E00	4.7E00	6.4E00
	j	0	0	4.7E-5	2.2E-7	SO ₃ ^{2-*}	2.2E+3	K ⁺	2.2E+3	CO ₃ ²⁻	3.7E+1						
	4 (3K)	96.3	3.1E+3	-	-	SO ₃ ^{2-*}	-	K ⁺	-	CO ₃ ²⁻	-	j/4(3K)	96.3	2.2E-7	2.2E+3	4.4E-1	4.4E-1

^aIncluding cost of storing or preparing for shipment the solid waste generated by the liquid treatment systems, but not including cost of permanent disposal.

^bHypothetical case for the incremental analysis showing liquid releases without treatments employed in Cases 2-4. Case 1 has no caustic scrubber on the fluorine cell off-gas and, therefore, no stream 7K.

^cLiquid waste treatment cost.

^dCost increase for better HF condensers to reduce the HF impurity in the fluorine.

^eCost of HF condensers on the hydrofluorination off-gas.

^fCost increase for better condensers on the fluorine cell (hydrogen) off-gas.

^gCost of carbonate leach recycle circuit.

^hProrated share of cost of evaporator-dryer system.

ⁱHypothetical case showing the effect of eliminating sodium from the feed to the model plant and no treatment of liquid effluent from sodium removal. Cost is a very rough estimate of increased cost to the model mills for producing a sodium-free feed; this cost is not included in summary tables.

^jHypothetical case for the incremental analysis showing load to the Case 4 (3K) KOH regeneration system. Stream not present in Cases 1 to 3.

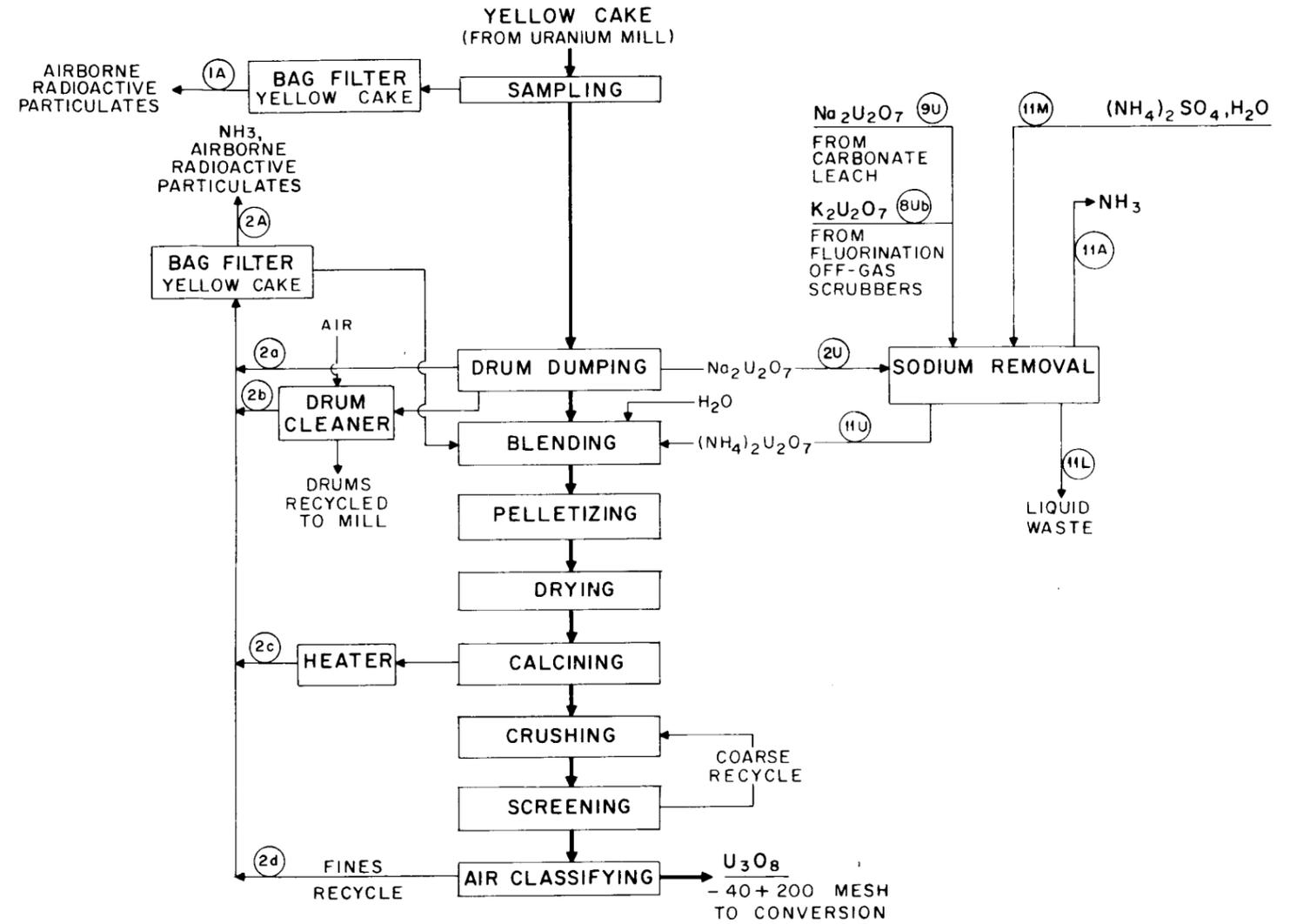


Fig. 4.1. Feed preparation system for the model fluorination-fractionation UF_6 plant, showing Case 1 off-gas treatment.

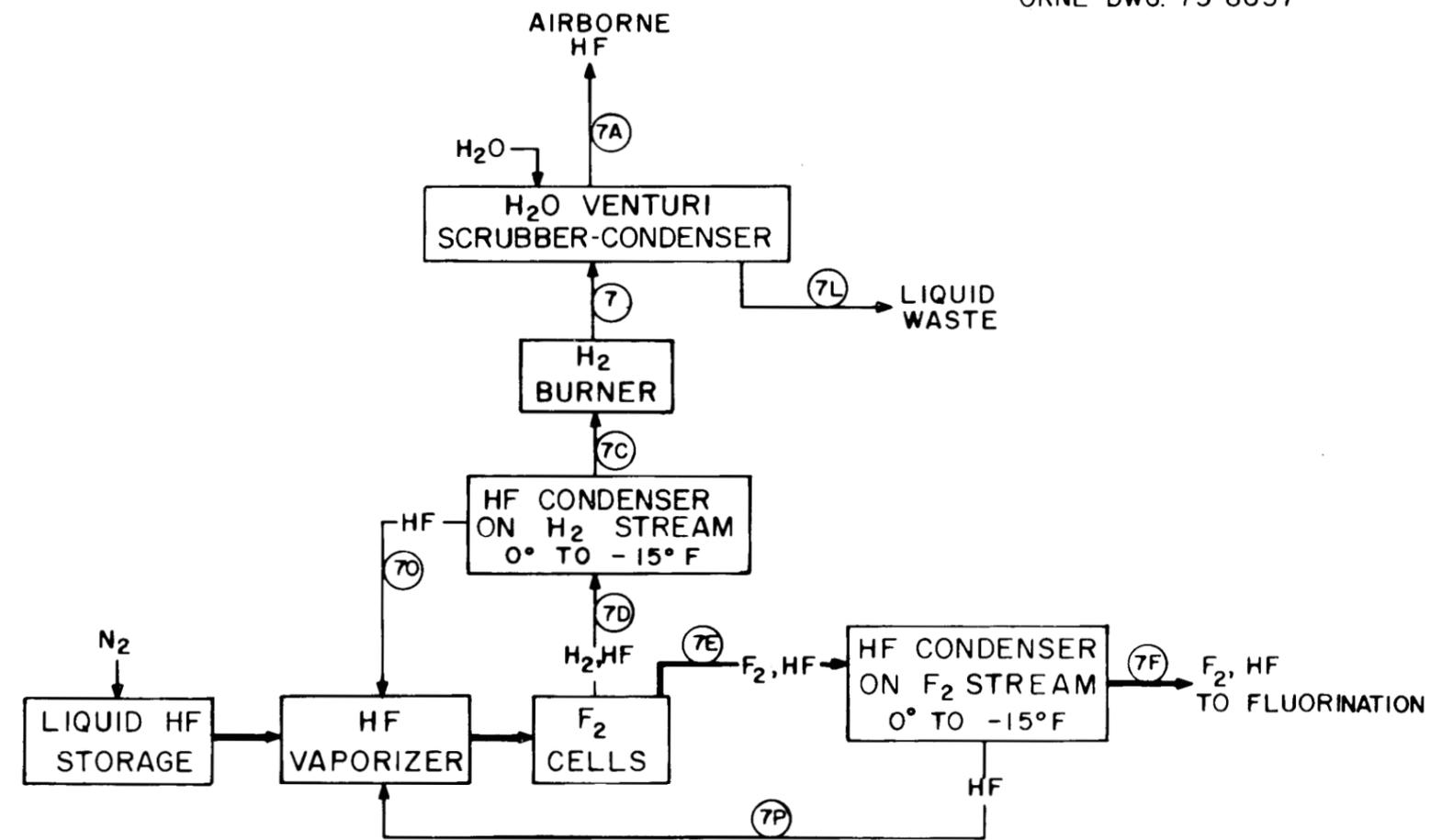


Fig. 4.3. Fluorine production system for the model UF_6 plants, showing Case 1 hydrogen off-gas treatment. (See fluorination for fluorine off-gas treatment.)

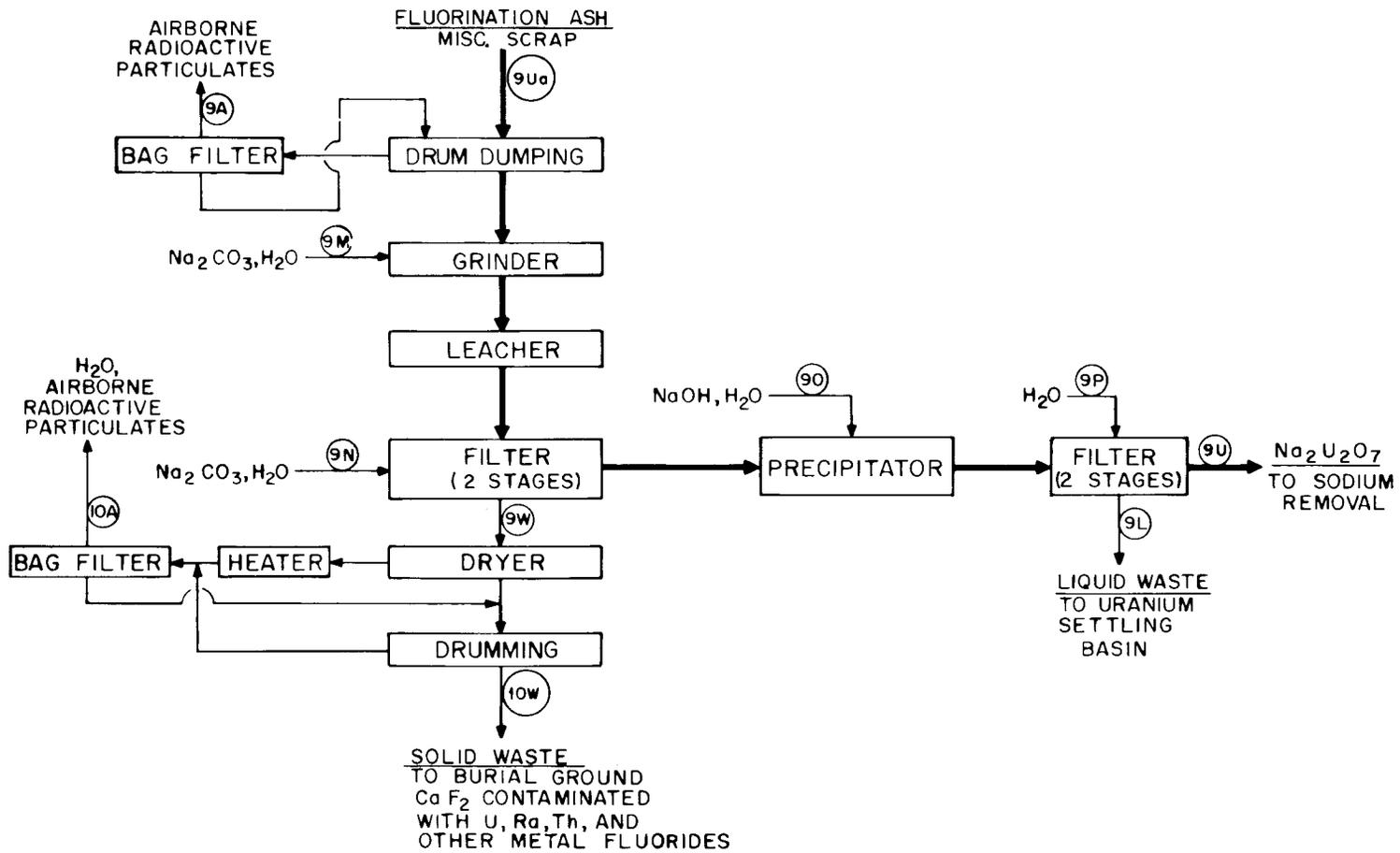


Fig. 4.4. Carbonate leach and solid radwaste treatment systems for the model fluorination-fractionation UF₆ plant - Case 1.

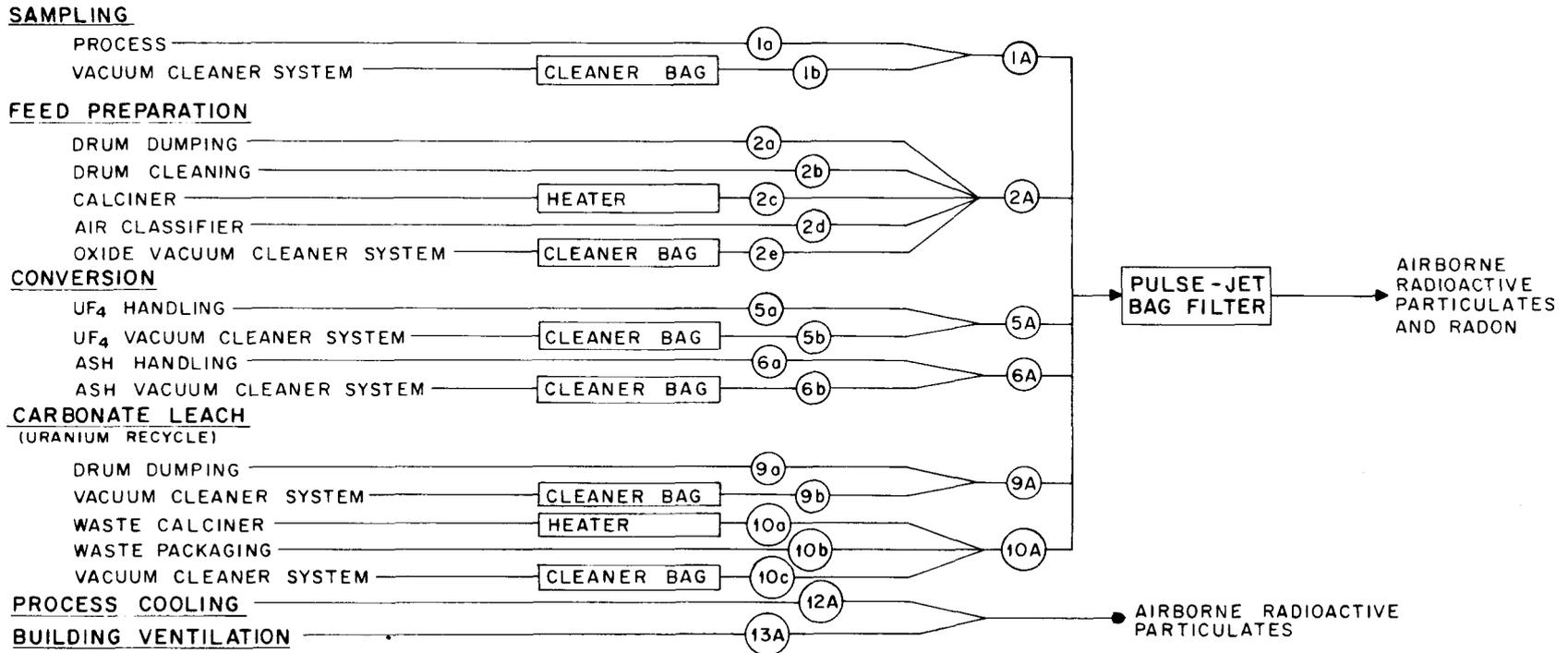


Fig. 4.6. Dust control effluent treatment systems for the model fluorination-fractionation UF₆ plant - Case I.

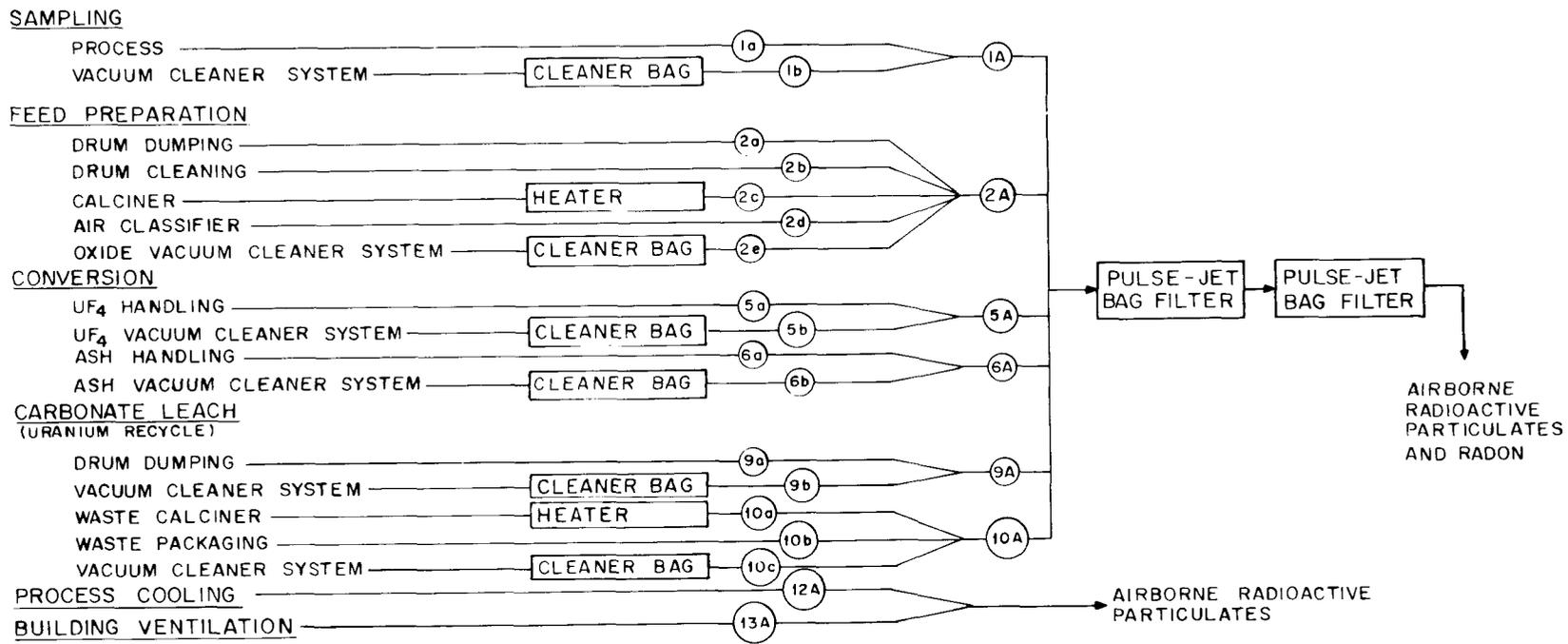


Fig. 4.7. Dust control effluent treatment systems for the model fluorination-fractionation UF_6 plant - Case 2.

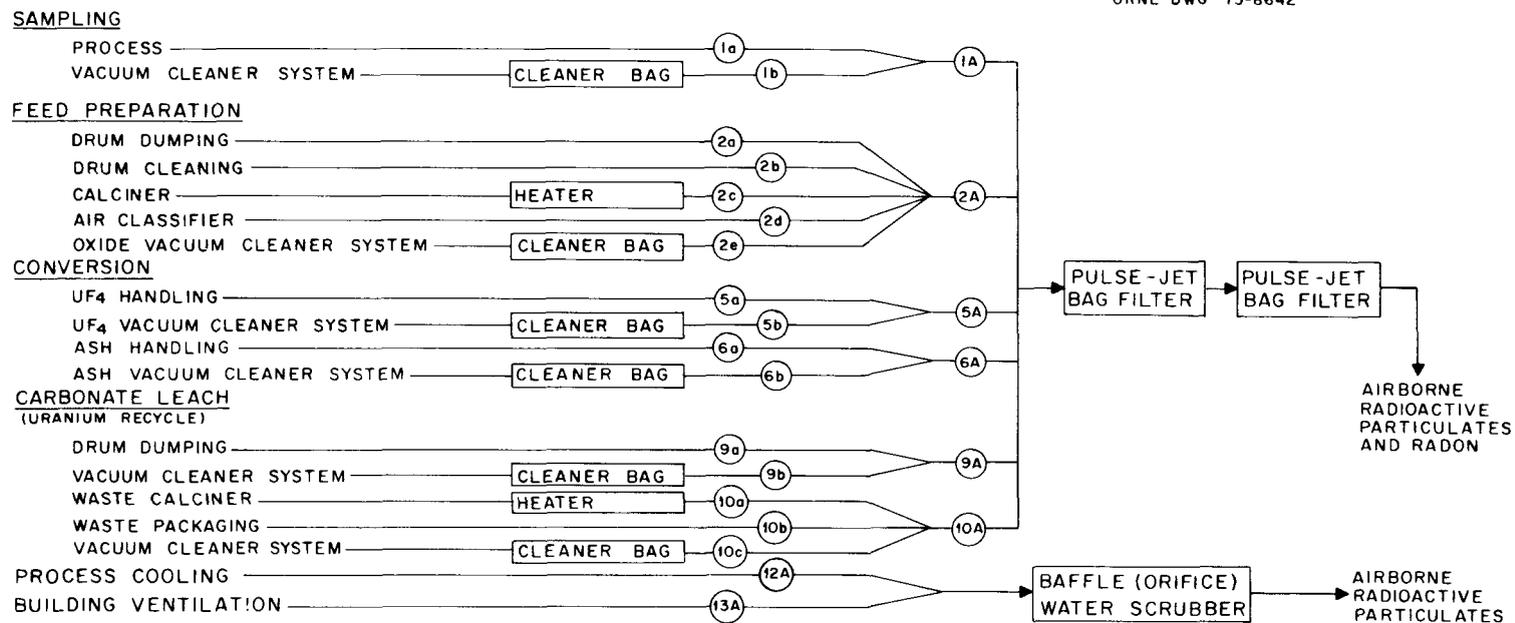
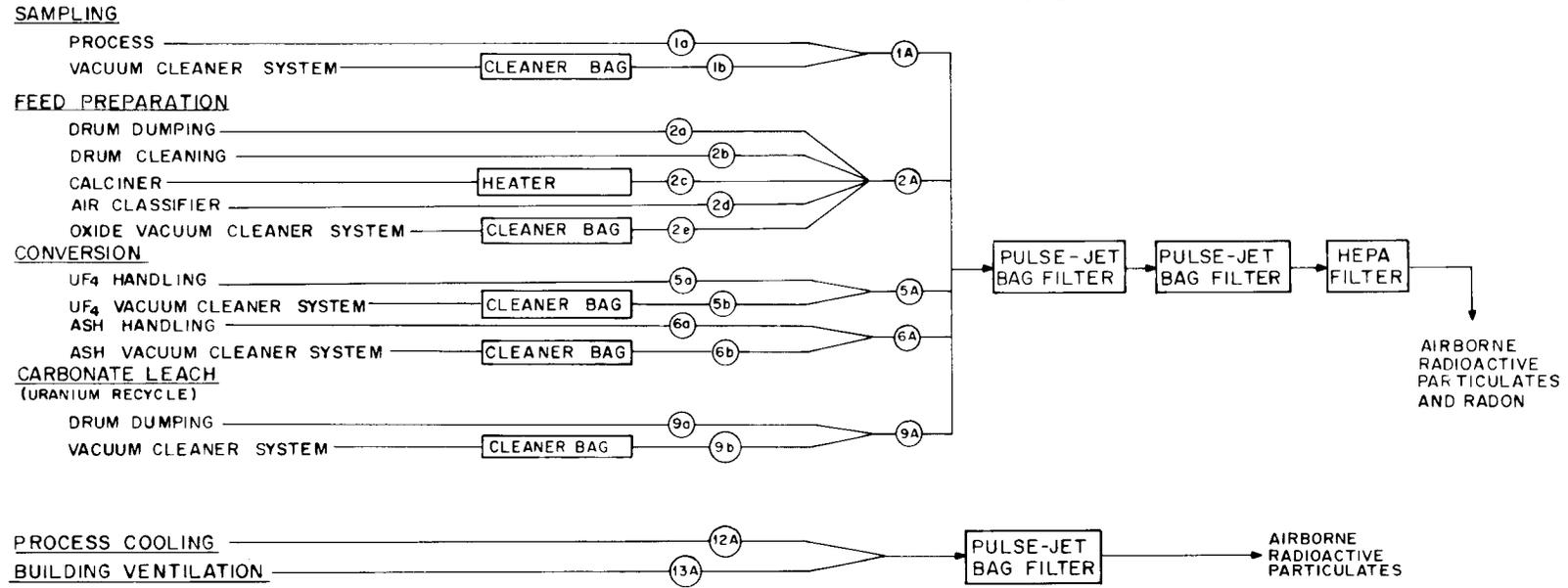


Fig. 4.8. Dust control effluent treatment systems for the model fluorination-fractionation UF₆ plant - Case 3.



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Fig. 4.9. Dust control effluent treatment systems for the model fluorination-fractionation UF_6 plant - Case 4.

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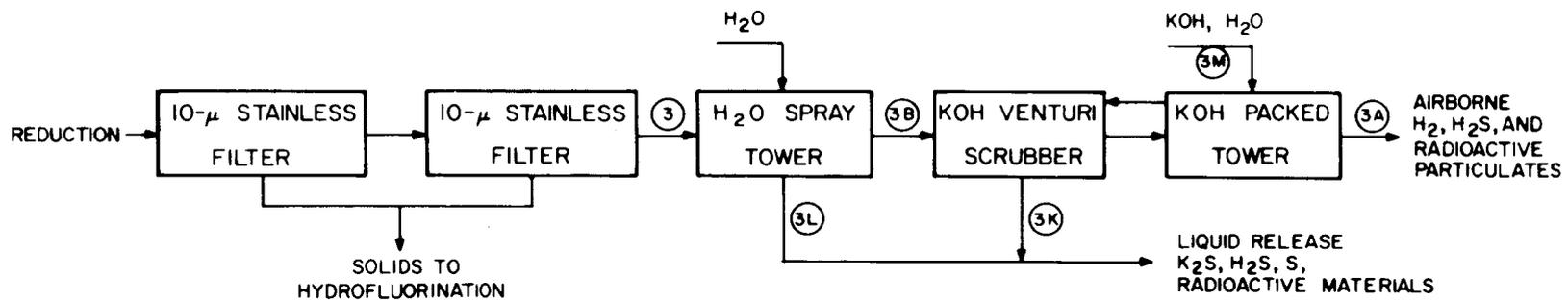


Fig. 4.10. Reduction off-gas treatment system for the model fluorination-fractionation UF₆ plant - Case 1.

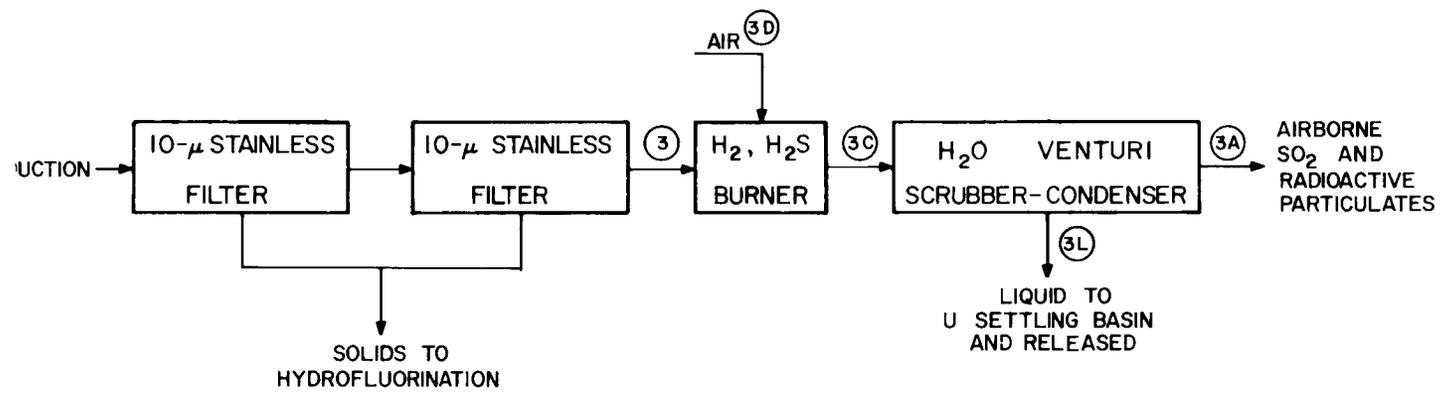


Fig. 4.11. Reduction off-gas treatment system for the model fluorination-fractionation UF₆ plant - Cases 2 and 3.

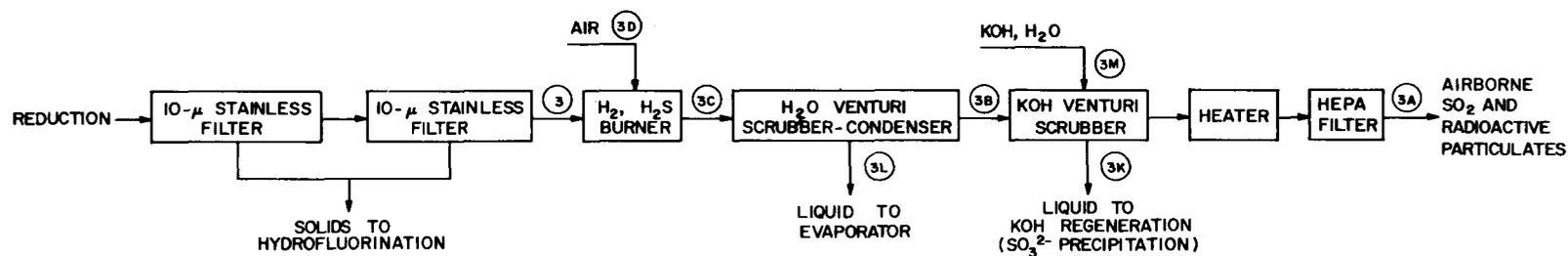


Fig. 4.12. Reduction off-gas treatment system for the model fluorination-fractionation UF₆ plant - Case 4.

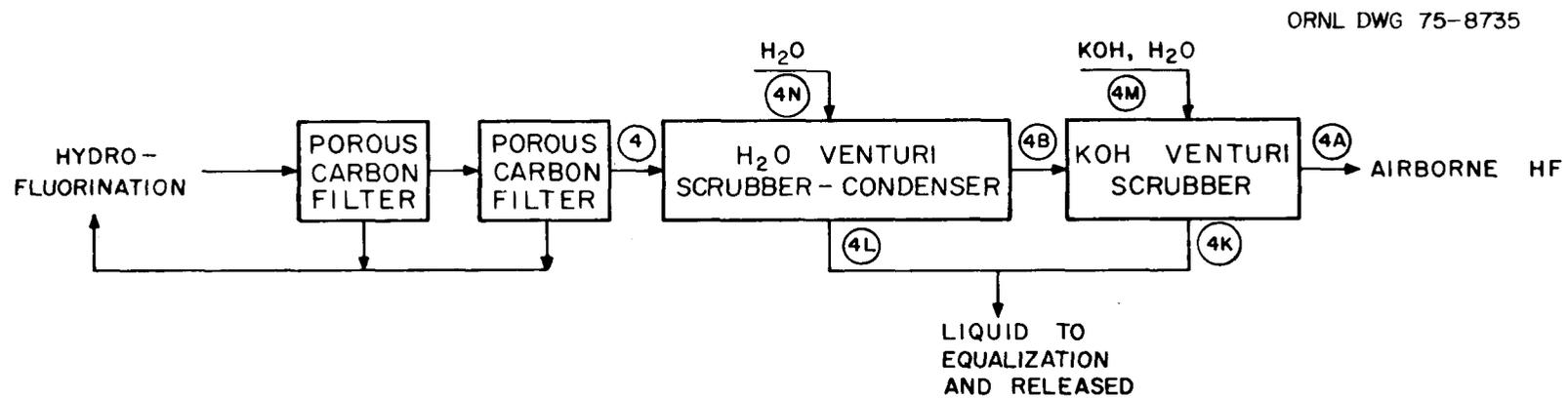


Fig. 4.13. Hydrofluorination off-gas treatment system for the model fluorination-fractionation UF_6 plant - Case 1.

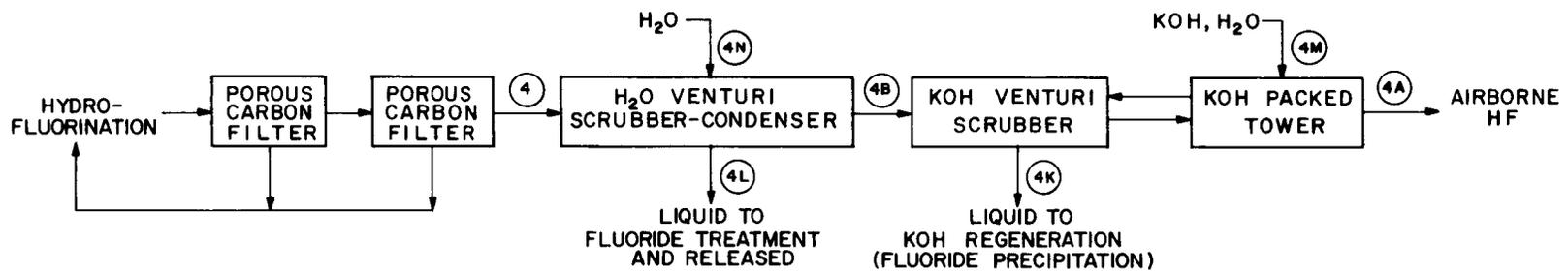


Fig. 4.14. Hydrofluorination off-gas treatment system for the model fluorination-fractionation UF₆ plant - Cases 2 and 3.

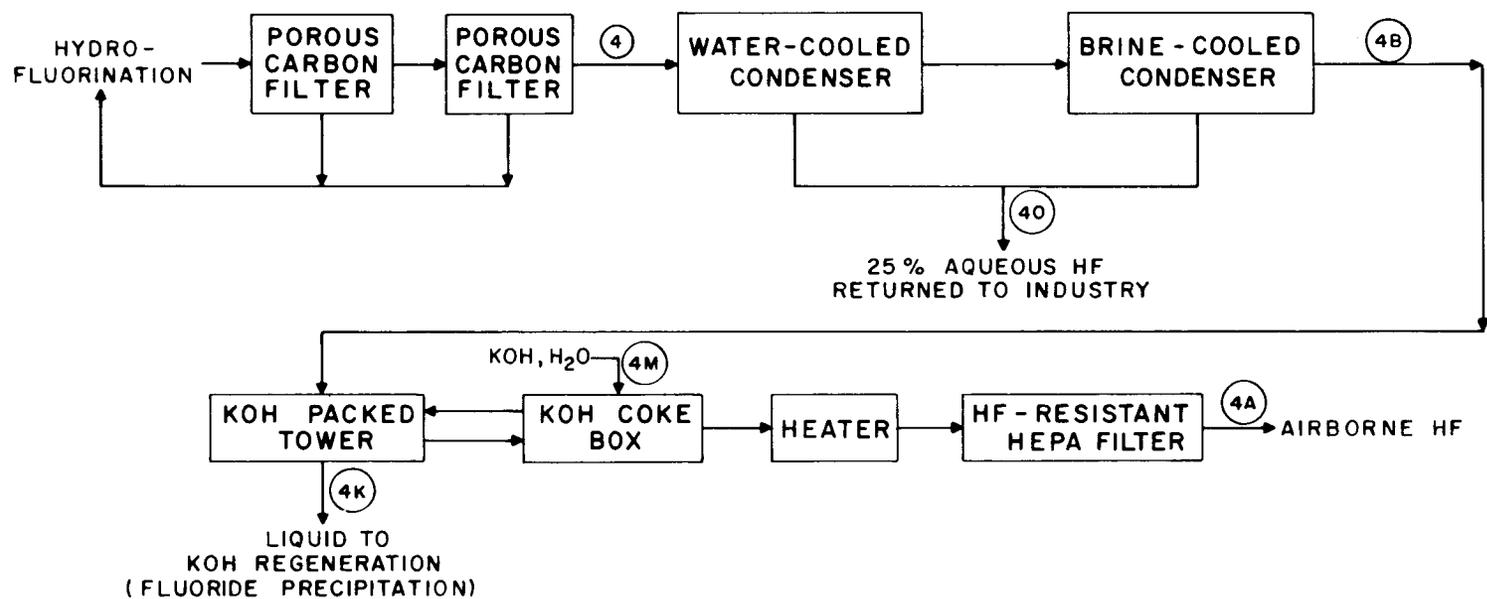
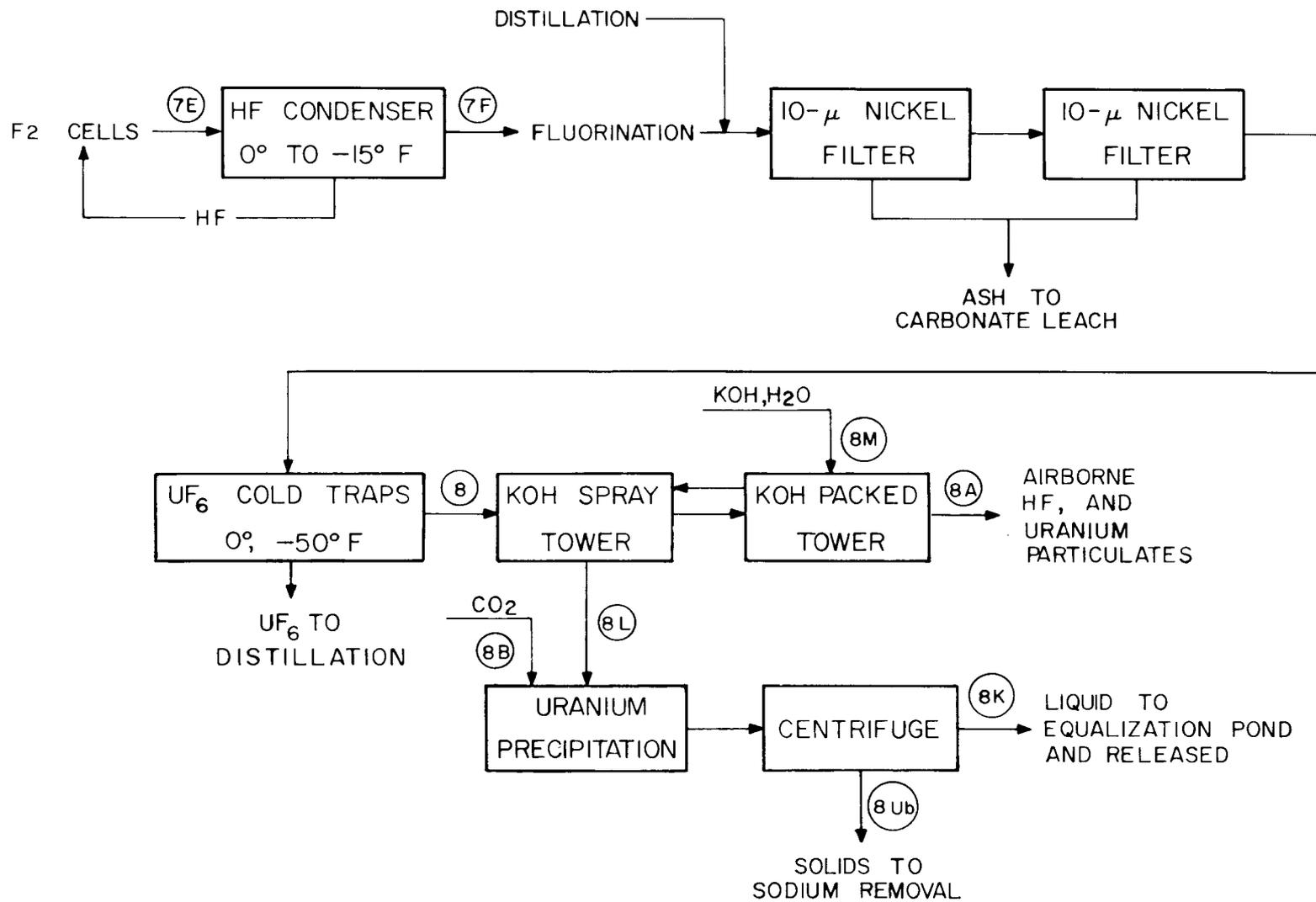


Fig. 4.15. Hydrofluorination off-gas treatment system for the model fluorination-fractionation UF₆ plant - Case 4.



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Fig. 4.16. Fluorination off-gas treatment system for the model fluorination-fractionation UF₆ plant - Case 1.

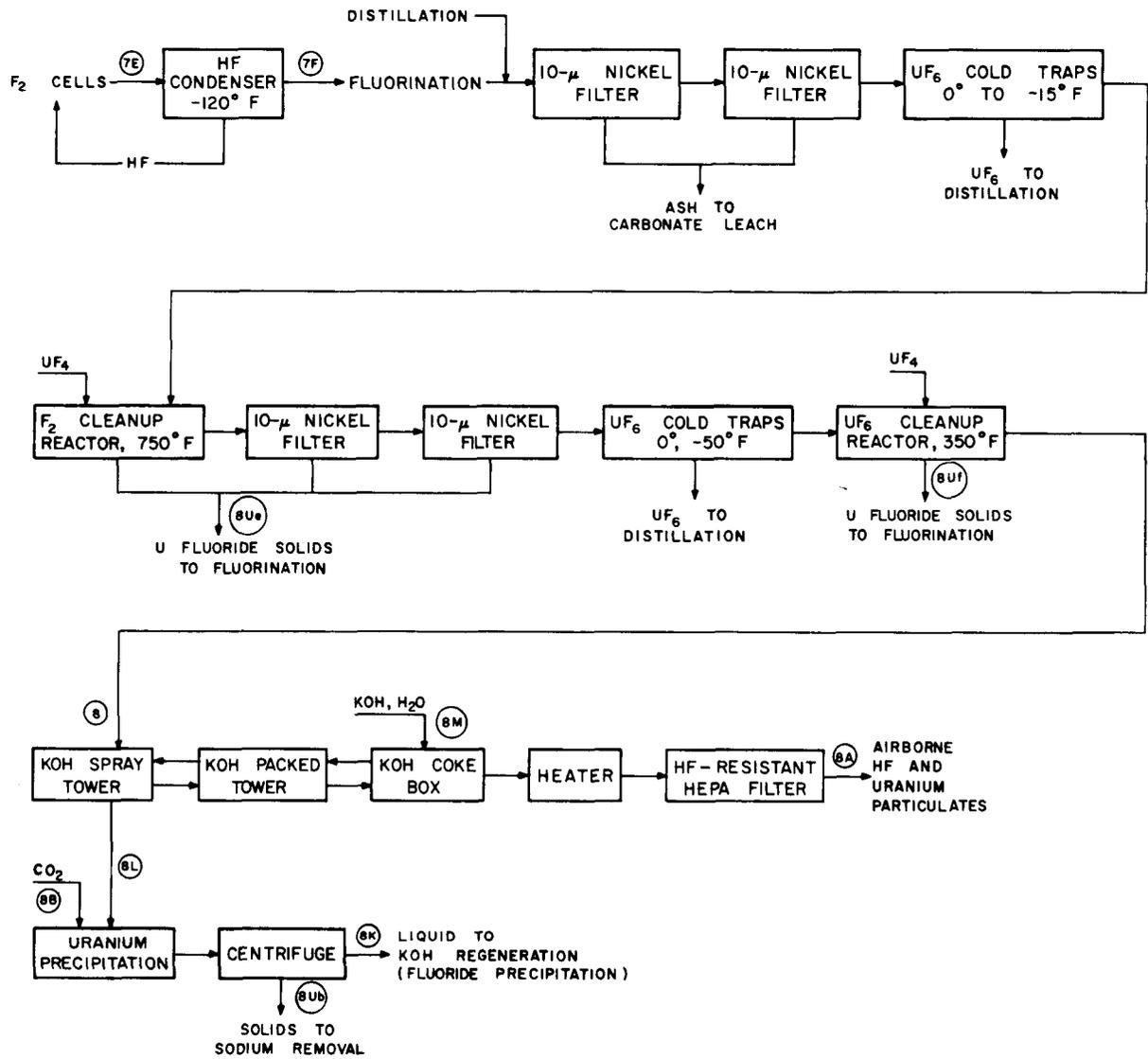


Fig. 4.18. Fluorination off-gas treatment system for the model fluorination-fractionation UF_6 plant - Case 4.

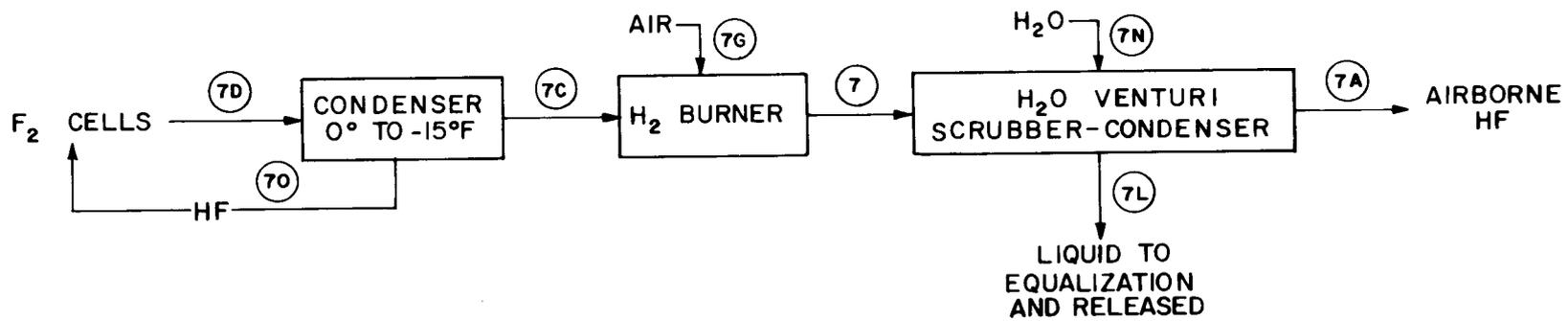


Fig. 4.19. Fluorine cell hydrogen off-gas treatment system for the model fluorination-fractionation UF₆ plant - Case I.

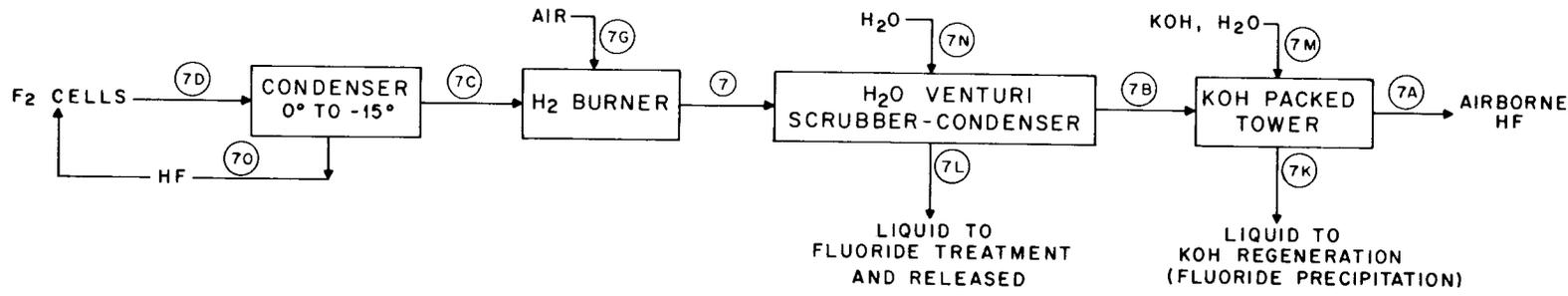


Fig. 4.20. Fluorine cell hydrogen off-gas treatment system for the model fluorination-fractionation UF₆ plant - Cases 2 and 3.

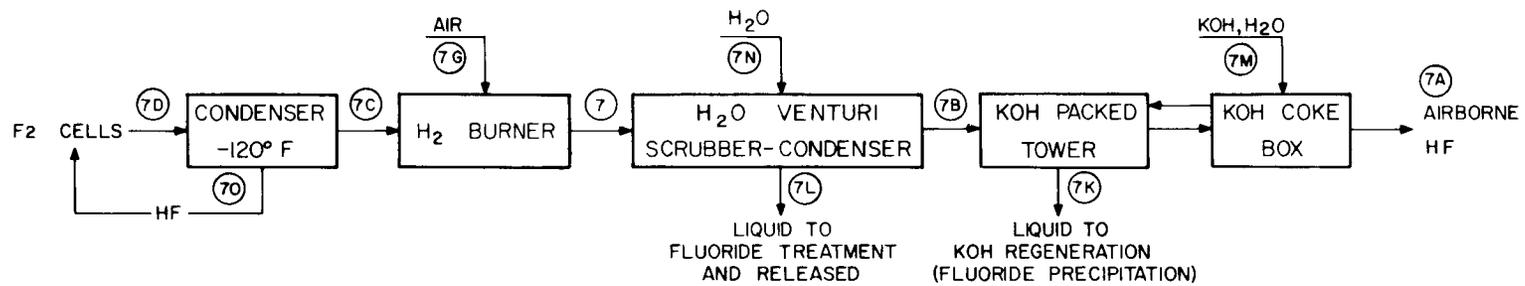


Fig. 4.21. Fluorine cell hydrogen off-gas treatment system for the model fluorination-fractionation UF₆ plant - Case 4.

REDUCTION SCRUBBERS

H₂O (3L)
KOH (3K)

H₂S, S, K₂S, U

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HYDROFLUORINATION SCRUBBERS

H₂O (4L)
KOH (4K)

HF, KF, U

FLUORINE CELL H₂ SCRUBBER

(7L) HF

FLUORINATION SCRUBBERS

(8K) KF, KOH, U

CARBONATE LEACH

(9L) Na₂CO₃, NaOH, NaF, U

SODIUM REMOVAL

(11L) (NH₄)₂SO₄, Na₂SO₄, U

MISC. WASTES

SANITARY
LAUNDRY
FLOOR AND LAB DRAINS, ETC.

URANIUM
SETTLING
BASIN
↓
SOLIDS
TO
CARBONATE
LEACH

EQUALIZATION

H₂O
(DILUTION)

LIQUID
RELEASE
H₂S, S, K₂S,
AND URANIUM

LIQUID
RELEASE
HF, KF, Na₂CO₃,
(NH₄)₂SO₄,
Na₂SO₄, AND
URANIUM

Fig. 4.22. Liquid chemwaste-radwaste effluent treatment system for the model fluorination-fractionation UF₆ plant - Case 1.

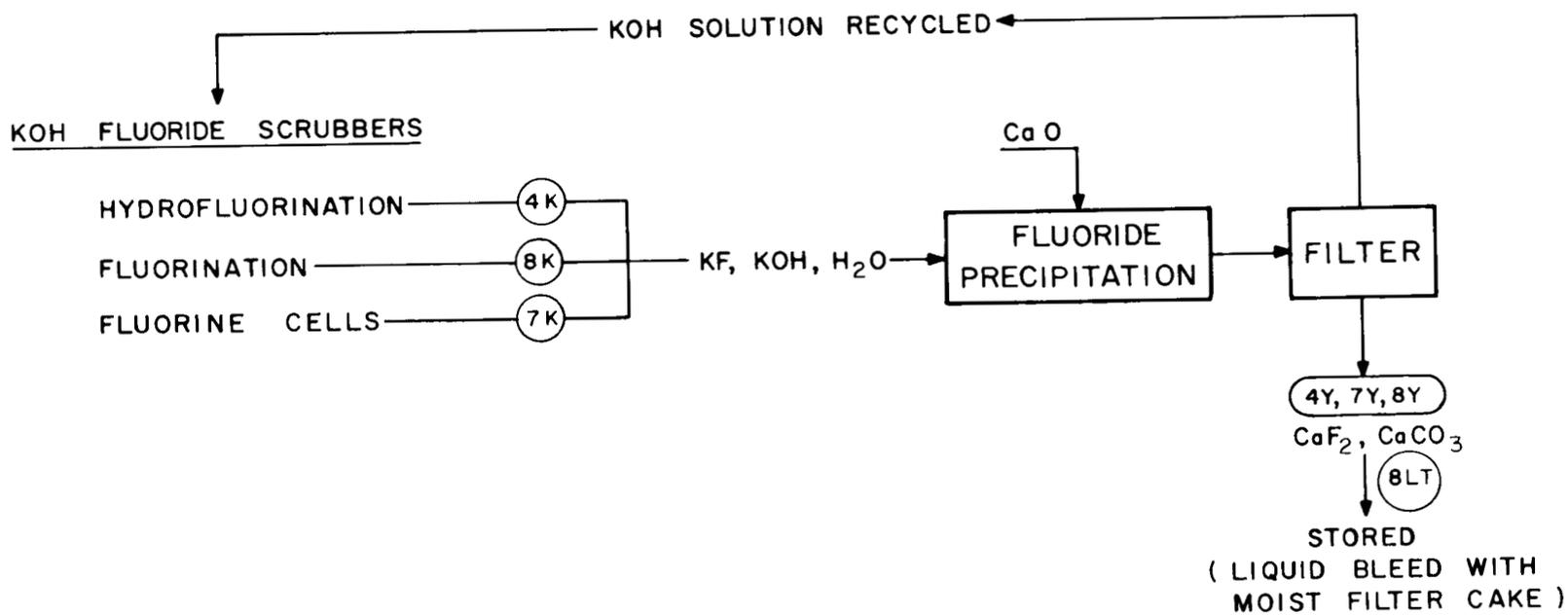


Fig. 4.23. Potassium hydroxide regeneration system for fluoride scrubber liquors for the model fluorination-fractionation UF₆ plant - Cases 2-4.

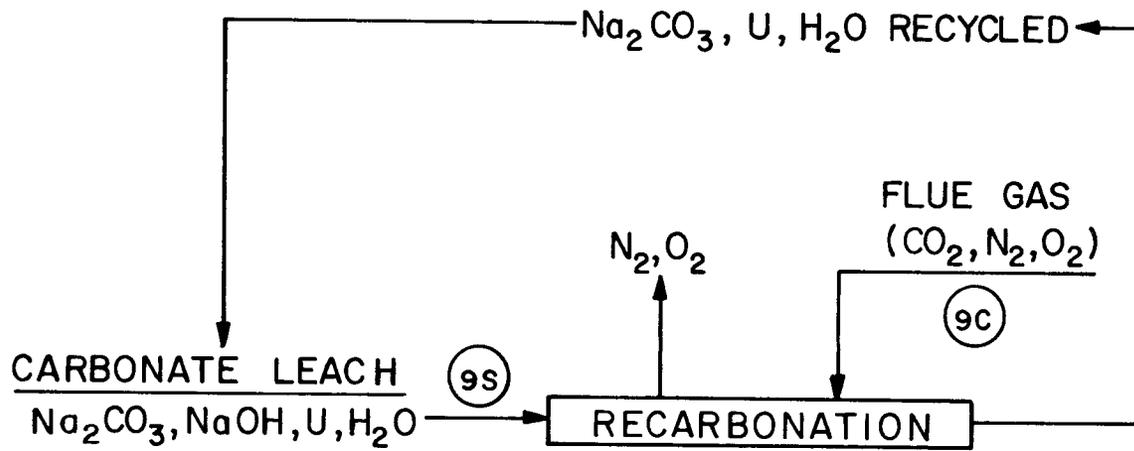


Fig. 4.24. Sodium carbonate regeneration system for carbonate leach solution for the model fluorination-fractionation UF₆ plant - Cases 2-4.

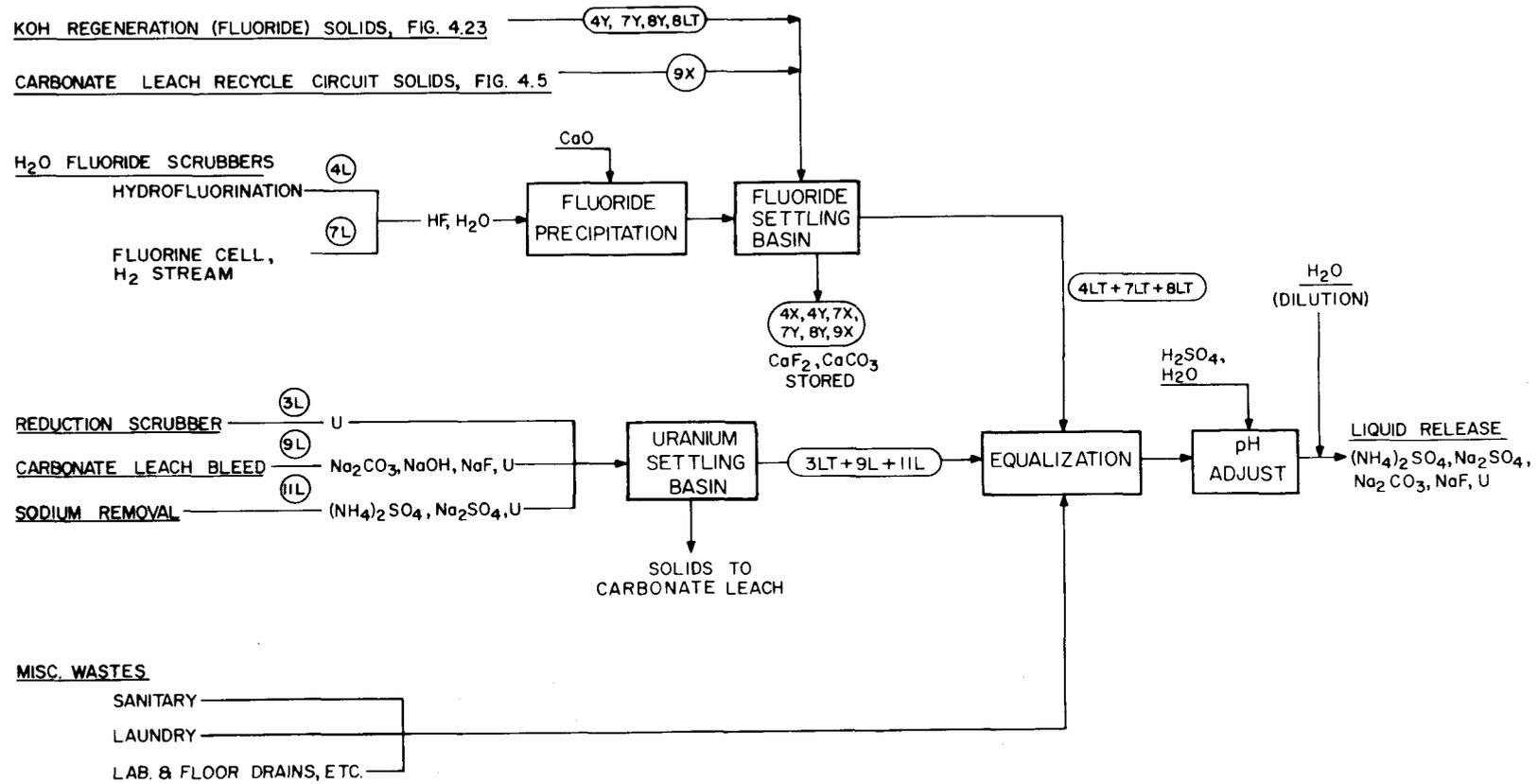


Fig. 4.25. Liquid chemwaste-radwaste effluent treatment system for the model fluorination-fractionation UF₆ plant - Case 2.

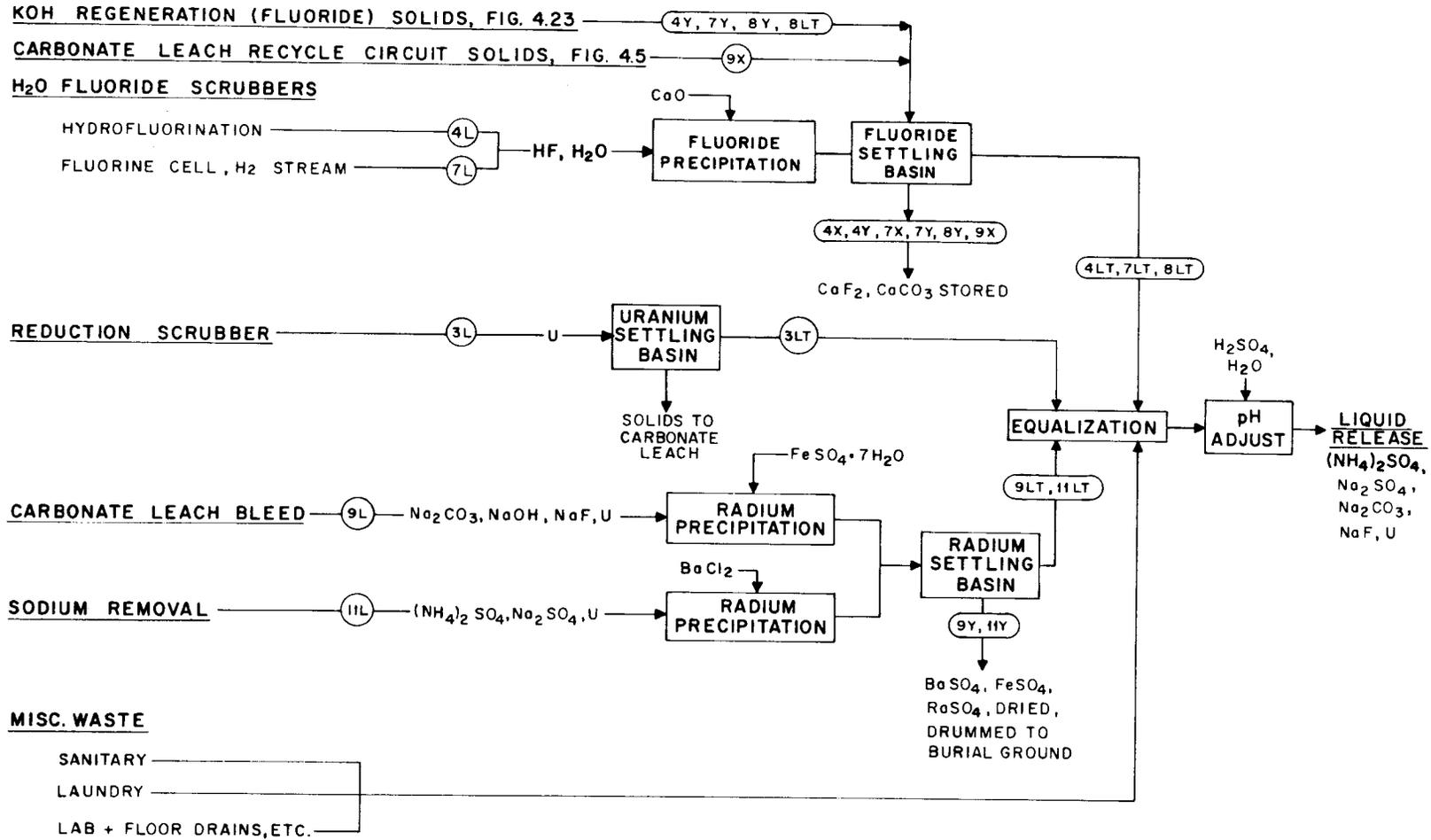
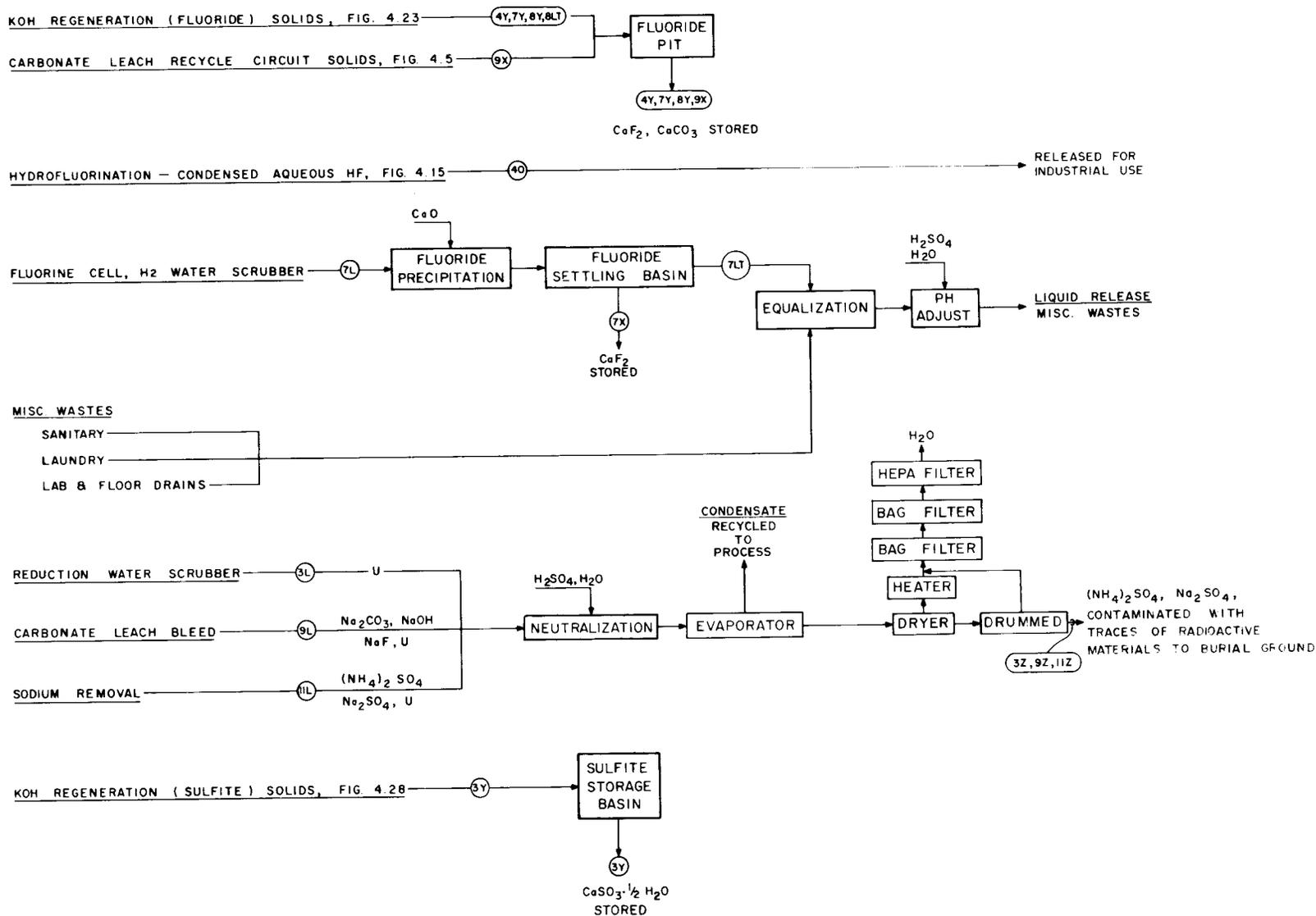
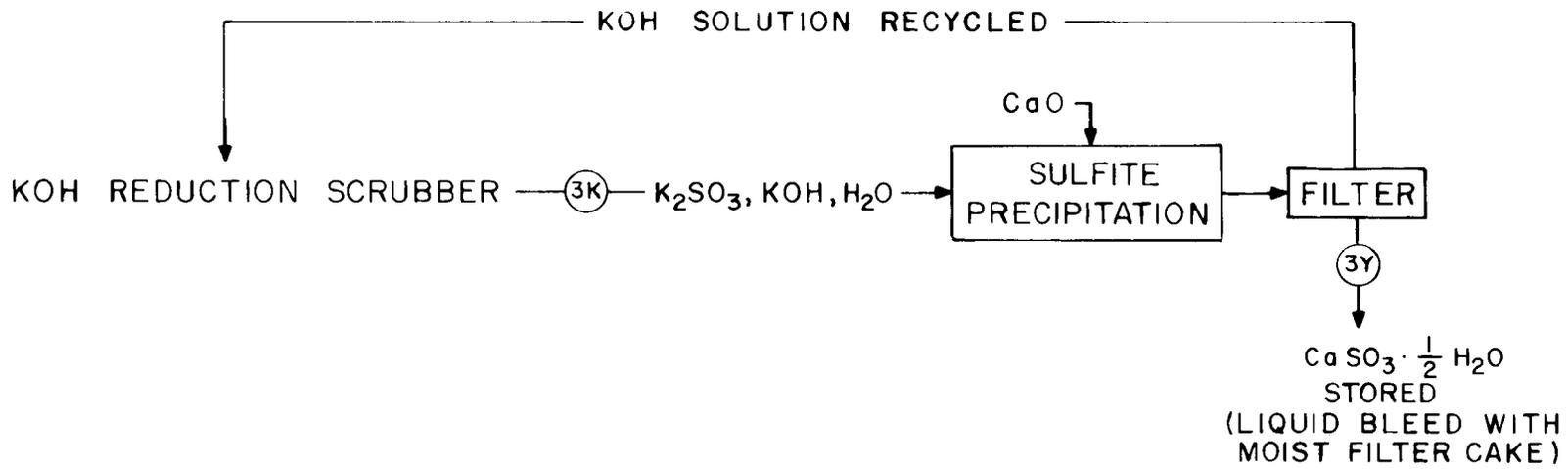


Fig. 4.26. Liquid chemwaste-radwaste effluent treatment system for the model fluorination-fractionation UF₆ plant - Case 3.



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Fig. 4.27. Liquid chemwaste-radwaste effluent treatment system for the model fluorination-fractionation UF₆ plant - Case 4.



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Fig. 4.28. Potassium hydroxide regeneration system for SO_2 scrubber liquors for the model fluorination-fractionation UF_6 plant - Case 4.

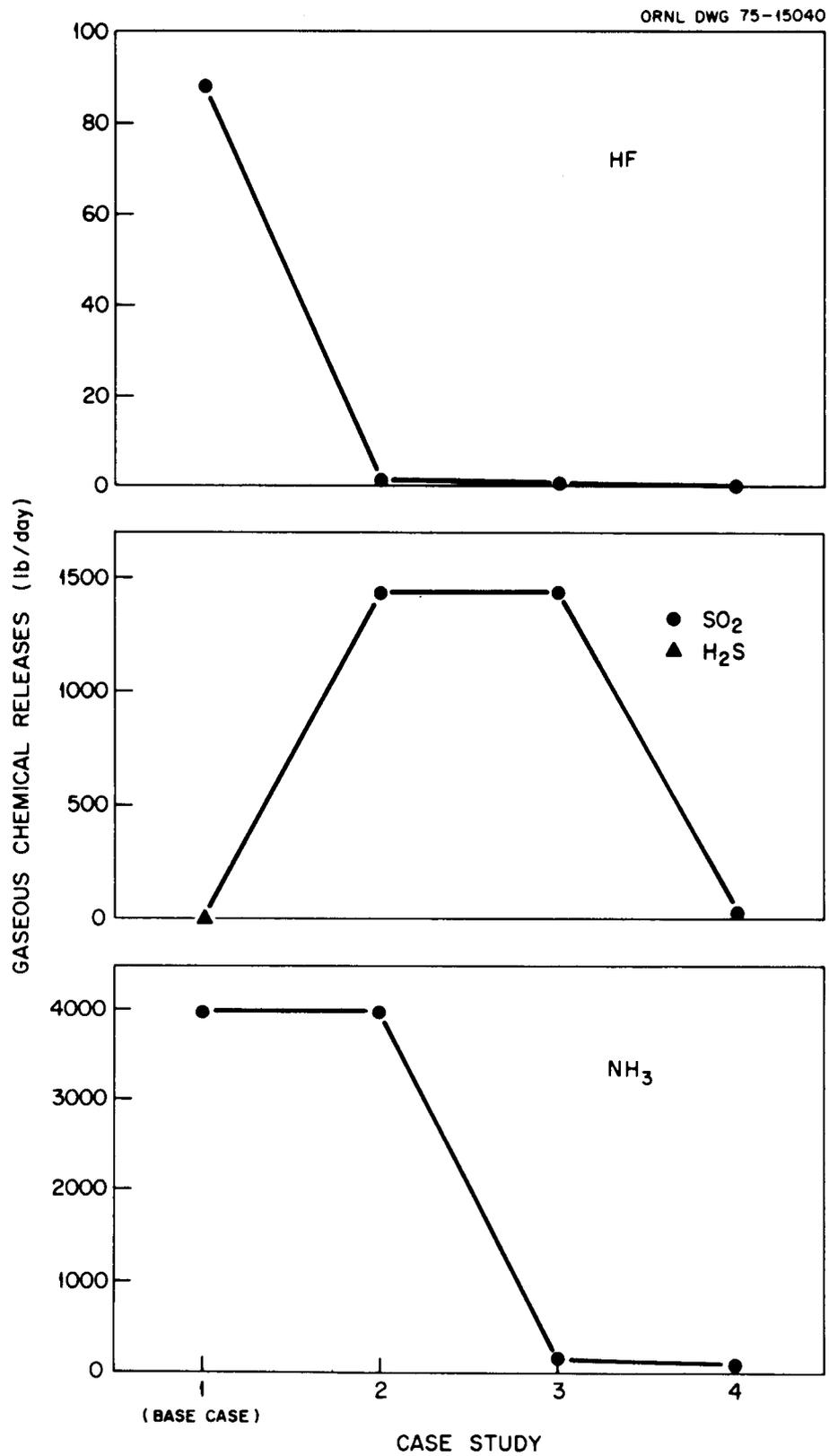


Fig. 5.1. Gaseous chemical releases from the model fluorination-fractionation UF₆ production plant as a function of case study.

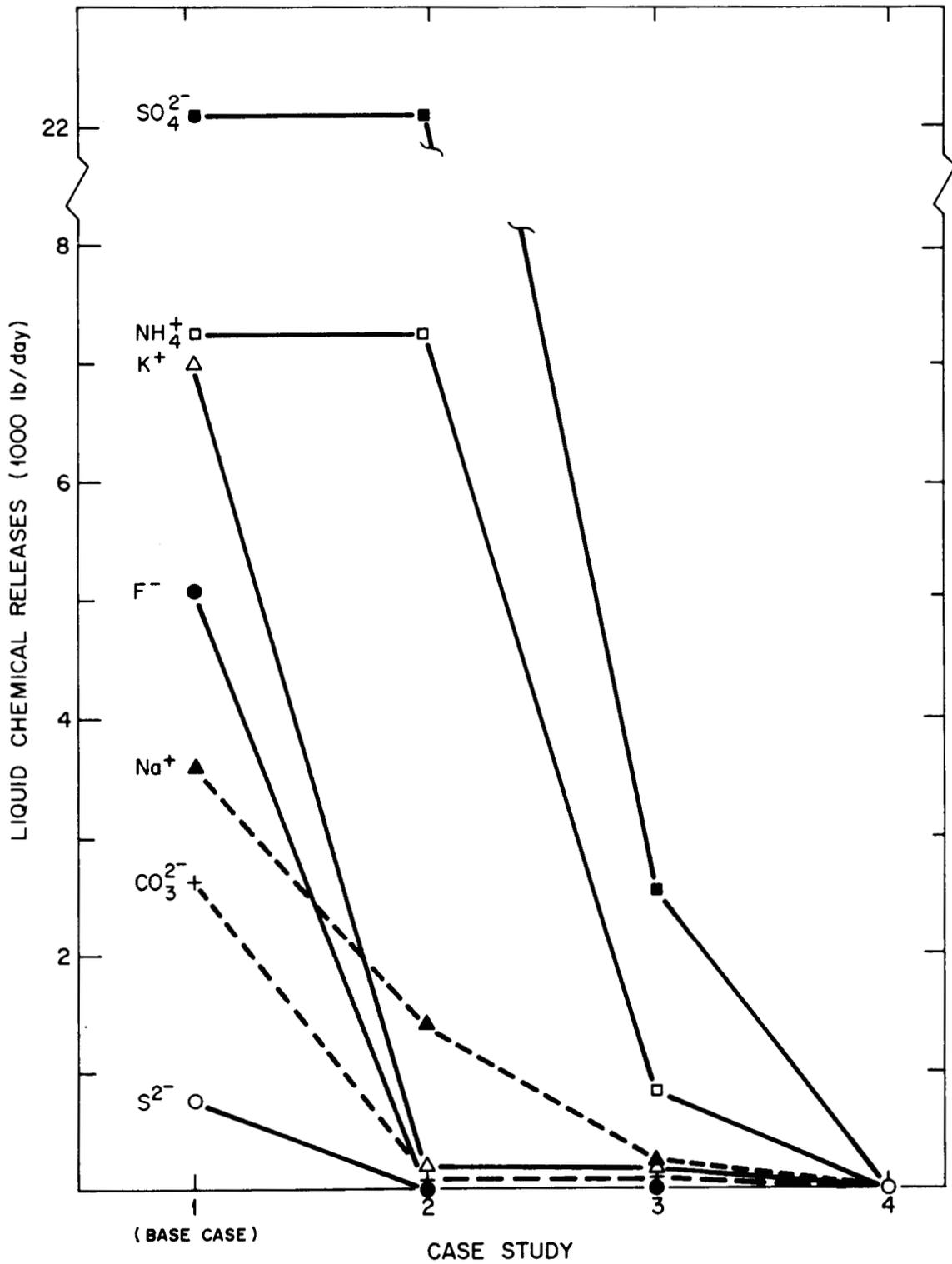


Fig. 5.2. Liquid chemical releases from the model fluorination-fractionation UF_6 production plant as a function of case study.

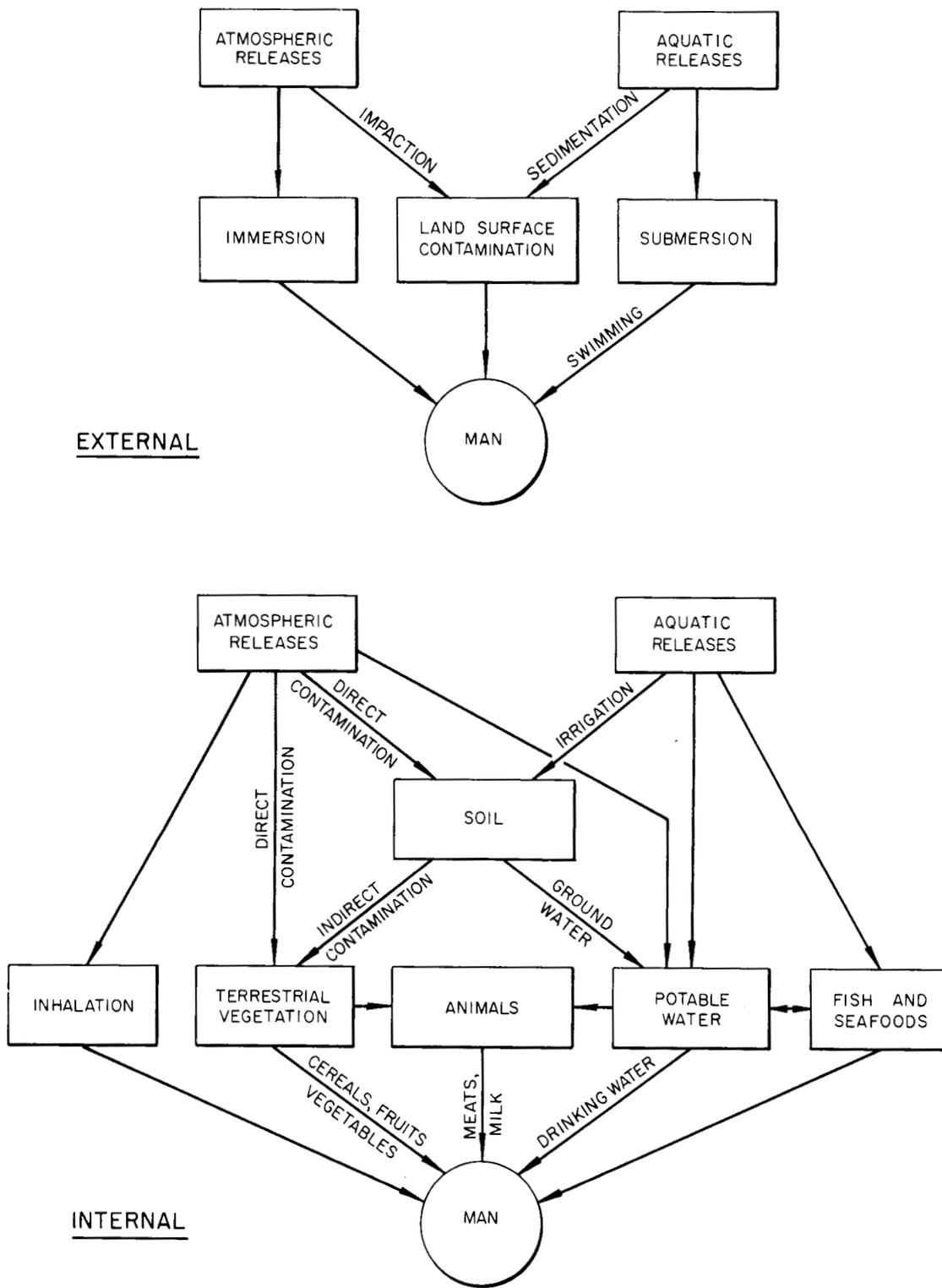


Fig. 7.1. Pathways for external and internal exposure of man.

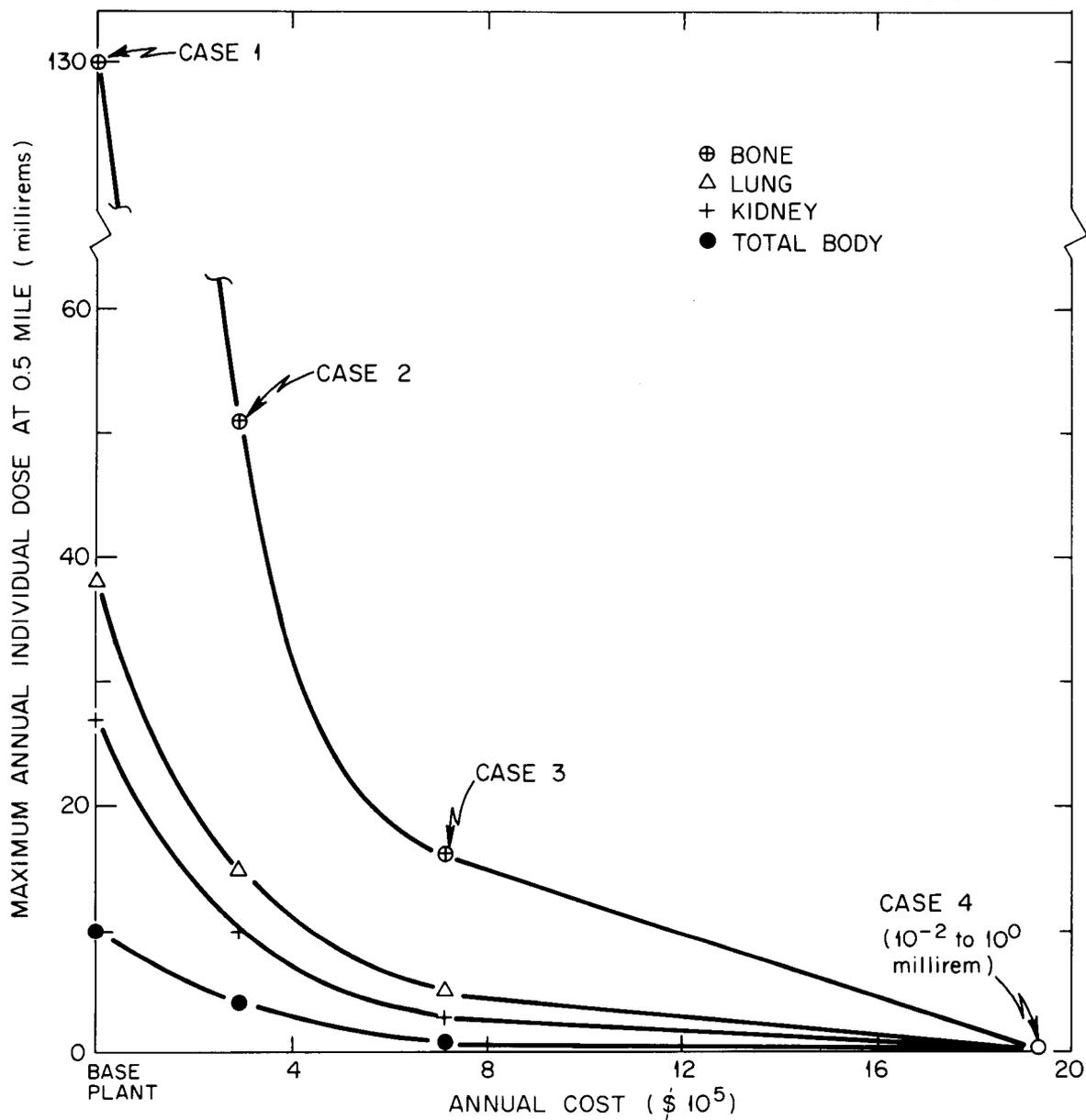


Fig. 8.1. Annual cost for reduction of maximum annual dose from airborne effluents at 0.5-mile distance from the model fluorination-fractionation UF_6 production plant. (Doses are for the feed containing "high" levels of ^{230}Th and ^{226}Ra impurities at the midwestern location.)

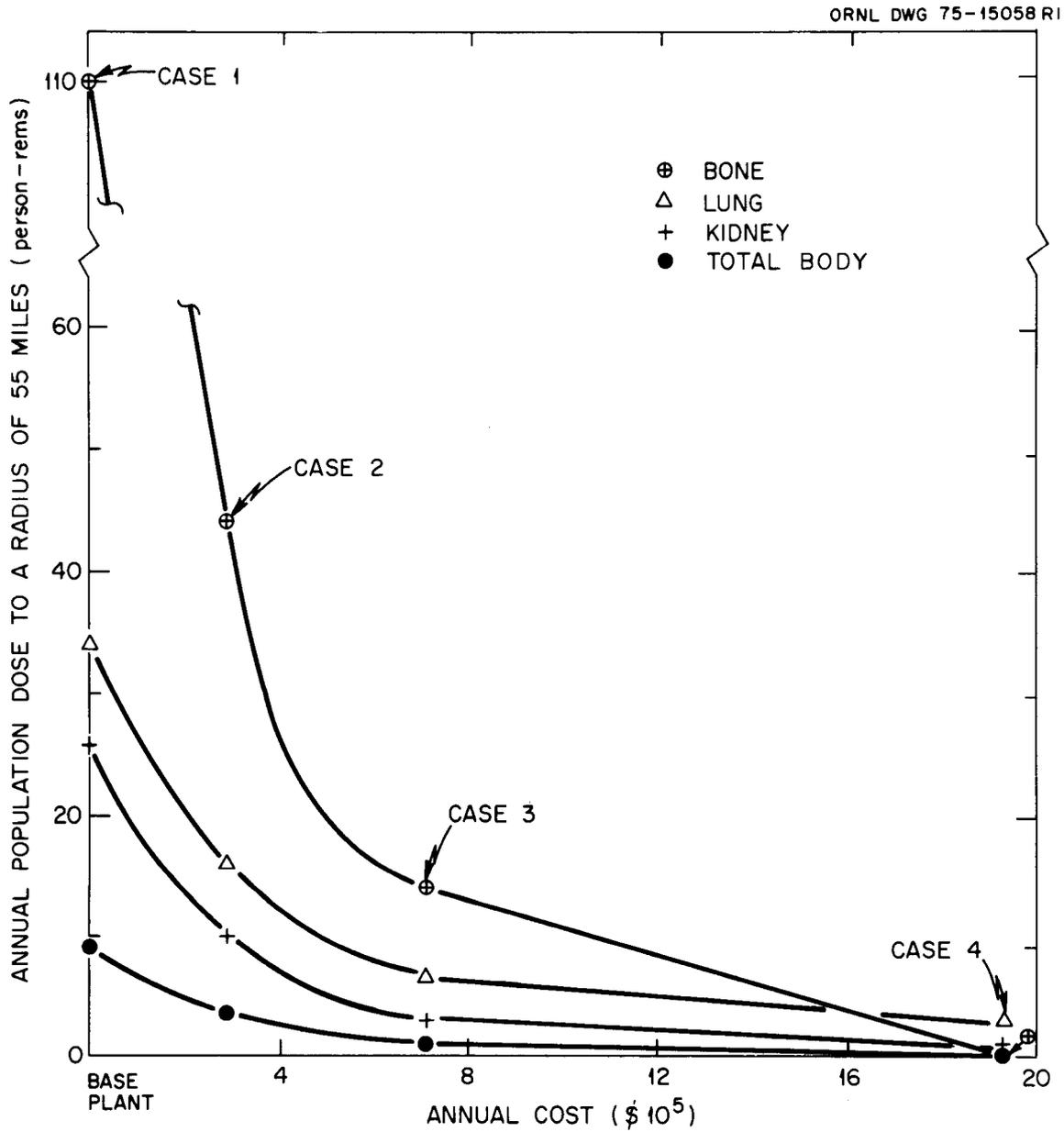


Fig. 8.2. Annual cost for reduction of annual population dose out to a radius of 55 miles from airborne effluents from the model fluorination-fractionation UF_6 production plant. (Doses are for the feed containing "high" levels of ^{230}Th and ^{226}Ra impurities at the midwestern location.)

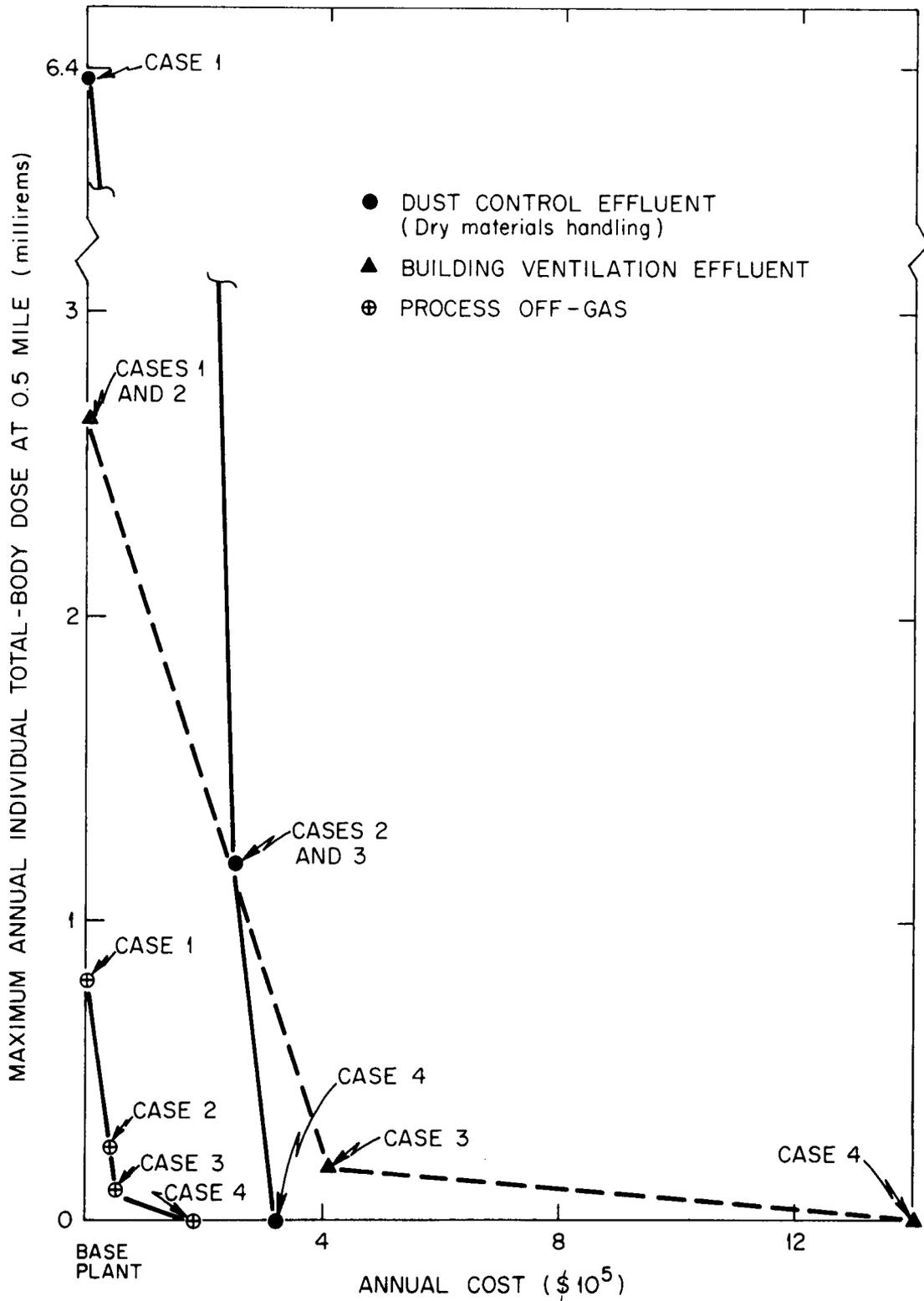
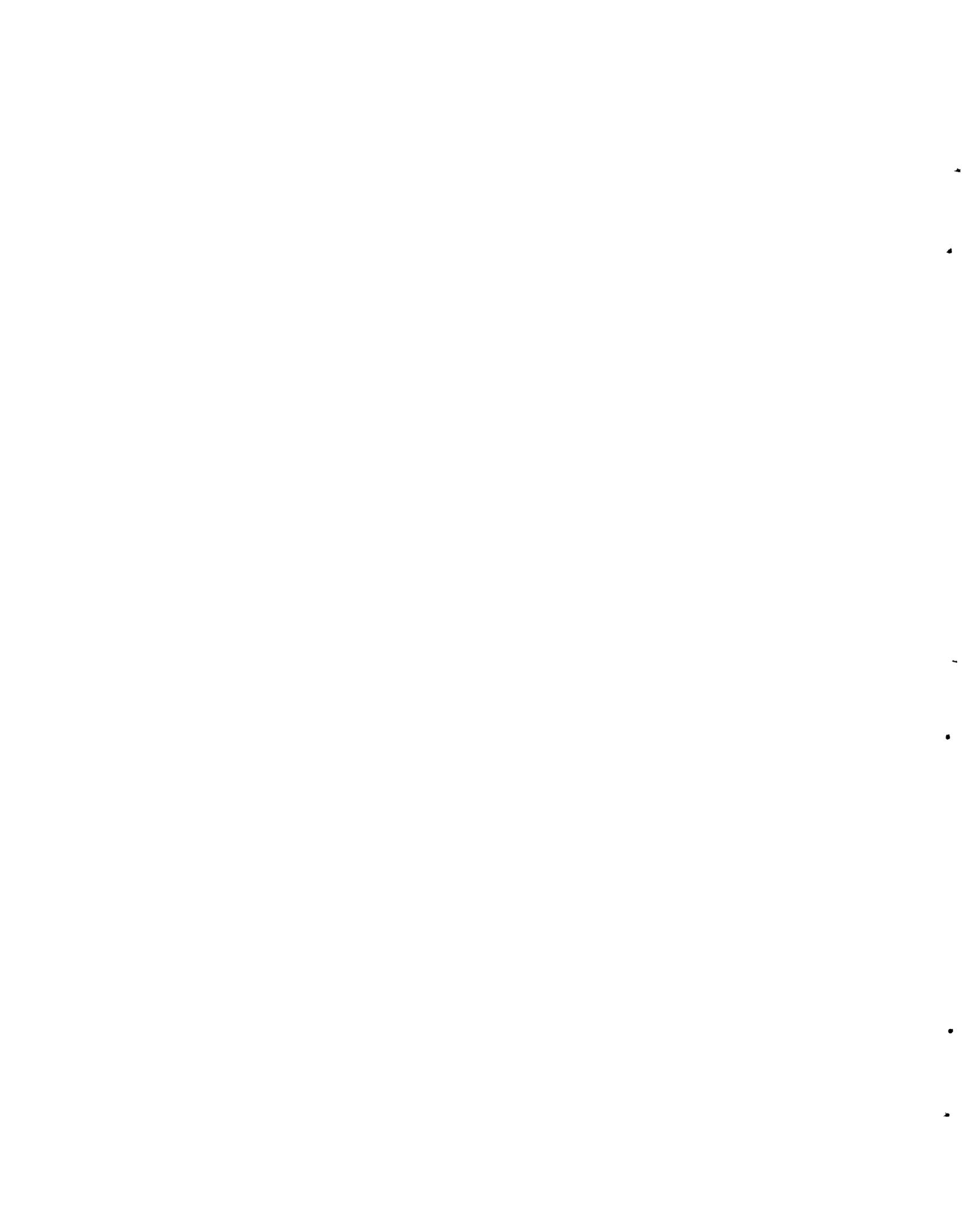


Fig. 8.3. Annual cost for reduction of maximum annual dose from dust control effluent, process off-gas, and building ventilation effluent at 0.5-mile distance from the model fluorination-fractionation UF_6 production plant. (Doses are for the feed containing "high" levels of ^{230}Th and ^{226}Ra impurities at the midwestern location.)



ADDENDUM: ASSESSMENT OF MODEL PLANT FOR FEED CONTAINING
"LOW" LEVELS OF ^{230}Th AND ^{226}Ra IMPURITIES

Members of the ORNL study team have been concerned about the ^{230}Th and ^{226}Ra contents of yellow cake. The available information was old (1960-1962)^{1,2} and based on obsolete mill circuits and questionable analytical procedures; yet this was the only data available in 1976 and early 1977. The concentrations of ^{226}Ra and ^{230}Th are important, since they are shown as major contributors to the dose in Sect. 7.0.

New data³ which became available as this report was nearly ready for publication indicate that the ^{230}Th value used for the feed to the model plant in Sects. 4.0-7.0 is high by approximately a factor of 5 and that the ^{226}Ra value is high by approximately a factor of 8. This has a significant effect on the 50-year dose commitment from airborne effluents. For example, in Case 2, at the midwestern site, the maximum individual total-body dose at 0.5 mile based on the new "low-impurity" feed is only 1.8 mrem compared with 3.8 mrem based on the old "high-impurity" feed, while the bone dose (the critical organ) based on the new feed is 18 mrem compared with 51 mrem based on the old feed. This is because (1) most airborne releases are crude uranium dusts containing the ^{230}Th and ^{226}Ra impurities, and (2) ^{230}Th and ^{226}Ra have long half-lives and are excreted from the body very slowly so that the individual continues to receive radiation from the ingested material for many years after the exposure to plant effluent. In contrast, uranium is excreted from the body fairly rapidly.

The new data on plant feed also affect the estimated quantities of radioactive materials in the solid wastes and the associated long-term ^{222}Rn release from the decay of the ^{226}Ra in these wastes. Although this is not part of the ALARA study, it would be of concern in considering the environmental impact of the burial ground. The new yellow cake analyses have little effect on the estimated doses from liquid effluents, since the major source terms contributing to exposure via liquid releases were estimated from solubility relationships rather than the plant feed.

A brief assessment of the model F-F UF₆ plant for a feed containing "low" levels of ²³⁰Th and ²²⁶Ra is presented in the subsections that follow. Except for changing the amounts of ²³⁰Th and ²²⁶Ra that enter the model plant in the form of impurities in the feed, the same assumptions are used in the Addendum as in Sect. 4.0-8.0. The most significant parameters have been calculated for the "low-impurity" feed, and sufficient information is provided in Sects. 4.0-8.0 to estimate other parameters.

A.1 Source Terms for Feed Containing "Low" Concentrations of ²³⁰Th and ²²⁶Ra

Recently, new data became available on the ²³⁰Th and ²²⁶Ra contents of the feed to the Allied Chemical Metropolis UF₆ production plant.³ This information consisted of the weighted-average feed to the Allied Chemical plant in 1976, as well as analytical data for 18 lots of yellow cake representing 12 domestic and 3 foreign producers. A tentative correlation of the Allied data identified by the producer with the probable milling process was made based on the study team's background knowledge of the milling industry. The general pattern for domestic ore concentrates is summarized in Table A-1.

The estimated feed to the model plant derived from the new data is presented in Table A-2. The higher value of either the actual Allied feed or the calculated composite of the domestic milling industry is used. The ²³⁰Th content is assumed to be 2800 pCi per gram of U_{nat}, based on the weighted-average feed to the Allied plant in 1976. This feed included concentrates which were from the Elliot Lake district in Canada and contained more thorium than domestic concentrates.^a The ²²⁶Ra content is estimated as 200 pCi per gram of U_{nat}, based on the composite product of the domestic milling industry (assumptions listed in Table A-3). This is slightly higher than the weighted average for the Allied feed of 172 pCi/U_{nat}.^b

^aThe composite product of the domestic milling industry is estimated to contain ~ 2000 pCi of ²³⁰Th per gram of U_{nat}.

^bThere may be a tendency for the F-F plant to process less than the industry's average of concentrates from the conventional alkaline (carbonate) leach circuit, which contain higher than average concentrations of ²²⁶Ra and sodium. This is because the F-F process charges a penalty for removing sodium from feed materials, while the SX-F process does not.

Source terms for airborne effluents based on the new "low-impurity" feed are presented in Table A-4; the quantities of radioactive materials in the solid wastes are listed in Table A-5. Assumptions, other than the amounts of ^{230}Th and ^{226}Ra which enter the plant as impurities in the feed, are the same as in Sect. 4.0. Liquid effluents would be similar to those described in Sect. 4.0 since the most important liquid source terms are estimated from solubility relationships and the volume of effluent, rather than the plant feed.

A.2 Environmental Impact for Feed Containing "Low" Concentrations of ^{230}Th and ^{226}Ra

A.2.1 Radiation dose commitments from airborne effluents

A.2.1.1 Doses to individuals. The maximum annual total-body doses and organ doses to individuals from all airborne effluents at 0.5 mile (800 m) from the model F-F UF_6 plant processing the "low-impurity" feed are summarized in Table A-6, assuming that 100% of the food is produced locally and that the release height is 5 m. Appropriate dose reduction factors can be applied when the release height is lower or higher (Sect. 7.1.2.5). The average dose to the individual at 0.5 mile is 47% of the maximum. Doses at other distances from the plant may be estimated from factors given in Sect. 7.1.2.6. For organs not listed, the doses are equal to or less than the value shown for total-body dose.

At the midwestern site, the maximum individual total-body dose (Table A-6) decreases from 4.9 mrem in Case 1 to 1.8 mrem in Case 2, which is about the practical limits of present technology (Sect 4.0). Additional dose reduction to 3.2×10^{-3} mrem is illustrated in Case 4. The dose to the bone (47 mrem in Case 1 and 18 mrem in Case 2) is approximately ten times higher than the total-body dose, and the doses to lungs and kidneys are, respectively, five and two times higher than the total-body dose. Treatment Case 2 is effective in reducing doses to body organs by more than one-half those for Case 1. Maximum individual doses for the New Mexico site are about 30% higher than for the midwestern site; however, the probability that an individual would reside within a 1-mile radius of the plant (Table 7.3) is low, based on the population distribution around uranium mills.

In Table A-7, comparable dose data are presented based on the assumption that none (0%) of the food consumed is produced locally. Under these conditions, the maximum individual total-body dose at 0.5 mile is 3.3 mrem in Case 1 and 1.3 mrem in Case 2, while the bone dose (the critical organ) is 24 mrem in Case 1 and 9 mrem in Case 2. Appropriate dose reduction factors can be applied when the food production and consumption pathways are known.^a

A.2.1.2 Doses to population. The annual dose commitments from airborne effluents to the population living within 55 miles of the model F-F UF₆ plant processing the "low-impurity" feed are summarized in Table A-8. At the midwestern site the population total-body dose decreases from 5.0 person-rem in Case 1 to 1.9 person-rem in Case 2, and the population bone doses from 42 person-rem to 16 person-rem. Population doses are much lower at the sparsely settled New Mexico site (e.g., 0.1 person-rem total body and 1.0 person-rem bone in Case 1).

A.2.1.3 Exposure modes and radionuclides. The relative contributions of exposure modes to the maximum annual individual total-body dose from airborne effluents are given in Table A-9 for Case 1. Exposure from contaminated ground accounts for 52% of the total-body dose, internal exposure from ingestion for 32%, and inhalation for the remainder.

The relative contributions of the principal radionuclides to the doses from airborne effluents are presented in Table A-10. The uranium isotopes contribute more than 85% of the total-body, lung, GI tract, and thyroid doses, 69% of the bone dose, and 74% of the kidney dose. Most of the remaining dose is contributed by the trace quantities of ²³⁰Th and ²²⁶Ra that enter the plant as impurities in the feed. Radon gas is a minor source of exposure, contributing only 0.03% of the total-body dose and 0.3% of the lung dose.

^aThe dose due to the ingestion may be obtained by subtracting the dose at 0% ingestion in the tables (which would be the dose from all other sources) from the dose at 100% ingestion. This ingestion dose could then be reduced by the appropriate factor according to the percentage of the food produced in the area and added back to the dose from other sources (0% ingestion) to obtain the total dose.

The relative contributions of the principal radionuclides to the exposure modes for airborne effluents are shown in Table A-11. In general, uranium isotopes are the major contributors; however, ^{230}Th makes a significant contribution to the dose via the inhalation pathway to total body (34%), bone (58%), and kidney (55%). The dose from submer- sion in air, which is quite small (Table A-9), is due almost entirely to ^{222}Rn and its daughters, ^{214}Pb and ^{218}Po . Radiation doses to certain organs are largely dependent on the specificity of certain radionuclides to accumulate in certain organs.

A.2.2 Radiological impact of liquid effluents

The radiological impact of the liquid effluent from the model plant processing the "low-impurity" feed is essentially the same as the model plant processing the "high-impurity" feed (Sect. 7.2). Case 1 doses to the total body and the lung from using the 15-cfs stream are about the same as the airborne doses. It is unlikely that anyone would routinely use the 15-cfs stream because of the high chemical content. It is more probable that the 1300-cfs river would serve as the drinking water source; in this case the dose from liquid effluents (0.1 mrem to total body, 1 mrem to bone) would be quite small as compared with the airborne dose.

A.3 Cost/Benefit Summary for the Model F-F Plant Processing a Feed Containing "Low" Concentrations of ^{230}Th and ^{226}Ra

The total annual costs (1973 dollars) for reduction of the radio- logical dose commitment and chemical exposure to the population surround- ing a model fluorination-fractionation UF_6 production plant processing the "low-impurity" feed are summarized in Tables A-12 and A-13 for the midwestern and New Mexico sites respectively. The amount of solid waste generated by the advanced liquid waste treatment systems is included since this waste increases the amount of land permanently committed. The total annual cost increases over the base case range from \$683,000 for Case 2 to \$2,908,000 for Case 4, and are equivalent to a contribution to power of 0.0013 to 0.0054 mill/kWhr.

The estimated capital cost of the base plant is \$35 million, including the Case 1 off-gas treatment. The increases in capital costs range from \$2.02 million for Case 2 to \$7.35 million for Case 4, or 6 to 21% of the cost of the base plant.

The total annual cost increase for reduction of dose from all airborne effluents is presented in Table A-14 and Figs. A-1 and A-2 for the midwestern site. For the base plant, the maximum annual individual dose commitments at 0.5 mile are 4.9 mrem to the total body and 47 mrem to the bone (the highest organ dose), and the annual total population doses out to 55 miles are estimated at 5.0 person-rem to the total body and 42 person-rem to the bone. These doses are for a base plant containing only treatment essential to the economic operation of the process. The addition of secondary bag filters and secondary or tertiary scrubbers on the process reduces the maximum individual doses to 1.8 mrem to the total body and 18 mrem to the bone. The annual cost of this dose reduction from Case 1 to Case 2 is high--\$94,000/mrem total body and \$10,000/mrem bone for the individual at the fence post or \$94,000/person-rem total body and \$11,000/person-rem bone for the general population out to 55 miles at the midwestern site (Table A-15). Case 2 represents about the practical limits of present technology. Further dose reductions to very low levels using advanced technology are possible, but the incremental annual cost/benefit is very high--i.e., \$39,000/person-rem bone from Case 2 to Case 3 and \$250,000/person-rem bone between Case 3 and Case 4 (Tables A-14 and A-15).

The relative importance of the various airborne treatment methods will be the same as discussed in Sect. 8.0, although the absolute cost/benefit ratio is less favorable (i.e., a smaller dose reduction per thousand dollars spent on waste treatment).

Cost/benefit relationships for treating liquid effluents from the model plant processing the "low-impurity" feed will be similar to those for the "high-impurity" feed described in Sect. 8.0.

A.4 References

1. January 1960 - Summary Report, WIN-112, National Lead Company, Winchester Laboratory (Feb. 1, 1960), pp. 6-14, 53-55.
2. E. C. Tsivoglou and R. L. O'Connell, Waste Guide for the Uranium Milling Industry, Technical Report W62-12, U. S. Public Health Service, R. A. Taft Sanitary Engineering Center, Cincinnati, Ohio (1962), pp. 28-31.
3. R. W. Yates (Health Physicist, Allied Chemical Metropolis UF₆ Plant), personal communication to M. B. Sears, Mar. 29, 1977.

Table A-1. Radioactive impurities in uranium ore concentrates^a

	²³⁰ Th (pCi/g U _{nat})	²²⁶ Ra (pCi/g U _{nat})
Weighted-avg. feed to Metropolis UF ₆ plant in 1976	2845 ^b	172
Mill process -- domestic mills ^c		
Amine solvent extraction	~ 500	~ 6
"Low" ion exchange ^d	~ 600	~ 3
"High" ion exchange	~ 6000	~ 300
Alkaline (carbonate) leach		
Conventional circuit	~ 2600	~ 900
Plus dissolution in H ₂ SO ₄ and reprecipitation with H ₂ O ₂	~ 300	~ 600
Solution mining plus ion exchange	~ 200	~ 60

^a W. Yates (Health Physicist, Allied Chemical Metropolis UF₆ plant), personal communication to M. B. Sears, Mar. 29, 1977.

^b Includes concentrates from the Elliot Lake district of Canada which are higher in ²³⁰Th than domestic concentrates.

^c Tentative correlation of the Allied data identified by producer with the probable milling process based on the ORNL study team's background knowledge of the milling industry. There is some uncertainty in the correlation since some companies own more than one mill or may have made changes in the mill circuits.

^d It seems likely that the "low" ion exchange concentrates received additional purification by the Eluex process. Eluex is an amine solvent extraction process which should have a selectivity somewhat similar to the conventional amine solvent extraction process. Details of the milling history of these lots are not known.

Table A-2. Feed to the model yellow-cake-to-UF₆ conversion plant containing "low" levels of ²³⁰Th and ²²⁶Ra

(Other assumptions are the same as those listed in Table 4.2.)

Principal radionuclides	Quantity fed (Ci/yr)
U _{nat}	3333 ^a
²³⁴ Th	3333
^{234m} Pa ^b	3333
²³⁰ Th	28 ^c
²²⁶ Ra	2.0 ^d
²²² Rn	2.0

^aThe "old" (prior to July 10, 1974) definition of a curie of natural uranium (U_{nat}) is used throughout this report to be consistent with the earlier report in this series on uranium mills. One curie of U_{nat} is the sum of 3.7×10^{10} dis/sec from ²³⁸U, plus 3.7×10^{10} dis/sec from ²³⁴U, plus 9×10^8 dis/sec from ²³⁵U. Under the "old" definition, 1 kg of U_{nat} is equivalent to 333.3 μCi of U_{nat}, or the sum of 333.3 μCi of ²³⁸U, 333.3 μCi of ²³⁴U, and 8.1 μCi of ²³⁵U. Under the current (July 10, 1974) definition, 1 kg of U_{nat} is equivalent to 677.0 μCi of U_{nat}, or the sum of 330.9 μCi of ²³⁸U, 330.9 μCi of ²³⁴U, and 15.4 μCi of ²³⁵U. There is approximately a 1% difference between the "old" and the "new" curie in calculating source terms, except for ²³⁵U.

^bMetastable ^{234m}Pa, $t_{1/2} = 1.18$ min.

^cThe ²³⁰Th content is assumed to be 2800 pCi per gram of U_{nat} based on the weighted-average feed (rounded to two significant figures) to the Allied Chemical Metropolis UF₆ Plant in 1976, including "high" thorium foreign concentrates.

^dThe ²²⁶Ra content is assumed to be 200 pCi per gram of U_{nat} based on the calculated composite product of the domestic milling industry (assumptions listed in Table A-3). This is slightly higher than the weighted average for the Allied feed of 172 pCi per gram of U_{nat}.

Table A-3. Assumptions for estimating the "low"-
²²⁶Ra feed to the model UF₆ plant

Mill process	Fraction of model UF ₆ plant feed ^a (%)	²²⁶ Ra content (pCi/g U _{nat}) ^b
Amine solvent extraction	45	6
Ion exchange plus Eluex	20	3 ^c
Ion exchange	20	300
Alkaline (carbonate) leach, "conventional" circuit	15 ^d	900

^a Estimated from the relative ore processing rates based on a survey of active mills made in the spring of 1973 (ORNL-TM-4903, p. 224).

^b Tentative correlation of the Allied data on the ²²⁶Ra content of domestic ore concentrates identified by producer with the probable milling process based on the ORNL study team's knowledge of the milling industry. There is some uncertainty in the correlation since some companies own more than one mill or may have changes in the mill circuits.

^c Assuming that mills using ion exchange plus Eluex (an amine solvent extraction process) produce the "low"-ion-exchange ore concentrate of Table A-1.

^d Assuming all alkaline (carbonate)-leached ore concentrate is produced by conventional circuit.

Table A-4. Airborne radwaste releases from the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant - "low-impurity" feed^a

(Other assumptions are the same as those described in Sect. 4.0.)

Airborne radwaste treatment case	U (kg/yr)	Principal radionuclides (Ci/yr)					
		U ^b _{nat}	²³⁴ Th	^{234m} Pa ^c	²³⁰ Th	²²⁶ Ra	²²² Rn ^d
1	664.2	2.21E-1	2.15E-1	2.15E-1	2.39E-3	1.72E-4	9.16
2	250.3	8.33E-2	8.22E-2	8.22E-2	9.27E-4	6.74E-5	9.16
3	77.0	2.57E-2	2.57E-2	2.57E-2	2.90E-4	2.07E-5	9.16
4	0.2	6.76E-5	7.28E-5	7.28E-5	6.70E-7	4.79E-8	9.16

^aPlant feed contains 2800 pCi of ²³⁰Th and 200 pCi of ²²⁶Ra per gram of U_{nat}.

^bOne curie of natural uranium is defined as the sum of 3.7 x 10¹⁰ dis/sec from ²³⁸U, 3.7 x 10¹⁰ dis/sec from ²³⁴U, and 9 x 10⁸ dis/sec from ²³⁵U; it is also equivalent to 3000 kg of natural uranium.

^cMetastable ^{234m}Pa, t_{1/2} = 1.18 min.

^dAs gas. Does not include ²²²Rn generated in dust particles by decay of ²²⁶Ra.

Table A-5. Solid chemwaste-radwaste generated by the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant--"low-impurity" feed^{a,b,c}
(Other assumptions are the same as those described in Sect. 4.0)

Source	Code	Quantity (lb/yr)	Principal radionuclides								
			U _{nat} ^d	Total (Ci/yr)				Average concentration (μCi/g)			
				²³⁴ Th, ^{234m} Pa ^e each	²³⁰ Th	²²⁶ Ra, ²²² Rn, ²¹⁰ Po, ²¹⁴ Pb, ²¹⁴ Bi, ²¹⁴ Po, each	U _{nat} ^d	²³⁴ Th, ^{234m} Pa ^e each	²³⁰ Th	²²⁶ Ra, ²²² Rn, ²¹⁰ Po, ²¹⁴ Pb, ²¹⁴ Bi, ²¹⁴ Po, each	
Avg. composition of earth's crust ^f											
Case 1											
Carbonate-leached ash from fluorination, principally CaF ₂ , dried and drummed for disposal	10W	2.21E+6	1.17E-1	1.17E-1	2.81E+1	2.00E00	1.2 E-4	1.2 E-4	2.8 E-2	2.0 E-3	
Still tops and bottoms, stored in gas-tight containers	8Uc + 8Ud	8.87E+4	1.67E00	1.67E00	7.49E-4	5.38E-5	4.2 E-2	4.2 E-2	1.8 E-5	1.3 E-6	
Total		2.30E+6	1.79E00	1.79E00	2.81E+1	2.00E00					
Case 2											
Carbonate-leached ash from fluorination, principally CaF ₂ , dried and drummed for disposal	10W	2.45E+6	1.17E-1	1.17E-1	2.81E+1	2.00E00	1.0 E-4	1.0 E-4	2.6 E-2	1.8 E-3	
Still tops and bottoms, stored in gas-tight containers	8Uc + 8Ud	8.87E+4	1.67E00	1.67E00	7.49E-4	5.38E-5	4.2 E-2	4.2 E-2	1.8 E-5	1.3 E-6	
CaF ₂ -CaCO ₃ stored in the fluoride settling basins	4X + 4Y + 7X + 7Y + 8Y + 9X	3.56E+6	1.21E-1	1.21E-1	2.47E-5	1.18E-5	7.5 E-5	7.5 E-5	1.5 E-8	7.3 E-9	
Total		6.10E+6	1.89E00	1.89E00	2.81E+1	2.00E00					
Case 3											
Carbonate-leached ash from fluorination, principally CaF ₂ , dried and drummed for disposal	10W	2.45E+6	1.17E-1	1.17E-1	2.81E+1	2.00E00	1.0 E-4	1.0 E-4	2.6 E-2	1.8 E-3	
Still tops and bottoms, stored in gas-tight containers	8Uc + 8Ud	8.87E+4	1.67E00	1.67E00	7.49E-4	5.38E-5	4.2 E-2	4.2 E-2	1.8 E-5	1.3 E-6	
CaF ₂ -CaCO ₃ stored in fluoride settling basin	4X + 4Y + 7X + 7Y + 8Y + 9X	3.56E+6	1.21E-1	1.21E-1	2.47E-5	1.18E-5	7.5 E-5	7.5 E-5	1.5 E-8	7.3 E-9	
Fe ₂ SO ₄ ·7H ₂ O and BaSO ₄ , dried and drummed for disposal	9Y + 11Y	1.80E+3	3.25E-6	3.25E-6	1.74E-9	2.69E-4	4.0 E-6	4.0 E-6	2.2 E-9	3.3 E-4	
Total		6.10E+6	1.89E00	1.89E00	2.81E+1	2.00E00					
Case 4											
Carbonate-leached ash from fluorination, principally CaF ₂ , cemented and drummed for disposal	10W	1.63E+7	1.17E-1	1.17E-1	2.81E+1	2.00E00	1.6 E-5	1.6 E-5	3.8 E-3	2.7 E-4	
Still tops and bottoms, stored in gas-tight containers	8Uc + 8Ud	8.87E+4	1.67E00	1.67E00	7.49E-4	5.38E00	4.2 E-2	4.2 E-2	1.8 E-5	1.3 E-6	
CaF ₂ -CaCO ₃ stored in lined fluoride pit	4Y + 7Y + 8Y + 9X	4.04E+5	3.54E-2	3.54E-2	1.81E-5	1.13E-6	1.9 E-4	1.9 E-4	9.9 E-8	6.1 E-8	
CaF ₂ stored in lined fluoride settling basin	7X	1.13E+5	-	-	-	-	-	-	-	-	
CaSO ₃ ·1/2H ₂ O stored in lined sulfite settling basin	3Y	9.39E+5	4.72E-5	4.72E-5	3.97E-7	2.82E-8	1.1 E-8	1.1 E-8	9.3 E-11	6.6 E-12	
(NH ₄) ₂ SO ₄ , Na ₂ SO ₄ evaporator residues dried and drummed for disposal	3Z, 9Z, 11Z	8.40E+5	4.03E-2	4.03E-2	9.58E-5	2.28E-4	9.3 E-5	9.3 E-5	2.2 E-7	5.2 E-7	
Total		1.88E+7	1.83E00	1.83E00	2.81E+1	2.00E00					

^aPlant feed contains 2800 pCi of ²³⁰Th and 200 pCi of ²²⁶Ra per gram of U_{nat}.

^bOnly radioactive materials in the yellow cake feed to the plant are considered; possible radioactive impurities in the chemical feed to the plant are not included.

^cStored 6 months so that ²³⁴Th and ^{234m}Pa are in secular equilibrium with ²³⁸U, and radium daughters through ²¹⁴Po are in secular equilibrium with ²²⁶Ra; assumes negligible loss of ²²²Rn gas during storage.

^dOne curie of U_{nat} is defined as the sum of 1 Ci of ²³⁸U, 1 Ci of ²³⁵U, and 2.43 x 10⁻² Ci of ²³³U; 1 Ci of U_{nat} is also equivalent to 3000 kg of U_{nat}.

^eMetastable ^{234m}Pa, t_{1/2} = 1.18 min.

^fEstimated by assuming the presence of 3 ppm of uranium in the earth's crust and secular equilibrium.

Table A-6. Maximum annual doses^a to individuals^{b,c} from airborne effluents from a model F-F UF₆ plant --
 "low-impurity" feed^d -- assuming that 100% of the food is produced locally

Airborne radwaste treatment case	Individual total body dose (mrem)	Adult organ doses (mrem)									
		GI tract	Bone	Thyroid	Lung	Muscle	Kidney	Liver	Spleen	Testes	Ovaries
<u>Midwestern site</u>											
1	4.9E00	4.7E00	4.7E+1	5.2E00	2.5E+1	4.5E00	1.1E+1	4.3E00	3.9E00	4.8E00	3.5E00
2	1.8E00	1.8E00	1.8E+1	2.0E00	9.6E00	1.7E00	4.3E00	1.6E00	1.5E00	1.8E00	1.3E00
3	5.7E-1	5.4E-1	5.6E00	6.1E-1	3.0E00	5.3E-1	1.3E00	5.1E-1	4.6E-1	5.7E-1	4.1E-1
4	3.2E-3	2.8E-3	2.3E-2	3.3E-3	7.8E-2	3.0E-3	2.4E-2	7.0E-3	1.2E-2	3.3E-3	2.3E-3
<u>New Mexico site</u>											
1	6.8E00	6.4E00	6.6E+1	7.3E00	3.6E+1	6.3E00	1.6E+1	6.0E00	5.4E00	6.7E00	4.8E00
2	2.6E00	2.4E00	2.5E+1	2.7E00	1.4E+1	2.4E00	6.0E00	2.3E00	2.1E00	2.5E00	1.8E00
3	7.9E-1	7.5E-1	7.8E00	8.5E-1	4.3E00	7.4E-1	1.9E00	7.1E-1	6.5E-1	7.9E-1	5.6E-1
4	4.4E-3	4.0E-3	3.3E-2	4.6E-3	1.1E-1	4.2E-3	3.4E-2	1.0E-2	1.7E-2	4.7E-3	3.3E-3

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

^bMaximum dose to individual at 0.5 mile (800 m) and downwind of the prevailing wind direction. Release height: 5 m. Average dose is 47% of the maximum.

^cAll food is produced and consumed at the location of the dose calculation. Daily intakes are 1.0 liter of milk, 0.25 kg of vegetables, and 0.3 kg of beef.

^d10,000-metric ton/yr fluorination-fractionation plant; plant feed contains 2800 pCi of ²³⁰Th and 200 pCi of ²²⁶Ra per gram of U_{nat}.

Table A-7. Maximum annual doses^a to individuals^b from airborne effluents from a model F-F UF₆ plant --
 "low-impurity" feed^c -- assuming that none (0%) of the food is produced locally

Airborne radwaste treatment case	Individual total body dose (mrem)	Adult organ doses (mrem)									
		GI tract	Bone	Thyroid	Lung	Muscle	Kidney	Liver	Spleen	Testes	Ovaries
<u>Midwestern site</u>											
1	3.3E00	1.3E00	2.4E+1	3.7E00	2.4E+1	3.0E00	6.1E00	2.7E00	2.3E00	3.3E00	1.9E00
2	1.3E00	4.8E-1	9.0E00	1.4E00	9.0E00	1.1E00	2.3E00	1.0E00	8.9E-1	1.2E00	7.2E-1
3	3.9E-1	1.5E-1	2.8E00	4.3E-1	2.8E00	3.5E-1	7.3E-1	3.2E-1	2.8E-1	3.8E-1	2.2E-1
4	2.7E-3	1.8E-3	1.6E-2	2.8E-3	7.8E-2	2.5E-3	2.2E-3	6.5E-3	1.1E-2	2.8E-3	1.8E-3
<u>New Mexico site</u>											
1	4.6E00	1.8E00	3.4E+1	5.1E00	3.4E+1	4.2E00	8.6E00	3.8E00	3.3E00	4.6E00	2.7E00
2	1.7E00	6.7E-1	1.3E+1	1.9E00	1.3E+1	1.6E00	3.3E00	1.5E00	1.2E00	1.7E00	1.0E00
3	5.4E-1	2.1E-1	4.0E00	6.0E-1	4.0E00	4.9E-1	1.0E00	4.5E-1	3.9E-1	5.4E-1	3.1E-1
4	3.8E-3	2.5E-3	2.3E-2	4.0E-3	1.1E-1	3.5E-3	3.2E-2	9.3E-3	1.6E-2	4.0E-3	2.6E-3

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

^bMaximum dose to individual at 0.5 mile (800 m) and downwind of the prevailing wind direction. Release height: 5 m.

^c10,000-metric ton/yr fluorination-fractionation plant; plant feed contains 2800 pCi of ²³⁰Th and 200 pCi of ²²⁶Ra per gram of U_{nat}.

Table A-8. Annual doses^a to the population^b from airborne effluents from a model F-F UF₆ plant--"low-impurity" feed^c

Airborne radwaste treatment case	Population total-body dose (person-rem)	Population organ dose (person-organ-rem)									
		GI tract	Bone	Thyroid	Lung	Muscle	Kidney	Liver	Spleen	Testes	Ovaries
<u>Midwestern site</u>											
1	5.0E00	5.0E00	4.2E+1	5.4E00	2.0E+1	4.6E00	1.0E+1	4.2E00	3.8E00	4.9E00	3.3E00
2	1.9E00	1.9E00	1.6E+1	2.0E00	7.6E00	1.7E00	4.0E00	1.6E00	1.5E00	1.9E00	1.3E00
3	5.9E-1	6.0E-1	5.0E00	6.4E-1	2.5E00	5.4E-1	1.3E00	5.1E-1	4.7E-1	5.9E-1	4.0E-1
4	1.3E-2	1.0E-2	6.7E-2	1.4E-2	2.8E-1	1.2E-2	1.1E-1	2.1E-2	2.1E-2	1.5E-2	8.4E-3
<u>New Mexico site</u>											
1	1.1E-1	1.1E-1	1.0E00	1.2E-1	5.7E-1	1.0E-1	2.5E-1	9.6E-2	8.6E-2	1.1E-1	7.6E-2
2	4.2E-2	4.0E-2	3.9E-1	4.5E-2	2.2E-1	3.9E-2	9.7E-2	3.7E-2	3.3E-2	4.1E-2	2.9E-2
3	1.3E-2	1.3E-2	1.2E-1	1.4E-2	7.4E-2	1.2E-2	3.2E-2	1.2E-2	1.1E-2	1.3E-2	9.0E-3
4	3.3E-4	2.6E-4	1.0E-3	3.4E-4	8.8E-3	3.1E-4	3.3E-3	5.9E-4	5.8E-4	3.7E-4	2.2E-4

^a50-yr dose commitment from exposure to effluents from one year's operation of the model plant. Release height: 5 m.

^bEntire population within 55 miles of the model plant; daily food intakes are 300 ml of milk, 0.25 kg of vegetables, and 0.3 kg of meat. All food is produced and consumed at the reference location.

^c10,000-metric ton/yr fluorination-fractionation plant; plant feed contains 2800 pCi of ²³⁰Th and 200 pCi of ²²⁶Ra per gram of U_{nat}.

Table A-9. Exposure modes contributing to total-body dose from airborne effluents of a model F-F UF₆ plant--"low-impurity" feed^a

Terrestrial exposure mode	Maximum annual individual total-body dose ^b (mrem)	Percent of total-body dose
Submersion in air ^c	2.2E-4	<0.1
Contaminated ground ^c	2.5E00	51.5
Inhalation ^d	8.2E-1	16.7
Ingestion ^e	1.6E00	31.8

^a10,000-metric ton/yr fluorination-fractionation plant; plant feed contains 2800 pCi of ²³⁰Th and 200 pCi of ²²⁶Ra per gram of U_{nat}.

^bCase 1 at 0.5 mile (800 m) downwind from the plant; midwestern site.

^cExposure for 100% of the time; no shielding.

^dInhalation rate of 20 m³ of air per day.

^eAll food is produced and consumed at the location of the dose calculation. Daily intakes are 1.0 liter of milk, 0.25 kg of vegetables, and 0.3 kg of beef.

Table A-10. Major radionuclides contributing to doses from airborne effluents from a model F-F UF₆ plant--"low-impurity" feed^a

Radionuclide	Percent of total-body or organ dose ^b					
	Total body	GI tract	Bone	Thyroid	Lung	Kidney
²²⁶ Ra	6.2	0.09	6.2	5.8	1.3	2.7
²³⁰ Th	6.5	0.20	24.4	6.0	5.5	22.2
²³⁴ Th	0.05	14.5	0.09	0.05	0.15	0.35
²³⁴ U	23.2	19.4	31.7	19.6	45.1	31.9
²³⁵ U	11.8	6.9	2.5	13.7	2.9	4.2
²³⁸ U	52.2	58.9	35.1	54.8	44.9	38.4
²²² Rn (as gaseous release) ^c	0.03	0.03	0.02	0.03	0.28	0.19

^aFluorination-fractionation plant; plant feed contains 2800 pCi of ²³⁰Th and 200 pCi of ²²⁶Ra per gram of Unat.

^bMaximum 50-yr dose commitment to individual at 0.5 mile (800 m) from exposure to Case 1 effluents from one year's operation of the model plant at the midwestern site.

^cIncludes daughters ²¹⁸Po and ²¹⁴Pb from assuming 7-min decay of ²²²Rn gas after it leaves the plant.

Table A-11. Major radionuclides contributing to exposure modes for airborne effluents from a model F-F UF₆ plant--"low-impurity" feed^{a, b}

Radionuclide	Percent of total-body exposure mode ^c				Percent of organ exposure mode					
	Submersion ^d in air	Contaminated ^d ground	Inhalation ^e	Ingestion ^f	Bone		Lung		Kidney	
					Inhalation ^e	Ingestion ^f	Inhalation ^e	Ingestion ^f	Inhalation ^e	Ingestion ^f
²²⁶ Ra	0.00	0.01	0.12	19.4	0.05	12.3	0.09	19.4	0.02	5.8
²³⁰ Th	0.00	0.12	37.7	0.45	57.9	1.10	6.3	0.45	55.3	1.3
²³⁴ Th	0.62	0.06	0.14	0.00	0.20	0.00	0.17	0.00	0.86	0.00
²³⁴ U	0.03	8.6	32.6	42.2	21.5	44.7	49.0	42.2	22.8	48.9
²³⁵ U	0.38	22.0	0.72	0.96	0.50	1.0	1.1	0.96	0.52	1.1
²³⁸ U	1.1	69.2	28.6	37.0	19.7	40.9	43.0	37.0	20.0	42.9
²²² Rn (as gaseous release) ^g	97.9	0.02	0.10	0.00	0.04	0.00	0.25	0.00	0.46	0.00

^aFluorination-fractionation plant; plant feed contains 2800 pCi of ²³⁰Th and 200 pCi of ²²⁶Ra per gram of U_{nat}.

^bCase 1 at 0.5 mile (800 m) downwind from the plant, midwestern site.

^cContributions of exposure modes to total-body dose given in Table 7.6.

^dExposure for 100% of the time, no shielding.

^eInhalation rate of 20 m³ of air per day.

^fAll food is produced and consumed at the location of the dose calculation. Daily intakes are 1.0 liter of milk, 0.25 kg of vegetables, and 0.3 kg of beef.

^gIncludes daughters ²¹⁸Po and ²¹⁴Pb, assuming 7-min decay of ²²²Rn gas after it leaves the plant.

Table A-12. Total annual cost increase for reduction of the environmental impact of the model 10,000-metric ton/yr fluorination-fractionation UF₆ production plant--"low-impurity" feed^a

MIDWESTERN SITE

	Case 1	Case 2	Case 3	Case 4
Annual cost increase over base	Base	\$6.83E+5	\$1.14E+6	\$2.91E+6 ^b
Environmental impact				
Maximum annual individual dose at 0.5 mile from airborne effluents, mrem ^c				
Total body	4.9E00	1.8E00	5.7E-1	3.2E-3
Bone	4.7E+1	1.8E+1	5.6E00	2.3E-2
Lung	2.5E+1	9.6E00	3.0E00	7.8E-2
Kidney	1.1E+1	4.3E00	1.3E00	2.4E-2
Annual total population dose out to 55 miles from airborne effluents, person-rem ^c				
Total body	5.0E00	1.9E00	5.9E-1	1.3E-2
Bone	4.2E+1	1.6E+1	5.0E00	6.7E-2
Lung	2.0E+1	7.6E00	2.5E00	2.8E-1
Kidney	1.0E+1	4.0E00	1.3E00	1.1E-1
Annual individual dose from liquid effluents, mrem				
15-cfs stream				
Total body	5.6E00	5.4E00	9.9E-2	-
Bone	5.9E+1	5.5E+1	1.6E00	-
1300-cfs river				
Total body	7.1E-2	6.5E-2	1.1E-3	-
Bone	7.4E-1	6.6E-1	1.8E-2	-
Chemical releases, lb/day ^d				
Gaseous effluents				
HF	8.8E+1	1.2E00	1.2E00	1.2E-1
H ₂ S	5.7E-1	-	-	-
SO ₂	-	1.3E+3	1.3E+3	2.6E+1
NH ₃	4.0E+3	4.0E+3	1.3E+2	1.1E+2
Liquid effluents				
F ⁻	5.1E+3	2.1E+1	2.1E+1	3.0E00
S ²⁻ or S	7.2E+2	-	-	-
CO ₃ ²⁻	2.6E+3	1.5E+2	1.1E+2	-
SO ₄ ²⁻	1.9E+4	1.9E+4	2.3E+3	-
NH ₄ ⁺	6.1E+3	6.1E+3	7.0E+2	-
Na ⁺	3.6E+3	1.4E+3	2.3E+2	-
K ⁺	7.0E+3	1.7E+2	1.7E+2	-
Solid waste generated, lb/yr ^e				
Containing 10 ⁻¹ to 10 ⁻² μCi of ²³⁰ Th/g and only slightly soluble				
	2.2E+6	2.5E+6	2.5E+6	1.6E+7
Containing <10 ⁻³ μCi of ²³⁰ Th/g and only slightly soluble				
	8.9E+4	3.6E+6	3.6E+6	1.5E+6
Containing <10 ⁻⁴ μCi of ²³⁰ Th/g but soluble				
	-	-	-	9.6E+5

^aMid-1973 dollars.

^bDoes not include cost to the mill of changing the plant feed.

^cFive-meter release height; 100% local food; plant feed contains 2800 pCi of ²³⁰Th and 200 pCi of ²²⁶Ra per gram of U_{nat}.

^dProcess effluents only; does not include combustion products from heating the plant or operating vehicles, or sanitary and laundry wastes.

^eLong-term hazard defined by ²³⁰Th parent since ²²⁶Ra will gradually grow to secular equilibrium with ²³⁰Th.

Table A-13. Total annual cost increase for reduction of the environmental impact of the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant--"low-impurity" feed^a

NEW MEXICO SITE				
	Case 1	Case 2	Case 3	Case 4
Annual cost increase over base	Base	\$6.83E+5	\$1.14E+6 ^b	\$2.91E+6 ^b
Environmental impact				
Maximum annual individual dose at 0.5 mile from airborne effluents, mrem ^c				
Total body	6.8E00	2.6E00	7.9E-1	4.4E-3
Bone	6.6E+1	2.5E+1	7.8E00	3.3E-2
Lung	3.6E+1	1.4E+1	4.3E00	1.1E-1
Kidney	1.6E+1	6.0E00	1.9E00	3.4E-2
Annual total population dose out to 55 miles from airborne effluents, person-rem ^c				
Total body	1.1E-1	4.2E-2	1.3E-2	3.3E-4
Bone	1.0E00	3.9E-1	1.2E-1	1.9E-3
Lung	5.7E-1	2.2E-1	7.4E-2	8.8E-3
Kidney	2.5E-1	9.7E-2	3.2E-2	3.3E-3
Annual individual dose from liquid effluents, mrem				
15-cfs stream				
Total body	5.6E00	5.4E00	9.9E-2	-
Bone	5.9E+1	5.5E+1	1.6E00	-
1300-cfs river				
Total body	7.1E-2	6.5E-2	1.1E-3	-
Bone	7.4E-1	6.6E-1	1.8E-2	-
Chemical releases, lb/day ^d				
Gaseous effluents				
HF	8.8E+1	1.2E00	1.2E00	1.2E-1
H ₂ S	5.7E-1	-	-	-
SO ₂	-	1.3E+3	1.3E+3	2.6E+1
NH ₃	4.0E+3	4.0E+3	1.3E+2	1.1E+2
Liquid effluents				
F ⁻	5.1E+3	2.1E+1	2.1E+1	3.0E00
S ²⁻ or S	7.2E+2	-	-	-
CO ₃ ²⁻	2.6E+3	1.5E+2	1.1E+2	-
SO ₄ ²⁻	1.9E+4	1.9E+4	2.3E+3	-
NH ₄ ⁺	6.1E+3	6.1E+3	7.0E+2	-
Na ⁺	3.6E+3	1.4E+3	2.3E+2	-
K ⁺	7.0E+3	1.7E+2	1.7E+2	-
Solid waste generated, lb/yr ^e				
Containing 10 ⁻¹ to 10 ⁻² μCi of ²³⁰ Th/g and only slightly soluble				
	2.2E+6	2.5E+6	2.5E+6	1.6E+7
Containing <10 ⁻³ μCi of ²³⁰ Th/g and only slightly soluble				
	8.9E+4	3.6E+6	3.6E+6	1.5E+6
Containing <10 ⁻⁴ μCi of ²³⁰ Th/g but soluble				
	-	-	-	9.6E+5

^aMid-1973 dollars.

^bDoes not include cost to the mill of changing the plant feed.

^cFive-meter release height; 100% local food; plant feed contains 2800 pCi of ²³⁰Th and 200 pCi of ²²⁶Ra per gram of Unat.

^dProcess effluents only; does not include combustion products from heating the plant or operating vehicles, or sanitary and laundry wastes.

^eLong-term hazard defined by ²³⁰Th parent since ²²⁶Ra will gradually grow to secular equilibrium with ²³⁰Th.

Table A-14. Annual cost for reduction of dose from airborne effluents at the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant--"low-impurity" feed

Case	Total annual cost increase over base (\$1000) ^a	Maximum annual individual dose at 0.5 mile (mrem) ^b				Annual total population dose out to 55 miles (person-rem) ^b			
		Total body	Bone	Lung	Kidney	Total body	Bone	Lung	Kidney
<u>Midwestern site</u>									
1	Base	4.9E00	4.7E+1	2.5E+1	1.1E+1	5.0E00	4.2E+1	2.0E+1	1.0E+1
2	290	1.8E00	1.8E+1	9.6E00	4.3E00	1.9E00	1.6E+1	7.6E00	4.0E00
3	714	5.7E-1	5.6E00	3.0E00	1.3E00	5.9E-1	5.0E00	2.5E00	1.3E00
4	1933	3.2E-3	2.3E-2	7.8E-2	2.4E-2	1.3E-2	6.7E-2	2.8E-1	1.1E-1
<u>New Mexico site</u>									
1	Base	6.8E00	6.6E+1	3.6E+1	1.6E+1	1.1E-1	1.0E00	5.7E-1	2.5E-1
2	290	2.6E00	2.5E+1	1.4E+1	6.0E00	4.2E-2	3.9E-1	2.2E-1	9.7E-2
3	714	7.9E-1	7.8E00	4.3E00	1.9E00	1.3E-2	1.2E-1	7.4E-2	3.2E-2
4	1933	4.4E-3	3.3E-2	1.1E-1	3.4E-2	3.3E-4	1.9E-3	8.8E-3	3.3E-3

^aMid-1973 dollars.

^bFive-meter release height; 100% local food; plant feed contains 2800 pCi of ²³⁰Th and 200 pCi of ²²⁶Ra per gram of Unat.

Table A-15. Incremental cost increase - dose reduction between case studies for airborne effluents from the model 10,000-metric ton/yr fluorination-fractionation UF₆ plant-- "low-impurity" feed^a

Case increment	Increase in annual cost (\$1000)	Decrease in maximum annual individual dose at 0.5 mile (mrem)		Decrease in annual dose to population out to 55 miles (person-rem)		Cost/benefit				
		Total body	Bone	Total body	Bone	Individual at 0.5 mile (\$1000/mrem)		Total population within 55 miles (\$1000/person-rem)		
		Total body	Bone	Total body	Bone	Total body	Bone	Total body	Bone	
<u>Midwestern site</u>										
1/2	290	3.1E00	2.9E+1	3.1E00	2.6E+1	9.4E+1	1.0E+1	9.4E+1	1.1E+1	
2/3	424	1.2E00	1.2E+1	1.3E00	1.1E+1	3.5E+2	3.5E+1	3.3E+2	3.9E+1	
3/4	1219	5.7E-1	5.6E00	5.8E-1	4.9E00	2.2E+3	2.2E+2	2.1E+3	2.5E+2	
<u>New Mexico site</u>										
1/2	290	4.2E00	4.1E+1	6.8E-2	6.1E-1	6.9E+1	7.0E00	4.3E+3	4.8E+2	
2/3	424	1.8E00	1.7E+1	2.9E-2	2.7E-1	2.4E+2	2.5E+1	1.5E+4	1.6E+3	
3/4	1219	7.9E-1	7.8E00	1.3E-2	1.2E-1	1.5E+3	1.6E+2	9.4E+4	1.0E+4	

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^a1973 dollars, 5-m release height; 100% local food; plant feed contains 2800 pCi of ²³⁰Th and 200 pCi of ²²⁶Ra per gram of U_{nat}.

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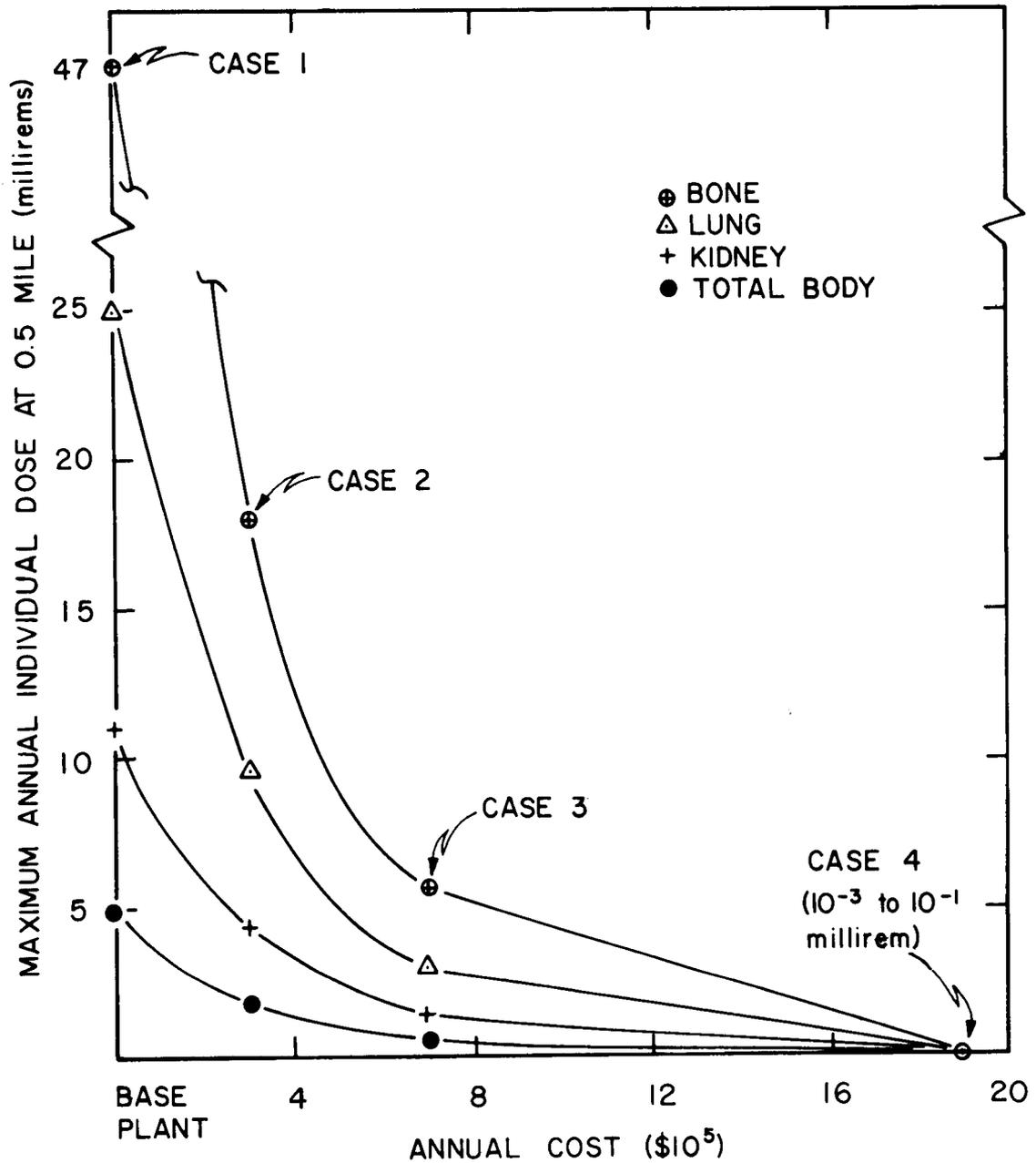


Fig. A-1. Annual cost for reduction of maximum annual dose from airborne effluents at 0.5-mile distance from the model fluorination-fractionation UF₆ production plant. (Doses are for the feed containing "low" levels of ²³⁰Th and ²²⁶Ra impurities at the midwestern location.)

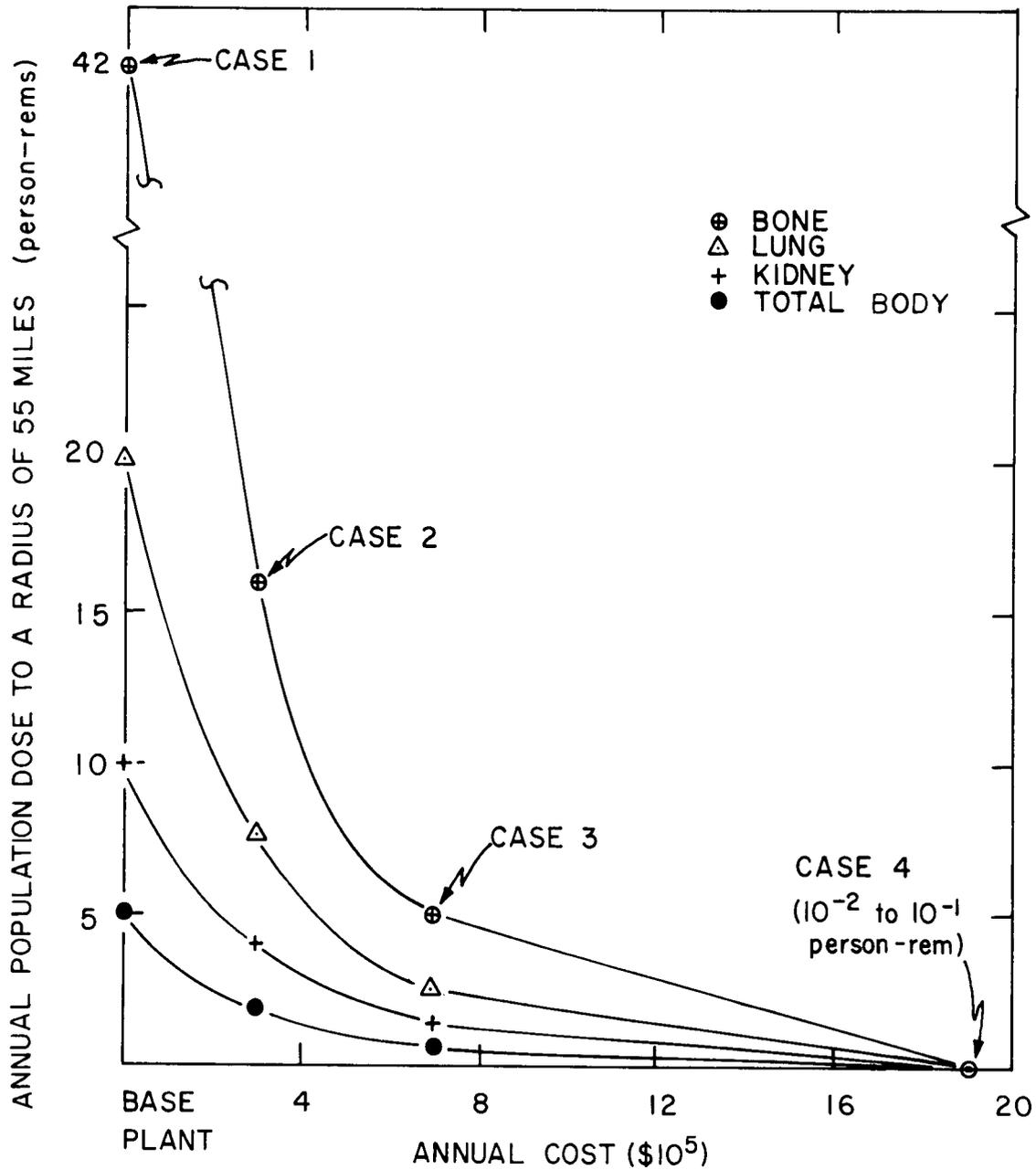


Fig. A-2. Annual cost for reduction of annual population dose out to a radius of 55 miles from airborne effluents from the model fluorination-fractionation UF_6 production plant. (Doses are for the feed containing "low" levels of ^{230}Th and ^{226}Ra impurities at the midwestern location.)

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