ORNL-TM-4903, Vol. 1
UC-11 - Environmental and
Earth Sciences

Contract No. W-7405-eng-26

CHEMICAL TECHNOLOGY DIVISION

CORRELATION OF RADIOACTIVE WASTE TREATMENT COSTS AND THE ENVIRONMENTAL IMPACT OF WASTE EFFLUENTS IN THE NUCLEAR FUEL CYCLE FOR USE IN ESTABLISHING "AS LOW AS PRACTICABLE" GUIDES — MILLING OF URANIUM ORES

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MAY 1975

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

The reports in this series are:

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

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

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

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

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

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

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ABSTRACT

A cost-benefit study was made to determine the cost and effectiveness of radioactive waste (radwaste) treatment systems for decreasing the release of radioactive materials from model uranium ore processing mills, and to determine the radiological impact (dose commitment) of the released materials on the environment. The study is designed to assist in defining the term "as low as practicable" in relation to limiting the release of radioactive materials from nuclear facilities. The base case model mills are representative of mills which will process a major fraction of the ore in the next 20 years. Each mill processes 2,000 short tons of ore per day. Additional radwaste treatment techniques are applied to the base case mill and the waste tailings area in a series of case studies to decrease the amounts of radioactive materials released and to reduce the radiological dose commitment to the population in the surrounding area. The cost for the added waste treatment operations and the corresponding dose commitment are calculated for each case. In the final analysis, radiological dose is plotted vs the annual cost for treatment of the radwastes. The status of the radwaste treatment methods used in the case studies is discussed. Much of the technology used in the advanced cases will require development and demonstration and is not suitable for immediate use. The methodology used in estimating the costs, detailed calculations, and tabulations are presented in ORNL-TM-4903, Volume 2. The methodology and assumptions for the radiological doses are found in ORNL-4992.

CORRELATION OF RADIOACTIVE WASTE TREATMENT COSTS AND THE ENVIRONMENTAL IMPACT OF WASTE EFFLUENTS IN THE NUCLEAR FUEL CYCLE FOR USE IN ESTABLISHING "AS LOW AS PRACTICABLE" GUIDES – MILLING OF URANIUM ORES

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1.0 SUMMARY AND CONCLUSIONS

A study was made to determine the dollar cost and effectiveness of radioactive waste (radwaste) treatment systems for decreasing the amount of radioactive and nonradioactive materials released from model uranium ore processing mills and to determine the radiological impact (dose commitment) of the released radioactive materials on the environment. Uranium mills recover uranium from natural ores as a concentrated, solid product called "yellow cake", which is then shipped to a conversion plant for further purification as a step in preparing the uranium for use in nuclear fuels. Two model mills, which are typical of currently operating mills and are representative of mills which will process a major fraction of the ore in the next 20 years, are used as base cases in this study. One mill uses the acid leach--solvent extraction process and the second the alkaline-leach process. Each mill processes 2,000 short tons of ore per day which contains 0.2% U_3O_8. The uranium in the ore is in secular equilibrium with its radioactive daughters. A total of 14.4 curies of radioactivity enters the mill each day of which 2.0 Ci is uranium and is recovered as product. The remaining 12.3 Ci is discharged in the liquid and solid wastes called tailings, which are impounded on-site near the mill. Most of the radionuclides remain insoluble during leaching and leave the mill with the solid tailings. The radionuclides of interest are ^{238}U, ^{234}U, ^{226}Ra, ^{230}Th, ^{234}Th, ^{210}Pb, ^{210}Bi, ^{210}Po, and ^{222}Rn.

Off-site releases of radioactive materials consist of airborne ore dust, yellow cake dust, tailings dust, and radon gas while the mill is active. After the mill has ceased operations, the tailings are stabilized by covering with earth topped by rock or vegetation to minimize wind and water erosion. However, radon gas will continue to be released from the stabilized tailings pile for thousands of years. No liquid or solid wastes are released directly to surface streams. Liquid waste disposal is by natural evaporation and seepage to the ground beneath the tailings impoundment area. The tailings area is sited where natural waters are not likely to contact the tailings, and no underground migration of the seepage beyond the plant boundary is expected. This corresponds to the current state of knowledge where there is no evidence of underground movement of radioactive materials beyond the plant boundary from tailings areas sited in the semiarid western states by current standards (Sect. 9.5.2). Little movement is predicted in a sample calculation (Sect. 7.6). However, the potential for the underground migration of radioactive materials in seepage of liquid effluents under some geological conditions, or as the result of leaching if water should contact the tailings is recognized. These potential releases might occur (1) at sites with high rainfall; (2) in wet storage areas, such as spent mines; and (3) in the event of some future geologic or meteorological change, which could form a fissure under the tailings area, or cause the water table to rise into the tailings, although these considerations are not variables in this study.

The waste treatment systems consist of methods which (1) reduce the amounts of airborne radioactive dusts and radon released from the mill and tailings area, (2) reduce the amount of radioactive liquid lost as seepage through the bottom of the tailings area, and (3) provide tighter long-term containment of the stored tailings. Unlike other segments of the nuclear fuel cycle, where solid wastes are shipped off-site to an approved repository or burial ground, the milling industry must address the problem of long-term, safe, on-site disposal of solid wastes. Treatments to reduce the amount of airborne radioactive materials released are correlated with the maximum annual individual dose commitments (mrem) to total body, bone, lung, liver, kidney, and spleen at 0.5 mile from the model mill, and with the annual average population total body dose (man-rem) out to a distance of 55 miles. Doses are not estimated for the release of radioactive seepage or the potential release of leach waters because of the lack of the detailed information required to calculate the underground movement of liquids and dissolved solids and because of the diversity of the sites to be considered. Treatments to reduce seepage and leaching are correlated with the amount of radioactive materials which might potentially be released in seepage or leach waters (Sects. 8.6 and 8.7). These treatments provide additional safety in the storage of the wastes and are effective in reducing potential doses if geologic or meteorologic changes should occur in the future.

A series of increasingly efficient (and expensive) radwaste treatment cases and their corresponding flowsheets are presented for treating the effluents from the model mills (Sect. 4). The general plan and objectives of the studies are summarized in Table 1.1. Many of the assumptions and treatment cases are based on the background survey of present industrial practices and laboratory research in radwaste management (Sect. 9.0). Seven conceptual cases are considered for treating airborne radwaste from the mill buildings. Similarly, five conceptual cases are considered for liquid effluents from the acid-leach mill, four for liquids from the alkaline mill, ten solid radwaste cases for the acid-leach mill, and nine solid radwaste cases for the alkaline mill. Treatment of the various effluent streams is assessed separately in Sects. 4 and 8 before they are combined in the summary cases of Sect. 1.1. Cost-benefit correlations of the combined treatment methods in Sect. 1.1 reveal only gross comparisons and mask many of the components of the cases, where comparisons can be made regarding the relative cost-benefit of alternative procedures. Comparisons of the components are presented in Sects. 8.2-8.8. Case 1 represents current, waste treatment methods and provides the base for the incremental analysis. Some Case 2 and Case 3 methods are also used currently, but on a limited basis. The different treatment segments can usually be combined in other ways — for example, Case 4 mill dust treatment might be used with Case 3 treatment of liquids and solids. Much of the technology used in the advanced cases has been used in other industrial applications but has not been applied at uranium mills; consequently, some additional development work may be required. All costs are estimated on the basis of the construction of a new mill (Sect. 6). Backfitting must be considered on an individual basis, although the advanced technology is generally suited to existing plants.

Each type of model mill is assessed at sites in Wyoming and in New Mexico which have environments that are characteristic of the majority of contemporary milling operations. About 80% of the tonnage of ore is processed in these two areas. The population distribution in these areas and the meteorologic data are derived from nearby first-order weather stations. Both areas are characterized by their low population densities, persistent winds, and arid climate.

The annual amounts of radioactive materials released (the source terms, Sect. 4), the capital, annual, and contributions to power costs (Sect. 6), and the radiological impact (the doses, Sect. 7) are calculated for each case for the model solvent extraction and the model alkaline-leach uranium mills sited in New Mexico and in Wyoming for three time periods: (1) the period while the mill is operating, (2) the interim period following mill closure while the tailings dry and before they are stabilized, and (3) the period after final stabilization of the tailings — a total of 38 case studies each examined over the three time periods. In many cases both the source terms and the costs vary with the site. This is in addition to the differences in the doses caused by differences in the meteorological dispersion at the two sites. The wind velocity and the amount of rainfall are two important site variables. The average wind velocity at the New Mexico site is 7 mph compared with 10 mph at the Wyoming site. Since the amount of tailings dust resuspended by the wind increases with the cube of the wind velocity, the small difference in wind velocity makes a difference of a factor of 13 between the two sites in the amount of windblown tailings dust released per acre of exposed, dry tailings (Sect. 7.2). The higher wind velocity also causes more dilution of the mill dusts and radon which are released, i.e., lower doses for equivalent sources in Wyoming than in New Mexico (Sect. 7.1). The net annual evaporation rate which is 7.25 ft in New Mexico and 4 ft in Wyoming determines the area of the pond required to evaporate the waste water (Sect. 4.4.2.1). This affects the size of the tailings dam, the area of the tailings impoundment basin, the area of wet and dry tailings while the mill is operating, and the area of tailings after the mill closes. All these variables affect the cost of waste treatment, except for Case 6 which has a metal evaporator and recycles all liquids. In addition, both the radon source terms (Sect. 4.4.3.2) and the amount of windblown tailings dust (Sect. 4.4.3.1) are proportional to the area of dry tailings, and are thus related to the net evaporation rate at the site. In addition, there are a number of complicated and interrelated parameters involved in the calculations which are discussed in detail in Sects. 4, 6, and 7.

Unless stated otherwise, conservative assumptions (i.e., those that maximize dose or cost) are made in estimating source terms, in selecting efficiency ratings for equipment, in estimating costs, in defining the movement of radionuclides in the environment, and in selecting food and liquid consumption patterns. Maximizing assumptions were used to be consistent with similar assessments of other segments of the nuclear fuel cycle. Results are valid only for the conditions specified, and do not represent an average, or any specific, mill. Maximizing assumptions which have a significant impact on the dose include: (1) the hypothetical individual lives and produces all of his food, including the feed for his animals, 0.5 mile downwind from the mill in the prevailing wind direction; (2) the mill processes a 6% moisture ore which produces a relatively large amount of dust; and (3) source terms for the tailings area are based on the worst year, i.e., the twentieth year, when tailings cover the maximum area and the release of radioactive materials is at a maximum. The milling industry is highly diversified, and each mill must be assessed on an individual basis. Conclusions drawn from the model mill studies based on maximum releases and maximum doses cannot be applied directly to a specific mill without considering the specific factors applicable to that site. It is beyond the scope of this report to discuss these variables in detail; however, information has been presented in both Sect. 4 and Sect. 7 for estimating cases other than the model mills. As an example, in the case which shows the highest dose commitments (the alkaline-leach mill sited in Wyoming), the maximum annual dose commitment to the bone is 1057 mrem. If, instead of the maximizing assumptions, it is assumed that: (1) the mill is processing a wet ore using no dust collector, (2) the source terms from the tailings area are the average releases over the 20-yr life of the mill, and (3) the hypothetical man's diet consists of 50% meat produced 0.5 mile from the mill in the prevailing wind direction, but all his other food is imported from outside the area, then the average annual bone dose is 100 mrem to the hypothetical man living 0.5 mile downwind. If the area in the prevailing wind direction from the mill for a distance of about 2 miles is not used for food production or residences, then the maximum annual bone dose to persons living 0.5 mile from the mill in directions other than the prevailing wind is only about 40 mrem. These assumptions are valid for many mills and significantly lower than the estimated dose.

1.1 Airborne and Liquid Effluents from Mill and Tailings Area During Mill Operation and After Mill Closure

The total annual costs for reduction of the radiological dose to the population surrounding the model mills during mill operation and after mill closure are summarized for Cases 1 to 7 in Table 8.1 and Fig. 8.1 for the model acid leach--solvent extraction mill at New Mexico and in Fig. 8.2 for the alkaline-leach mill at New Mexico. Similar summaries for the Wyoming site are presented in Table 8.2 and Figs. 8.3 and 8.4. The total annual costs include all costs for treatment of airborne and liquid effluents from the mill and tailings area during mill operation and after mill closure and include the amounts required to reduce the release of radioactive materials in seepage or potentially in leach waters, even though the liquid releases do not contribute to the calculated dose. These annual costs vary from about $175,000 in Case 1 to nearly $10,000,000 in Case 6c.

The maximum annual individual doses are shown in Tables 8.1 and 8.2 for whole body and organs at a distance of 0.5 mile from the operating model mills and their associated tailings impoundments near the end of the 20-year life of the mills when the tailings cover the maximum area. The doses for whole body and bone drop from Case 1 to Case 2. For example, near an operating New Mexico solvent extraction mill, the doses to an individual assuming that 100% of the food is produced locally drop from about 37 mrem for total body and 400 mrem for bone in Case 1 to about 6 and 73 mrem, respectively, in Case 2 at a total annual cost increment of $27,000. About 45% of this dose reduction is the result of covering the tailings beach to prevent wind resuspension of tailings at an annual cost of $7,000 (Sect. 8.3). At the Wyoming solvent extraction mill the 100% food ingestion dose drops from 61 mrem for total body and 640 mrem for bone in Case 1, to 5 and 59 mrem, respectively, in Case 2 at a total annual cost increment of $26,000. At the Wyoming alkaline-leach mill the 100% food ingestion dose drops from 102 mrem for total body and 1057 mrem for bone in Case 1, to 6 and 66 mrem, respectively, in Case 2 at a total annual cost increment of $25,000. If no food is produced near the mill, the doses drop from about 2 mrem in Case 1 to 0.4 mrem in Case 2 for total body and from about 60 to 10 mrem for bone. Case 1 is the only case in which tailings dust becomes airborne from an exposed beach during operation of the mill. In subsequent cases, the tailings beach is coated with a chemical spray to prevent resuspension of the tailings by the wind. Consequently, in Cases 2 to 7, radon is the only radioactive material that is released from the tailings area. The decrease in the total body and bone dose in Cases 2 to 7 is the result of the improved dust removal systems applied to the gaseous effluent from the mill. The mill dusts contain ^{226}Ra which is a major contributor to total body and bone dose.

After the mill is closed, the tailings pile is stabilized to prevent the movement of airborne tailings particles and to decrease the emanation rate of radon. Thus, radon is the only radioactive material released from the tailings pile after mill closure (with the exception of the interim period, Sect. 8.4). The radon lung dose from the stabilized tailings area after the mill is closed is higher in Cases 1 and 2 than the radon lung dose from the combined mill and tailings area during operation of the mill because the radon is attenuated by the pond water which covers a fraction of the tailings during operation of the mill. In later cases, the stabilization treatment lowers the radon dose. Overall, the radon dose from the stabilized tailings pile in New Mexico decreases from 100 mrem in Case 1 to 2×10^{-3} mrem in Case 7 and the total annual costs increase from $175,000 for Case 1 to nearly $10,000,000 for Case 6. In addition to the lung dose from the radon, which is continuously released from the tailings after the mill closes, there is also a long-term dose from the long-lived radioactive materials which were dispersed while the mill was operating. The long-term total body dose to an average individual living within 50 miles is 1.4×10^{-3} mrem/yr and the bone dose is 7.6×10^{-3} mrem/yr at the model mill that released the greatest amount of radioactive materials (Sect. 7.5.1). Since these doses are small compared to the background dose, no cost correlations are made for the long-term period for the dose received from the particulates dispersed by the operating mill and the active tailings area.

In Sections 8.2 to 8.7, the total costs are separated into costs for reduction in release of airborne radioactive materials and costs for treatment of liquid wastes to reduce the amount of radioactive materials released in seepage or potentially in leach waters, and these costs are compared with the maximum dose to the individual or the amounts of materials released in seepage water. While the mill is operating, the total whole body dose to the population out to a distance of 55 miles is 1 to 3 man-rem in Case 1 and less than 0.2 man-rem in Cases 2 to 7 (Tables 8.1 and 8.2). After the mill is closed and tailings have been stabilized, the total annual whole body dose to the population out to 55 miles is less than 0.01 man-rem in Case 1. Therefore, no cost correlations are made with the population dose.

1.2 Contribution of the Cost of Radwaste Treatment to Yellow Cake and Total Nuclear Power Costs

The capital cost of the model uranium mill is estimated at $13,000,000. The capital costs of radwaste treatment added to the model mill range from $357,000 for Case 1 to $10,591,000 for Case 7 (Tables 6.1 and 6.2). In the special case where the conventional sulfuric acid leach is replaced with a nitric acid leach, the net increase in capital cost is $29,959,000. For current practice (Case 1), the maximum annual cost of radwaste treatment is $180,000, which is equivalent to $0.07/lb of U_3O_8 and 0.003 mills/kWhr. The annual costs increase from this base case to a maximum of $9,900,000 for Case 6b for the alkaline-leach mill, which is equivalent to $3.65/lb

U_3O_8 and 0.173 mills/kWhr. This highest cost is less than 3% of an estimated total power generation cost of 7 to 10 mills/kWhr.

The maximum radwaste treatment cost which does not involve the use of expensive HEPA filters, charcoal delay trap, and incorporation of tailings in cement or asphalt is $1,778,000. This is equivalent to $0.66/lb U_3O_8 and 0.032 mills/kWhr. It contributes less than 0.4% to the total cost of nuclear power. This cost will cover high efficiency, reverse jet, bag filters and high energy venturi scrubbers on the airborne effluents from the mill (Case 4), neutralization or copperas treatment of liquids, an asphalt-lined tailings basin with a clay core dam, and a 1-in. asphalt membrane topped by 2 ft of earth stabilized with 6 in. of crushed rock (Case 7). This combination of Case 4 treatment for airborne mill dusts and Case 7 treatment of liquid and solid wastes reduces the maximum individual total body dose and most organ doses to less than 1 mrem/yr (100% food ingestion), the maximum bone dose to less than 7 mrem/yr, and the long-term radon lung dose to less than 0.002 mrem/yr. It reduces loss by seepage to 0.1% and provides some protection against future leaching of radioactive materials from the tailings by complete encasement in an asphalt membrane. The radon dose from the active mill and active tailings area can be reduced only by the use of expensive additional treatments.

1.3 Conclusions

The incremental analysis of the impact of additional radwaste treatment at uranium ore mills indicates that the greatest dose reduction and the most effective cost-benefit ($/mrem reduction in dose) are obtained as follows:

1. Minimize the airborne movement of tailings particles from the tailings area by covering the exposed beaches during operation of the mill and during the interim drying period after the mill is closed. The tailings are permanently covered (stabilized) in all case studies after the interim drying period.
2. Use more efficient dust collectors on ore dust streams at mills processing dusty (6% moisture) ores.

3. Use more efficient dust collectors on yellow cake streams at alkaline-leach mills.
4. Minimize the long-term release of radon from the stored tailings by placing thicker earth covers over the tailings.

The use of more efficient dust collectors, as in Case 2, on ore dust streams at mills processing wetter (8-10% moisture) ores or on yellow cake dust streams at acid-leach mills is of secondary priority relative to the treatment of the tailings area. In Cases 3 through 7, the use of increasingly efficient dust collectors (except where dusty ores are processed), the radon retention unit on the airborne mill effluents, and the 1-in. asphalt membrane over the tailings area for radon retention in Case 7 are of marginal relative value. The incorporation of tailings wastes in cement or asphalt is relatively expensive and has marginal relative value, if the purpose is to reduce the release of radon. However, this treatment is effective in decreasing the amounts of radioactive materials lost in seepage or that potentially may be lost by leaching. The need for incorporation of tailings must be determined on an individual basis for each site where the geology, soil properties, and climate are known.

The assessment of the environmental impact of uranium milling is complicated and involves a large number of parameters including the internal mill leaching and uranium recovery process, the waste treatment methods, the nature of the ore, the natural evaporation rate at the site, the annual average wind velocity, the frequency and wind distribution pattern, the food production and consumption pattern in an arid region where there is ranching but otherwise little food is grown, and the geology of the site. The milling industry is highly diversified, and each mill must be assessed as an individual case. General conclusions drawn from the model studies based on maximum releases and maximum doses should not be applied to a specific site without considering the specific variables that apply at that site. It is beyond the scope of this report to discuss these variables in detail; however, information has been presented in both Sect. 4 and Sect. 7 for estimating cases other than the model mills.

The dose commitments presented in this survey are stated in terms of the dose commitment received in the 20th year of operation of the mill. This study does not address in detail the problem of the individual who lives near the mill throughout the entire 20 years operation of the mill plus the 2-year interim period. As discussed in Sect. 7, the total body and bone doses are primarily from ingested radium and thorium, which are not removed at an appreciable rate from the body by radioactive decay or excretion. The individual who lives all his life near the mill accumulates a permanent body burden from each year's exposure. Therefore, in assessing radwaste treatment it is important to consider not only the maximum effects from the year which produces the highest exposure, as has been done in this study, but also the cumulative effects from exposure to many years operation of the facility.

2.0 INTRODUCTION

This study was performed to determine the cost and the effectiveness of radioactive waste treatment systems that are used, or could be used, at uranium ore processing mills to decrease the amount of radioactive and nonradioactive materials released to the environment. A second objective is to determine the impact of the radioactive releases on the environment. The effectiveness of the alternative radioactive waste treatment systems that are considered is measured by comparing the amounts of radioactive materials released by the various systems and the impact of these releases on the environment. The amount of radioactive materials released in each case is called the "source term," since these values are the source or initial numbers used in evaluating the impact of radioactive releases on the environment. The impact on the environment is assessed and compared with the radioactive waste treatment costs as the basis for a cost-benefit analysis. The radioactive materials are uranium in secular equilibrium with its daughter products.

The function of uranium mills is to extract uranium in concentrated form from naturally occurring ore deposits for shipment to a uranium conversion facility and ultimate use as a nuclear fuel. The radioactive waste materials are impounded in an on-site tailings retention area. A small fraction of the radioactive materials is released as airborne particulates from the mill and by wind erosion of dry tailings. Radon gas will be released from both the mill and the tailings. Liquid effluents are impounded in the tailings area with varying degrees of containment. Unlike other phases of the nuclear fuel cycle where solid radwastes are packaged and shipped off-site to an approved repository, the uranium milling industry must solve the problem of safe, permanent, on-site solid waste disposal.

Two model mills which are representative of currently operating mills are used as base cases in this study. However, the model mills do not represent the design for any particular existing facility. The radiological impact of the mills is considered at two typical sites, i.e., in Wyoming and New Mexico. Since the tailings represent a perpetual source of radioactive effluents long after the mill is closed, both the short-term environmental impact of the operating mill and the long-term impact of the solid waste are estimated. Increasingly efficient radioactive waste treatment systems are added to the "base" plant, and the annual cost and environmental impact of each case are calculated as the basis for cost and benefit analysis. It was not feasible to include all possible variations of base plants and radioactive waste treatment systems, but sufficient information is provided in this study to permit the costs and impacts for other radioactive waste treatment systems to be estimated by extrapolation or interpolation from the data provided. The base case illustrates the important features of current plants. The advanced cases use technology which ranges from that currently in use at the newest mills to the foreseeable limits of available technology on the basis of expected typical operations over the next 20 years.

Some of the technology used in the advanced cases is in an early stage of development and is not suitable for immediate use in existing plants. However, it is necessary to use this technology in the study to predict cost-benefit relationships over the next few decades. In most cases, alternative technology to accomplish a given objective is nonexistent.

3.0 OBJECTIVES AND ASSUMPTIONS

3.1 Objectives

The objectives of this study are: (1) to determine the dollar cost to reduce the amount of radioactive materials released to the environment from mills which use current treatment systems, to very low levels using advanced, complex treatment systems; and (2) to determine the environmental impact of the radioactive effluents released from these conceptual installations. 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 with 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, the fraction released is essentially the same 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, the uranium content of the ore processed, and environmental parameters such as the net annual evaporation rate and the wind speed. The volumes and composition of radioactive wastes are based on typical flows at mills today.

Estimates are made of the average radioactive and nonradioactive releases and the cost of radioactive waste treatment operations over the 20-year lifetime of the ore processing mill. In a similar study for nuclear power reactors,[1] great emphasis was placed on maintaining continuous operation of the power plant. Consequently, the more complex radioactive waste treatment systems contained redundant (parallel) treatment units to ensure continued operation should one of the units become inoperable. In the milling 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 Plants

A model acid-leach mill and a model alkaline leach mill were selected which are typical of plants operating in 1973 and are representative of the plants that will process the major load of ore in the next two decades (Sects. 9.1 and 9.2). On a daily basis, the mills will process 2000 tons* of ore containing 0.2% U_3O_8. Steps basic to all mills are crushing, grinding, chemical leaching wherein the uranium is dissolved from the ground ore, and recovery of the uranium from the leach solutions. The acid leach mill will also have a solvent extraction step to purify the leach solutions. The waste treatment methods used in the Case 1 (base case) studies are representative of current waste handling methods. Since some mills use portions of the advanced technology, which is illustrated in Cases 2 and 3, the average releases for the industry are currently lower than those listed for the Case 1 study.

3.3 Management of Radioactive Wastes

The most complex flowsheets in this study illustrate very low, but not "zero", release of radionuclides.

Airborne Effluents. — Airborne effluents consist of radon gas and radioactive particulates from both the mill and the tailings area. Off-gases from the mill are treated such that increasingly large fractions of the dust are retained, and the tailings are covered to eliminate wind-blown dust. A radon diffusion barrier is placed over the tailings in advanced cases. The amount of radon released during the milling process itself is small compared with the quantities released from the tailings piles. Therefore, treatment for gaseous radon from the mill off-gas has been postponed to the most advanced case.

Liquid Effluents. — Liquid effluents are handled by impounding all

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*Short ton, 2000 lb/ton.

liquids in a pond with zero release to surface waters. Loss of radioisotopes by seepage to the environment is reduced in advanced cases by employing more tightly sealed impoundment systems and chemical treatment. In the most advanced cases, liquid streams are purified and recycled.

Solid Wastes. — Solid wastes are retained in an on-site tailings impoundment area. In the earlier cases, the solid wastes are stabilized by covering with earth or rock to prevent wind and water erosion, but perpetual maintenance and surveillance will be required. A radon diffusion barrier of earth is placed over the solid wastes, beginning with Case 3. In the advanced cases, the solid wastes are treated by burial and by fixation in asphalt or cement. This reduces the need for perpetual maintenance and returns the surface land to limited use.

3.4 Cost Parameters

Base cases are selected which are representative of mills operating in 1973 but do not represent the design for any particular existing facility. Capital and annual costs are estimated for different waste effluent treatment segments in a series of case studies. The Case 6c study involves the use of a completely different internal mill flowsheet, i.e., the use of a nitric acid leach step, in addition to the advanced waste treatment methods. Consequently, the costs for Case 6c are taken as the incremental costs above those required for a conventional sulfuric acid leach mill. The calculation of incremental annual costs for a variety of waste treatment methods is a primary objective of the study. They are correlated with the changes in environmental impact for each case study in Sect. 8.0. The estimated costs are based on a new plant using direct maintenance. No attempt is made to estimate backfitting costs for present plants. Complete details of the cost estimating procedure are listed in Sect. 6.0 and ORNL-TM-4903, Vol. 2.

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 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 mills are located at each of two sites in Wyoming and New Mexico which have environments that are characteristic of the majority of contemporary milling operations. About 80% of the ore tonnage is processed in these areas, and the remainder in Texas, Colorado, and Washington (Sect. 9.1). The Wyoming and New Mexico areas are characterized by their low population densities and semiarid conditions. The population distribution for the sites is determined by averaging the distributions around several mills in these locations. Similarly, the meteorological data for each site are derived from the first-order weather stations in these areas, i.e., Albuquerque, New Mexico, and Casper, Wyoming. Site No. 1 is located in an arid environment characteristic of central New Mexico. The region is represented by mesa topography, low rainfall, desert physiognomy, and sparse vegetation. Chronic winds prevail in the desert environment, and dust storms are common. Site No. 2 is located in the Wyoming basin on an intermountain plateau which borders on the Great Plains. The region is characterized by rolling foothill topography, semiarid climate, and a grassland-shrub physiognomy. Rainfall is sufficient for an effective ground cover of vegetation which,if not disturbed by overgrazing, shows minimal erosion by the wind. Persistent winds prevail in both locations, and dust storms occur where vegetation is scarce. Consequently, the movement of radioactive gas and dusts from the tailings piles and the impact of these materials on the environment are the major factors that are assessed in this study.

The difference in impact at the two sites is the result of meteorological differences which cause the movement of different amounts of radioactive materials and different distributions of these materials throughout the surrounding areas. Surface water is not considered to be an important pathway for movement of radioactive materials because of the general absence of surface water in these locations, and because tailings waters are not released to surface waters in the case studies. Underground aquifers provide drinking water for local populations at both sites. Estimates are made for the movement of radioactive materials which seep from the tailings pond. Site selection is described in detail in Sect. 7.0.

3.7 Radiological Impact

Radiation doses to the population surrounding the model mills are estimated using the procedures which have been standardized for environmental impact statements for light-water-cooled nuclear power stations by the USAEC-Regulatory.[1] Pathways for external radiation dose from sources outside the body and for internal dose from sources inside the body are considered. Immersion in the radon gas, airborne mill dusts, and tailings particles as they are diluted and dispersed leads to external exposure, while inhalation leads to 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. The pathways for movement of the radioactive materials are considered to be the same at the two sites because of the generally similar ecological conditions at these locations.

The difference in meteorological conditions at the two sites is the principal factor that controls the difference in radiological impact at these locations. The estimated radiation doses to individuals, to the human population, and to the biota are calculated for annual distances out to 55 miles in 22.5° sectors using the site parameters listed in Sect. 7.0. Doses to individuals are calculated for the total body and individual organs. Population doses (man-rem) are the sum of the total body doses to all individuals in the population considered. Details of dose models, assumptions, and methods are given in Sect. 7.0.

3.8 References

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

4.0 SOURCE TERMS FOR RELEASE OF RADIOACTIVE MATERIALS

The function of uranium mills is to extract uranium in concentrated form from naturally occurring ore deposits which generally contain 3 to 6 lb of U_3O_8 per ton of ore (0.15 to 0.30% U_3O_8). The product is a semirefined uranium compound (U_3O_8 or $Na_2U_2O_7$) called yellow cake, which is then shipped to a conversion plant for further purification as a step in preparing the uranium for use in nuclear fuels. Liquid and solid wastes called tailings are impounded near the mill. Off-site releases of radioactive materials consist of airborne dusts and radon gas from the mill and from the tailings impoundment area. Depending upon the geology and the water table, there is also a potential for the underground migration of radioactive materials in seepage of liquid effluents or as the result of leaching of tailings.

A series of increasingly efficient (and expensive) radwaste treatment cases are presented for a model acid-leach mill and a model alkaline-leach mill at two sites, New Mexico and Wyoming (Summary, Table 1.1). Many of the assumptions and treatment cases are based on the background survey of present industrial practices and laboratory research in radwaste management (Sect. 9.0). Seven conceptual cases are considered for treating airborne radwaste from the mill buildings. Similarly, five conceptual cases are considered for liquid effluents from the acid-leach mill, four for liquids from the alkaline mill, ten solid radwaste cases for the acid-leach mill, and nine solid radwaste cases for the alkaline mill. Treatment of the various effluent streams is assessed separately, before they are combined in the summary (Table 1.1). In many cases, both the releases of radioactive material (the source terms) and the costs will vary with the site because of differences in the net annual evaporation rate and the windspeed. Treatment of the various effluent streams is assessed separately (Sects. 4.3 and 4.4) before they are combined in the summary (Table 1.1). Source terms are shown on an annual basis for three time periods: (1) the period during operation of the mill, which is assumed to be 20 years; (2) the interim period following mill closure, while the tailings dry and before they are stabilized; and (3) the period after final stabilization and covering of the tailings. The source-term tables include costs and doses for the separate treatment segments; however, discussion of costs, doses, and cost-benefit is deferred until Sects. 6-8.

Generally, the release of radioactive material decreases and the cost increases with increasing case number. Case 1, the base case, represents typical, current, waste management methods and provides the base for the incremental cost analysis. The case studies assume that the mill is processing a 6% moisture ore which produces a relatively large amount of dust. Estimates of releases from mills processing wetter ores are also presented in Sect. 4.3.3. Since many mills process wetter ores, and since some of the treatment methods illustrated in Cases 2 and 3 are presently used, the average releases by the industry as a whole are lower than those estimated for Case 1. Estimates of the release of airborne radioactive materials from the tailings area are based on annual average wind speeds. The effect of unusually strong windstorms is discussed in Sects. 7.2, 7.4.2, and 9.2, but a statistical analysis of this variable is beyond the scope of this survey. Estimates of the releases of airborne radioactive materials from the mill, seepage losses, and leach rates are based on conservative assumptions in selecting treatment efficiency ratings which tend to maximize the amounts released. The advanced cases are subdivided into (a) and (b) when alternate radwaste treatment methods have similar source terms for airborne and seepage releases but the long-term integrity of the waste toward leaching is not the same. Some of the equipment and waste management methods suggested in the earlier cases can probably be backfitted to existing mills. Much of the technology proposed in the advanced cases is in an early stage of development and is not ready for immediate use. Technical descriptions of the systems and the calculated amounts of radioactive materials that would be released for each case, the source terms, are given in Sects. 4.3 and 4.4.

4.1 Description of Model Mills

The process of uranium extraction varies among the mills due, in part, to differences in the chemical composition of the ore. Steps basic to all mills are crushing, grinding, chemical leaching (wherein the uranium is dissolved from the ground ore), and recovery of the uranium from the leach solutions. The mill processes fall into three general types: acid leach--solvent extraction (10,100 tons/day), acid leach--ion exchange (9,100 tons/day), and alkaline leach (3,350 tons/day) (Sect. 9.2, Table 9.1). A model acid-leach mill and a model alkaline-leach mill are considered because they generate different wastes in regard to liquid volume, bulk chemicals, and radioactive element concentration. The alkaline-leach model mill is based on the conventional flowsheet. Amine solvent extraction with an ammonium sulfate strip was selected for the model acid-leach flowsheet since this appears to be the trend of the future. Most of the waste treatment methods proposed for the model solvent extraction process are suitable for use with any of the acid-leach flowsheets; however, the source terms and costs may be different. A more-detailed discussion of the selection of the model mills is presented in Sect. 9.

Each model mill is selected to have a daily capacity of 2,000 tons* of ore containing 0.20% U_3O_8. Assuming secular equilibrium, each member of the uranium decay chain is present at 515 μCi per ton of ore. The mill is assumed to operate continuously for 365 days per year for 20 years. Each mill is evaluated at two geographic sites that together represent most of the known reserves in the United States; i.e., a Wyoming site, and a New Mexico site (Sect. 9.1). Although mining per se is not the subject of this study, the type of mine that is involved is designated when it is used to receive waste as a means of disposal. Open-pit mines are typical in Wyoming, while underground mines are typical in New Mexico. The ore body lies at least 150 ft below the surface of the earth, and the mine is assumed to be wet. The long-term trend is toward deeper, wetter ores and underground mines. The model mill is located within 3,000 ft of the mine, and the ore is trucked on privately owned land.

4.1.1 Acid Leach--Solvent Extraction Mill

The flowsheet for the acid leach--solvent extraction mill is shown in Fig. 4.1; chemical consumption is given in Table 4.1. The ore is dumped from trucks and passed through the grizzly to the primary crushing

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*Short ton, 2,000 lb/ton.

circuit, which is operated 16 hr/day. Here the ore is crushed to 1/2 in., screened, and the oversize material recycled to the crusher. The fine ore is elevated to four storage bins which are vented through a dust collector to a short stack on the roof. The ore is conveyed on endless rubber belts. Air exhaust hoods are located on the crusher, at the screens, and at each transfer point. The air is passed through a dust collector before being discharged through a roof vent.

The ore is then wet ground in rod mills as a slurry containing 65% solids. The ore is ground to less than 28 mesh and discharged into the leach circuit, which consists of eight tanks in series with a total residence time of 7 hr. Sulfuric acid and an oxidant, sodium chlorate, are added continuously. The solution containing the dissolved uranium is separated from the solids by countercurrent washing in a countercurrent decantation (CCD) circuit. The slurry is passed through hydroclones to separate the coarse sand fraction, and the sand is washed in a series of six classifiers. The overflow from the classifier joins the hydroclone overflow, and the slimes are washed in a series of six thickeners. Flocculants are added to promote settling. The solids are washed with fresh water and recycled raffinate from the solvent extraction circuit. The washed slimes and sands are pumped to the tailings pond. The sands are 70% of the ore processed; the slimes are 30%. The total weight of waste solution accompanying the sands and slimes to the tailings pond is 150% of the ore processed.

The uranium is recovered from the leach liquor by countercurrent contact in four extraction stages with a long-chain amine dissolved in kerosene. The uranium is stripped from the solvent in four stages with an aqueous solution of ammonium sulfate. The solvent is recycled back to the extraction circuit. The uranium is precipitated by addition of gaseous ammonia, concentrated, and partially washed in thickeners and collected in filters. The washed precipitate is dried in a continuous steam-heated dryer. The dried uranium precipitate, commonly called yellow cake, is packaged in 55-gal steel drums for shipment to a refinery. Overall recovery of uranium as product is 91% of that contained in the ore. The thorium content of the yellow cake is assumed to be 1.4×10^{-2} μCi/g

U_3O_8 (5% of the total thorium), and the radium content 5.5×10^{-4} µCi/g (0.2% of the total radium) (Sect. 9.3.2). No other significant radionuclides are present (Sect. 9.3.2). The air streams from the dryer and hoods over the packaging area are combined and passed through a dust collector. A small liquid bleed stream from the uranium precipitation circuit is sent to the leach circuit. Any liquid spillage or leakage throughout the mill is collected in floor sumps and returned to the appropriate circuit. The only liquid waste stream is that leaving with the sands and slimes to the tailings area.

4.1.2 Alkaline-Leach Mill

The flowsheet for the alkaline-leach mill is shown in Fig. 4.2; the chemical consumption is given in Table 4.1. The ore receiving, crushing, conveying, and fine ore storage facilities are the same as those described for the acid leach mill (Sect. 4.1.1). The wet-grinding system consists of a ball mill operated in closed circuit with a classifier. The grinding is done at 65% solids in a sodium carbonate--bicarbonate solution. The ore is ground finer than for acid leach, i.e., 35% less than 200 mesh. The uranium is leached from the ore in two stages consisting of a 5-hr leach at 65 psig pressure and 200°F, followed by an 18-hr leach at atmospheric pressure and 185°F. The solids are separated and washed free of uranium by three stages of countercurrent filtration. The solids, which consist of a 50-50 mixture of sands and slimes, are repulped with fresh water and pumped to the tailings pond. The weight of waste solution sent to the pond is 105% of the ore processed.

The uranium is recovered from the leach solution by addition of sodium hydroxide, which forms insoluble sodium diuranate (yellow cake). The precipitate is filtered, washed, and dried in a steam-heated dryer. The product is packaged in 55-gal drums for shipment. The off-gas from the dryer and packaging area is passed through a dust collector before discharge to a roof stack. Overall recovery of uranium is 93% of that contained in the ore. The radium content of the yellow cake is 5.5×10^{-3} µCi/g U_3O_8, representing about 1.8% of that in the ore (Sect. 9.3.2). No other significant radionuclides are present (Sect. 9.3.2).

4.2 Composition and Amount of Radioactive Material Processed by the Model Mill

The model mill will process 2,000 tons of ore per day containing 0.20% U_3O_8 as natural uranium. The ^{238}U is assumed to be in secular equilibrium with its 13 radioactive daughter products (Sect. 9.3.1, Fig. 9.1, and Table 9.2), so that the concentration of each of the 14 radionuclides is 515 μCi per ton of ore. A total of 14.4 Ci of radioactivity enters the mill per day, of which 2.1 Ci is uranium and is recovered as product. The remaining 12.3 Ci is discharged in the waste. Most of the radionuclides remain insoluble during leaching and leave the mill with the solid tailings. Acidic liquid wastes contain ~50% of the thorium but only a few percent of the other radionuclides (Sects. 9.3.2 and 9.5.1). Alkaline liquid wastes contain very small amounts of the radionuclides (Sects. 9.3.2 and 9.5.1). Airborne effluents consist of dust particles from ore and yellow cake handling in the mill, wind erosion of tailings, and radon gas which emanates from both the ore and the tailings. Ore dusts released from the mill are assumed to be 2.4 times as rich in radioactive materials as the mill feed (Table 9.12, Sect. 9.3.3). See Sect. 9.0 for a more detailed discussion of the radioactive materials in the different effluent streams.

The radionuclides of primary concern are: U_{nat},* ^{226}Ra, ^{230}Th, ^{234}Th, ^{210}Pb, ^{210}Bi, ^{210}Po, and ^{222}Rn. The other daughter products are not listed as source terms, either because they individually contribute less than 0.02% of the total relative hazard or because they have half-lives of less than 2 hr and do not accumulate in the bioenvironment. The relative hazard is estimated by dividing the curies present in one ton of ore 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). The only nuclide excluded because of its small contribution (less than 0.02%) to the relative hazard is ^{234}Pa. The short-lived

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*One curie of natural uranium (U_{nat}) is defined in 10 CFR 20 as the sum of 3.7×10^{10} dis/sec from ^{238}U plus 3.7×10^{10} dis/sec from ^{234}U plus 9×10^{8} dis/sec from ^{235}U; it is also equivalent to 3,000 kg of natural uranium.

daughters are included in the dose of the longer-lived parent. For example, the short-lived daughters of ^{222}Rn, namely ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po are included when the inhalation dose from ^{222}Rn is calculated. The Radiation Concentration Guides for the nuclides of interest are listed in Table 9.3; the half-lives are given in Fig. 9.1.

4.3 Airborne Effluents from the Model Mill

Numerous opportunities arise for the formation of airborne radioactive dusts in the milling processes — ore crushing, screening, transferring, etc., and the yellow cake drying and packing. Dust-producing activities are essentially the same in all mills and are unrelated to the chemical flowsheet. Radon is released during the crushing and grinding operations. In the case studies, air streams exhausted from the mill buildings are treated by a variety of dust collectors, filters, and radon decay traps to reduce the spread of airborne radioactive material. The assumptions used in source term calculations and the design basis for the cost estimates are listed in Table 4.2. Many of the assumptions are based on the material presented in survey Sects. 9.3, 9.4, and 9.7.2. Current practices in the industry are described in the survey Sect. 9.4. The control of airborne effluents from the tailings area is discussed with the treatment of solid waste (Sect. 4.4).

4.3.1 Treatment Methods

4.3.1.1 Wet Scrubbers.[1-3] — 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 which is recycled to the process. Gases such as ammonia in the dryer off-gas may be removed by wet scrubbers. The stack effluent will usually be well cleaned but will contain some unwetted fines, mists, and a steam plume. The temperature and moisture content of the inlet gas are essentially unlimited. Equipment size and initial cost are reasonable, but the operating cost is high for the high-efficiency scrubbers that have large power consumption. Wet scrubbers are standard industrial equipment available "off the shelf" in a variety of sizes.

The efficiencies of various wet scrubbers ranging from 93.6 to 99.9% under plant conditions for a standard industrial test dust (roughly equivalent to the efficiencies on 5-μ particles) are given in Table 4.2. In general, the efficiencies are directly proportional to the pressure drop and, for a given type, show little variation among manufacturers. The efficiencies decrease with decreasing particle size. For example, the orifice- or baffle-type collector is 93% efficient on 5-μ particles, 75% on 2-μ particles, and only 40% on 1-μ particles. The more efficient scrubbers do a much better job on fines. For example, a high-energy venturi is 99% efficient on 2-μ particles. All wet scrubbers are quite efficient at removing particles larger than 10 μ.

Orifice or Baffle Scrubber. — Air flows through a stationary baffle at high velocity, carrying the water in a heavy turbulent sheet. The centrifugal force exerted by the rapid changes in direction of flow causes the dust particles to penetrate the water film. The efficiency is 93.6%. Orifice scrubbers are widely used in the uranium milling industry today.

Wet Impingement Scrubber (irrigated target, perforated plate). — The gas stream, carrying both dust particles and water droplets from preconditioning sprays, is directed through perforated plates to impinge on baffle plates. The gas velocity acts to atomize water on the perforated plate. Particles are collected on vaned mist eliminators and are withdrawn along with the solids collected in the liquid overflow from the impingement plate. The efficiency is 97.9%. Impingement scrubbers are widely used in uranium mills.

Venturi Scrubber. — Water 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. The venturi must be followed by a mist collector. Efficiencies range from 99.5 to 99.9%, depending upon the pressure drop. Venturi scrubbers are currently being used on the yellow cake dryer at one mill and on a dry ore grinding circuit at another.

4.3.1.2 Bag Filters.[1-3] – The bag filter is quite efficient for removing fine dusts down to 1 μ from cool, dry air streams. Bag filters cannot be used on hot, moist streams such as the dryer off-gas. Dusty gas flows through a filter made of a woven or felted material and deposits particles in the voids. As the voids fill, a cake builds on the fabric surface and the pressure drop increases to a point where the solids must be removed by shaking or by a reverse jet of air. Efficiencies range from 99.7 to 99.9%. The equipment is bulky. The most efficient type uses thick felt bags cleaned by a ring of small air jets which moves continuously up and down the bag. Bag filters are currently used at two mills to treat dusty air from ore handling, and at two mills to treat the yellow cake packaging air stream. A salable yellow cake product is collected.

4.3.1.3 HEPA Filters. – 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 1,000 cfm. The modules are formed into banks to achieve the required capacity for filtering air. The filter medium is a pleated mat of woven fiber glass. 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-μ particles; (2) a resistance of 1.0 in. H_2O when clean, and up to 6 to 10 in. H_2O when in service and operated at the rated air flow capacity; and (3) a rigid casing extending the full depth of the medium.[4] 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-μ smoke).[4]

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

1. A high efficiency for the filters can be ensured by constructing a tight installation such that all of the gas to be treated

passes through the filters with no bypass. The filters should be tested, before and after installation, and also periodically while in service, by a method such as the dioctyl phthalate smoke (DOP) test. Continuing pressure drop measurements can indicate whether the filters are plugging or have been ruptured.

2. HEPA filters are strictly backup and must be preceded by high-efficiency dust collectors. Assuming an average particulate capacity of 4 lb/unit, HEPA filters on the yellow cake off-gas from the model mill would need to be replaced every 8 days using an impingement precleaner, every 26 days with a low-energy venturi, or every 132 days with a high-energy venturi or reverse jet bag house.
3. Excessive moisture can impair the efficiency of the filter. It is mandatory to remove all entrained moisture or to heat the air 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. There is a deficiency of the type of operating data that can be extrapolated for design purposes.[5]

4.3.1.4 Charcoal Delay Traps. — Since radon has a relatively short half-life of 3.8 days, systems which delay the noble gases can be used effectively to reduce the total activity by radioactive decay. In the dynamic absorption process, a gaseous species in a flowing carrier gas stream is physically adsorbed on the surface of a solid adsorbent. Although the adsorbate is not bound permanently to the adsorbent, its exit from the adsorption bed is delayed with respect to the carrier gas. Thus, the short-lived noble gas disappears by radioactive decay while it is retained on the charcoal bed. Currently, activated charcoal is used to remove krypton and xenon from the gaseous effluents of nuclear generating plants.[6-8] It should also be possible to remove radon by dynamic absorption in a charcoal bed. The decontamination or removal factor for radon can be calculated from the equation given by Adams *et al.*,[8] using 6,000 as the adsorption coefficient for radon on charcoal at room temperature.[9,10] Theoretically, a five-stage charcoal bed containing 3,000,000 lb of charcoal should remove 99% of the radon from a 5,000-cfm air stream.[11]

The following items apply to the design and operation of charcoal adsorption beds:

1. A filter is needed upstream of the charcoal bed to prevent plugging of the bed, and a HEPA filter is needed downstream of the bed because ^{220}Rn daughters (and, by inference, ^{222}Rn daughters) are not quantitatively retained in the bed. The daughters are formed as small, dust particles.
2. Relative humidity of the air stream must be <50%.
3. Shielding will be required because of the increasing radioactivity level.
4. Buildup of mass and heat is negligible.
5. Large charcoal beds are a potential fire hazard.
6. There is a deficiency of both laboratory and operating data that can be extrapolated for design purposes.

It is possible to reduce the size of the charcoal beds by lowering the temperature; however, the capital cost of a Freon scrub system to dry the moist air is estimated as $2 million or $3 million for 1,000 cfm.[11]

4.3.1.5 Windbreaks Around Ore Unloading Area. — Beginning with Case 4, windbreaks are added around the ore unloading area to reduce wind drying of the ore and the resulting dust problems. Some mills use windbreaks today. The amount of dust and radon arising in the ore unloading area cannot be estimated because it is a minor source compared with the tailings areas. Ore is trucked to the typical mill as it is needed, unloaded, and fed to the grizzly with relatively little dusting. Ore is not ordinarily stockpiled near the mill unless the mine is some distance away.

4.3.2 Case Studies

A series of increasingly efficient (and expensive) treatments for removing particulate matter from mill off-gas streams are presented in Tables 1.1 and 4.3-4.5. Flowsheets for the treatment cases are shown in Figs. 4.3-4.14; the equipment is listed in Sect. 6.0. Case 1 is the base case for the model mill used in the incremental cost analysis. Orifice- or baffle-type wet scrubbers are used to clean the air from the crusher building and ore bins, and a wet impingement scrubber is used to clean the off-gas from the uranium concentrate drying and packaging operations. More efficient dust collectors are used in Cases 2 to 6; however, other than stronger ductwork to withstand the increased pressure drop in the dust-collecting system, there are no basic changes in the mill design. Case 7 includes a charcoal delay trap for radon decay applied to the exhaust air stream from the crusher building, ore bins, and grinding mill. When the charcoal trap is used, it is necessary to reduce the volume of air to be treated by building tighter systems and wetting dusty ores. Airflows from ore-handling operations were reduced from 22,000 cfm (industry average for a mill with ventilation) to 3,500 cfm (minimum in a mill with ventilation). Reduction of the airflow in the earlier cases would reduce the costs for dust collection. It is also necessary in Case 7 to build a hood and duct system to collect the radon from the grinding circuit, which is normally ventilated by the general building airflow. Radon treatment was postponed to Case 7 because the amount of radon released during milling in the earlier cases is small compared with the quantities emanating from the mine and tailings pile. A stack is not used on the model uranium mills. The net effect of dispersion through a stack is to decrease individual dose at the boundary but to increase total population dose. This is particularly true at uranium mills where the population density is low near the mill and increases at distances where the towns are located.

4.3.3 Calculation of Source Terms

The treatment methods and the estimated airborne emissions from the model mills are presented in Tables 4.3 and 4.5, based on maximum releases at the present time for Case 1. Emissions are given both in curies of ^{238}U and in pounds of particulates, since future trends indicate that tighter restrictions may be applied to particulates independent of the radiological impact. The complete list of source terms is given in Tables 4.6-4.9; the concentrations of airborne radionuclides in stack or vent air streams are shown in Table 4.10. The design and calculated releases for the model mills may be compared with the survey data in Sects. 9.3, 9.4, and 9.7.2.

Crusher releases from mills vary widely due to differences in the moisture content of the ore (Table 4.4) and differences in the amount of ventilation and type of air treatment (Survey Table 9.9). "Average" releases at the present time are probably only 1/5 to 1/10 the maximum releases estimated for the 6% moisture ore, which produces a relatively large amount of dust. For example, a mill processing an ore containing 8% moisture releases only about 1/8 as much ore dust as does a mill processing a 6% moisture ore and using the same type of dust collector. A mill processing a wet (9 to 10%) moisture ore and using no dust collector would release about 1/5 as much dust as the mill processing the 6% moisture ore and using an orifice-type collector. Mills handling wetter ores do not need as much ventilation to meet the occupational limits for dust inhalation. The use of lower airflows, in turn, would result in lower treatment costs than are shown in Table 4.3. Some Wyoming mills process such wet ores that no ventilation is required, and the amount of airborne ore dust leaving the mill is minimal. Of the six mills visited by the study team in the spring of 1973, two were processing dusty ores, one was processing an 8% moisture ore, and three were processing wet ores. Five of the six mills were using dust collectors. Future projections of the environmental impact of the milling industry should be based on the estimates for wet ores in Table 4.4, rather than the maximum releases of Table 4.3.

Treatment of yellow cake dust is similar at all mills, with the exception of one mill which uses a highly efficient venturi scrubber (Survey Table 9.10). Average losses by the industry are probably about 0.8 times the maximum releases (Survey Table 9.12). The radium plus thorium in the yellow cake contribute more than half the total body and bone dose (100% locally produced food) due to yellow cake dusts (Sect. 7.4.1). Because data are not available for the amine solvent extraction process, the ^{226}Ra activity of the yellow cake is assumed to be 0.2% and the ^{230}Th activity is assumed to be 5% of the ^{238}U activity, based on data for the obsolete alkyl phosphoric acid solvent extraction process.[12,13] These estimates may be high for the amine solvent extraction process. Although the ion exchange process is not part of this study, it should be noted that at one ion exchange mill the ^{226}Ra content of the yellow cake is only 0.06% of the ^{238}U activity and the ^{230}Th is only 0.8% of the ^{238}U activity.[14] The radium activity of the alkaline-leach yellow cake is assumed to be 2% of the uranium, based on flowsheets similar to those in use today.[12,13] However, the data are 15 years old and probably should be rechecked, as improvements have been made in radium analytical techniques since that time.

4.4 Liquid and Solid Effluents from the Model Mill

Uranium mills produce large quantities of liquid and solid wastes, i.e., 1 ton of solid waste and 1.05 tons (model alkaline-leach mill) or 1.50 tons (model acid leach--solvent extraction mill) of liquid waste for each ton of ore processed. The compositions of the wastes are given in Tables 4.11 and 4.12. Except for seepage losses, most of the radionuclides in the liquid effluent ultimately are retained as solid waste following natural evaporation or treatment. The solid waste differs from gaseous and liquid wastes because it remains after the mill has closed as a possible long-term source of hazardous effluents. At the end of the 20-year life of the model mill, the waste pile will contain ~77,000 Ci of radionuclides, i.e., 7,500 Ci of each member of the ^{230}Th decay chain plus 500 to 700 Ci each of ^{238}U and its daughters above ^{230}Th (Fig. 9.1). Unlike other phases of the nuclear fuel cycle where solid radwastes are shipped off-site to an approved repository, the uranium milling industry is concerned with on-site solid waste disposal.

In the case studies, liquid and solid effluents from uranium mills are treated to reduce or prevent contamination of air, surface water, underground water, and surrounding surface land. Wastes are impounded in on-site retention areas of varying degrees of containment. Soluble species may be precipitated from liquids or the water evaporated for recycle to the mill. Solids may be covered to prevent wind and water erosion, or incorporated in asphalt or concrete to improve the long-term integrity of the stored waste. A radon diffusion barrier may be placed over the solids. Management of liquid and solid wastes is intertwined because the liquid is often used as a transportation vehicle for the solids, while the slimes fraction of the solids cannot be readily separated from the liquid. Many of the assumptions and treatment cases were developed from the background survey of present industrial practices and laboratory research in radwaste management (Sect. 9.0).

4.4.1 Waste Management Methods

4.4.1.1 Tailings Impoundment. — The main repository for uranium mill wastes currently is an on-site tailings impoundment which retains all solids and liquids except those lost by seepage or wind erosion. In the semiarid climate of the model mill sites, the natural evaporation rate, 4 ft net annually in Wyoming and 7.25 ft in New Mexico, is sufficient to dispose of the water. The maximum pond area required is 194 acres for the model solvent extraction mill located in Wyoming, using an evaporation pond with a sealed bottom to minimize seepage. This includes a 20% safety factor for such contingencies as an abnormally low evaporation rate over several years. The liquid level will not be steady in a typical pond where the bottom has a natural slope. For example, the liquid level will rise rapidly during the first several years. Then, as the increased area causes increasing evaporation, the level will rise more slowly. In the typical case where solids are impounded in the same basin, the solids cause an additional rise of the pond level. During the last several years of the 20-year mill life, the liquid inventory will be almost constant, i.e., evaporation, seepage, and liquid retention by the solids will balance the flow from the mill. For simplicity, a wedge with a square surface has been chosen to describe the pond and resultant tailings deposit for purposes of evaporation, construction, and source term calculations (Fig. 4.15).

The tailings retention area is sited within 3,000 ft of the mill near the upper reaches of a gently sloping natural drainage area, and at least 200 ft from any surface stream or permeable formation such as alluvial deposit or volcanic rock. Site selection is very important to avoid contamination of surface streams and drinking water supplies (Sects. 9.5.3 and 9.6.4). The pond is formed by construction of a dam across the lower end of the site. The geologic structures of the substrate are such that whatever seepage occurs is essentially uniform across the surface and does not communicate with water-bearing strata that may be used in the food chain to man. Diversion dams and ditches are constructed to prevent surface water from entering the pond during operation and flowing through the waste deposit after stabilization. The dam itself is located where the required surface area for evaporation and volume for solids storage is provided.

In early cases, a starter dam or dike is constructed of native borrow material, while the remainder of the dam is built from the tailings themselves. The tailings are hydraulically classified either by hydroclones or settling to provide the sand fraction for the dam. The criteria for the construction of the tailings retention dam are given in an AEC licensing guideline,[15] which enumerates minimum information requirements such as drawings, design, geologic data, and maintenance plans. Criteria are supplied with regard to site, construction material, dam size and shape, freeboard, seepage control, protection of surface, construction methods, maintenance, and inspection. Additional information about the design of dams for mill tailings including computer programs for stability analysis and phreatic waterline estimation is given in a review paper by Kealy and Soderberg.[16]

In later cases where seepage is minimized, the dam is constructed to retain water. A clay core is keyed to impervious rock strata such as shale, and the remainder of the dam is constructed of compacted borrow material. No tailings are used in the dam itself, but the sands are deposited along the upstream side, forming a beach to keep the dam from becoming water-saturated and to protect it from erosion by waves on the pond. Core drillings and surveying are done to ensure a good foundation for the dam and low seepage through the bottom of the pond. In some cases, the bottom and sides of the pond are lined with an impervious membrane of 5/16-in.-thick asphalt laid on a firm native soil base to minimize seepage. Acidic wastes are neutralized before they are placed in an asphalt-lined pond, since acid will chemically damage the lining.

4.4.1.2 Precipitation of Soluble Radioisotopes. — Uranium mills have large volumes of liquid effluents which are either acidic or basic and contain dissolved radioisotopes in addition to other chemicals (Sect. 9.5.1). Radionuclides can be precipitated from the liquid wastes (Sect. 9.5.6) to reduce the amount released to the environment through seepage and accidents.

Lime neutralization of acid-leach effluents to a pH of 8 will precipitate 90% of the radium,[12] most of the heavy metal ions such as thorium, uranium, arsenic, etc., and anions such as sulfate, as well as eliminating the excess acidity (Sect. 9.5.6). In the absence of direct data for the other radionuclides, 90% precipitation is assumed in the source-term calculations, although theory indicates that probably >90% of the thorium is removed. Slaked lime is added to the tailings slurry (liquid and solids) from the last washing stage in the CCD circuit of the mill. Three tanks in series, with a total residence time of 2 hr, are used to effect complete crystallization of the gypsum ($CaSO_4 \cdot 2H_2O$) product. This minimizes delayed gypsum deposition in the pipeline to the tailings pond. Equipment for receiving, storing, and slaking of the lime is necessary to provide for continuous operation. The theoretical lime requirement is 34.4 tons of $Ca(OH)_2$ per day.

Copperas. — Radium is the only radionuclide, except uranium, which dissolves to any significant extent during alkaline leaching, and most of it precipitates with the uranium concentrate product (Sect. 9.3.3). The small amount of dissolved radium in alkaline waste solutions can be reduced by treatment with copperas, $FeSO_4 \cdot 7H_2O$ (Sect. 9.5.6). A 75% removal efficiency is assumed for a single-stage treatment.[12] Copperas is mixed as a dilute solution with the waste slurry in the amount of 0.2 g of $FeSO_4 \cdot 7H_2O$ per liter of solution. Mixing is accomplished in the pipeline to the tailings pond. Solids separation is not made after the precipitation, since the purpose of the treatment is to reduce the concentration of radionuclides in solution. The copperas requirement is 0.42 ton/day.

4.4.1.3 <u>Metal Evaporators</u>. – Distillation retains soluble salts in the liquid effluent as a concentrated solution which can be further treated for disposal while the condensate is recycled to the mill. An overall separation (decontamination) factor of more than 10,000 between condensate and concentrated liquor is generally attained for nonvolatile contaminants treated in a single-stage evaporator. The condensate will be purer than the usual water supplied to a mill in a semiarid climate. Wastes containing sulfuric acid are neutralized with lime before evaporation.

Distillation is also used in one advanced case (Case 6c) to recover water and nitric acid for recycle to the mill and to concentrate the soluble salts. In this case, a single-stage evaporator is used, along with a rectification tower, to prepare concentrated nitric acid (13 *M*). The equipment is constructed of stainless steel. This type of equipment is commonly used at nuclear power plants and nuclear fuel reprocessing plants, but the evaporator required is much larger than any now used in other nuclear facilities.

4.4.1.4 <u>Temporary and Interim Control of Tailings Dust</u>. – All case studies have provisions for limiting the blowing of tailings dusts during the interim period after mill operations have ceased and before the tailings are stabilized and, except for Case 1, provide temporary dust control while the mill is operating. Temporary and interim tailings dust control has not been practiced to any great extent in the past, although a few mills have small, experimental, vegetation plots and the "new" Rifle pile was sprinkled and vegetation established after the mill was placed on a standby basis (Sect. 9.6.6). AEC policy now requires a plan for interim dust control as part of the environmental review in issuing or renewing mill licenses.[17] It is anticipated that these rules will apply to all currently operating mills as their licenses are renewed.[17] Control of dust in the active tailings area while the mill is operating is not presently required, provided the total airborne effluents are below MPC at the site boundary.[17]

Temporary Tailings Dust Control, Mill Active. — A chemical spray was selected for temporary control of dusts on dry, exposed beaches in the case studies. A chemical such as calcium magnesium lignosulfonate is applied in aqueous medium using a lightweight traveling sprinkler head.[18] Water pressure propels the sprinkler so that there is no need to use vehicles or heavy equipment which could mire in the slime areas. Although the chemical coating is not permanent, it generally lasts at least a year, which is sufficient since the coating is buried later under tailings and must be reapplied periodically anyway. The tailings slurry is placed in the basin in a manner such that all tailings are either wet or are beneath the temporary coating. While the model mill is active, at least half (and sometimes essentially all) of the tailings are wet, depending upon the process and the natural evaporation rate at the site. The area requiring temporary control thus varies from 12 to 78 acres. Cost estimates are based on covering all exposed tailings every other year. An alternative treatment is a temporary cover of mine waste or earth. This is considerably cheaper (a factor of 10 less) in situations where (1) the tailings beach is consolidated sand which will support earth-moving equipment, and (2) earth-moving equipment can be borrowed from the mine so that no capital investment is required. Sprinkling to control dust is not practical in winter when pipes must be drained to prevent freezing.

Interim Tailings Dust Control, Mill Closed. — After the mill closes, the pond must evaporate or be drained (water pollution problem) and the tailings allowed to dry before the pile can be stabilized. This may require a period of several years, during which there will be large areas of dry tailings that are free to move when the winds blow. The slimes pond may never dry completely, since the thin crust which forms over the quagmire retards further evaporation. Generally, the pile can be worked in one to three years if the pond is drained or dries rapidly. The interim cover is laid periodically whenever the area of exposed, dry tailings reaches some maximum value. With the mill closed, personnel are not readily available to continuously lay cover. Chemical spray[18] is used for interim dust control in the case studies. Alternatively, mine waste or earth cover could be used by employing an outside contractor with a dragline to lay cover near the slimes pond. While some of the temporary earth cover would be disturbed to obtain sandfill for the slimes pond, probably 75% of it would not be disturbed in the final grading and stabilization of the pile.

4.4.1.5 Stabilization of Tailings. — All case studies provide long-term stabilization of the tailings against wind and water erosion after the mill has ceased operations. Stabilization of uranium mill tailings is required by current AEC policy under the National Environmental Policy Act (NEPA), and by the states of Arizona, Colorado, Oregon, Tennessee, Texas, and Washington.[19] Experience in stabilizing piles is discussed in the survey Sect. 9.6.6.

In the case studies after mill operations have ceased and the pond has evaporated or been drained, the pile is graded to provide a gradual slope and eliminate depressions where water might collect. Side slopes are stabilized with riprap, dikes, and reduction of grades. Drainage ditches are provided around the pile edges to prevent surface runoff from neighboring land from reaching the tailings. The tailings are then covered with 6 in. (or more) of earth topped by 6 in. of either coarse rock or vegetation. Rock was selected for New Mexico, since the natural precipitation (6 to 8 in./year) will not support a vegetation cover. The experience in reclaiming both the Monticello tailings pile and the Exxon mine waste pump indicates that the 14-in. annual precipitation at the Wyoming site is sufficient to maintain vegetation without irrigation. Some maintenance will probably be required in perpetuity, such as repair of storm or animal damage, cleaning out diversion ditches, replacing fences, occasional reseeding, etc. Access would be restricted by appropriate fences and signs. Inspection at regular intervals and following floods, avalanches, earthquakes, or other natural events of significance is necessary to ensure that the integrity of the cover is maintained.

4.4.1.6 Radon Diffusion Barrier. — Radon-222 gas will emanate from the tailings pile unless both the ^{226}Ra parent (half-life, 1,620 years) and thorium grandparent (half-life, 83,000 years) are removed or a radon diffusion barrier is placed over the pile to retard the rate of diffusion and permit part of the radon to decay in transit (Sect. 9.7.1).

Thick earth covers of 8 to 20 ft will reduce the radon emanation by 80 to 98% (Fig. 4.16) and will also stabilize the pile from wind and surface water erosion. The earth covers are topped by either coarse rock (New Mexico) or vegetation (Wyoming). In source term calculations to determine the amounts of ^{222}Rn released, it is assumed that the earth cover has the attenuation properties for retarding the release of ^{222}Rn of coarse building sand containing 4% moisture (Fig. 4.16, Sect. 9.7.1). This is probably realistic for New Mexico. In Wyoming, where the soils are likely to contain more moisture, the radon attenuation factor may be higher. The radon attenuation factor is a logarithmic function such that the thinner (6-in. or 2-ft) earth covers, which eliminate the release of windblown dusts, have little effect on the radon emanation rate.

Asphalt is an excellent radon diffusion barrier.[20] A 1/4-in.-thick asphalt membrane topped by a 2-ft earth cover is equivalent to 16 ft of earth containing 4% moisture; a 5/16-in.-thick membrane is equivalent to 20 ft of earth. A 1/4-in. membrane has been satisfactory for lining a leach dump.[21] This appears to be about the minimum thickness that materially reduces the radon emanation,[18] and also appears to be about the minimum that can be applied. Thicker membranes provide increased durability and increased radon attenuation. The earth cover protects the asphalt from weathering, especially from freezing and thawing. The earth cover is topped by coarse rock or vegetation. Periodic inspection, including air sampling for radon or radon daughters and occasional patching of cracks, will be necessary.

4.4.1.7 Burial of Tailings. — Unlike other phases of the nuclear fuel cycle where solid radwastes are packaged and shipped off-site to an approved repository, the uranium milling industry is concerned with permanent, on-site, solid-waste disposal. In the advanced cases, solid radwaste is buried in landfills under 20 ft of earth. Burial is above the water table to avoid leaching of radioisotopes by natural waters. The surface is contoured to minimize wind and water erosion, and topped by vegetation or coarse rock. This returns the surface land to limited use such as grazing. It minimizes the long-term maintenance and inspection that are necessary to ensure the integrity of the pile and reduces the likelihood that an individual will inadvertently dig into a pile. The location of the pile and restrictions on excavation and construction projects are noted on the deed. Cost estimates are based on burying all tailings in landfill. Two feet of earth is removed from the tailings basin before milling operations are started in order to provide a readily accessible supply of earth for part of the cover. Topsoil is saved separately. The remaining cover must be hauled from mine waste dumps or other sources.

While only general treatment methods are used in this study, the possibility of returning wastes to the mine could also be considered. In Wyoming, mills are located near the open-pit mines; thus it may be possible in later years to return some tailings to the mine. After ore has been mined from the first pit, the pit could be partially backfilled with mine waste from subsequent mining operations until the bottom is well above the water table, and then sealed with the asphalt membrane to retard liquid seepage. Underground mines are generally wet and, therefore, are not usually suitable for burial of untreated wastes because of the leaching problem. It may be feasible to place wastes fixed in cement in the underground mines. This was not included as a case study because there are insufficient data to estimate the amount of leaching that may occur or the movement of the leached radionuclides. If safe, placing wastes in underground mines has the obvious advantage of not disturbing the surface land.

4.4.1.8 Fixation in Asphalt. — Incorporation of a variety of industrial wastes in asphalt has been demonstrated in pilot plant studies and applied in small plants.[22] Asphalt provides an impervious coating on the solid particles so that water penetration is low; consequently, leach rates of water-soluble salts are low. Leaching of slightly soluble salts such as radium sulfate would be extremely low. The asphalt coating is also an effective barrier to the diffusion of radon, thereby reducing its release to the environment. As applied to the wastes from a uranium mill, only the slimes fraction and solution wastes are incorporated in asphalt. The sand fraction accounts for 50 to 70% of the solid waste but contains only about 15% of the radioactive materials (Sect. 9.3.3). The assumptions used in calculating source terms from materials incorporated in asphalt or cement are described in a separate report by Godbee and Joy.[20]

Waste solutions and slime underflow from the mill thickeners are neutralized with slaked lime, and the solids are dewatered in a thickener followed by a continuous filter. The filter cake is mixed with asphalt in a continuous wiped-film evaporator operated at 160°C to yield a water-free product. It is important to minimize the moisture content of the filter cake in order to avoid a large evaporation load on the evaporator. Agitator paddles wipe the heated walls of the evaporator at ~200 rpm and provide effective mixing and satisfactory heat transfer. The product, which can contain up to 60% slime solids, is fluid at the operating temperature and can be pumped to the final disposal site. The asphalt mix plant would be located near the disposal area to minimize the length of pipeline.

4.4.1.9 Fixation in Cement. — Incorporation in cement is an established method of waste disposal at nuclear installations. The cemented wastes are then transferred to licensed burial grounds or pumped as a grout belowground on-site into impervious strata such as shale.[23] Mill tailings stabilized with Portland cement to make a "weak" concrete have been used as backfill in Canadian mines to support the mine roof and walls.[24-28] Prior experience with cemented backfill in mines has been confined to nonradioactive tailings and mostly the sand fraction, although one nickel mine has successfully incorporated 50% minus 325 mesh slimes in cement and used the cemented product as backfill in mines.[26] Application of the cemented backfill technique to uranium mill tailings could serve the dual functions of mine support and tailings disposal. However, as noted in Sect. 4.4.1.7, placement of tailings in wet mines is not included in the case studies.

Fixing of tailings wastes in cement is used in the case studies for total solids (sands and slimes) and for slimes alone. In both cases the wastes from the model acid-leach mill are neutralized with slaked lime.

The waste slurry is dewatered to obtain at least 60% solids before being mixed with Portland cement. The ratio of cement to waste solid affects strength, leach rate of radioactive materials, and cost. Preliminary laboratory tests have shown that the ratio must be at least 1 part cement to 20 parts tailings to obtain a minimum strength.[29] Resistance to leaching is also minimum. A ratio of 1/5 yields better strength and leach resistance at higher cost. Cement products made with slimes only have less strength and less permeability than those made with both sand and slimes. Leaching data are not available for cemented products made from slimes. However, data are available relative to the leaching of ^{90}Sr from cement products containing Oak Ridge National Laboratory low-level waste.[23] Additional study is needed to evaluate the use of cement for fixation of uranium mill wastes. The leach rates for wastes incorporated in cement have been estimated by Godbee and Joy,[20] based on preliminary data using a ^{90}Sr tracer in cemented uranium tailings specimens.[29]

4.4.1.10 Nitric Acid Mill Flowsheet. — This treatment differs from the other cases in that it is not a treatment of a mill effluent, but is a replacement for the entire sulfuric acid leach--solvent extraction process used in the mill for the recovery of uranium. The purpose is to leach most of the radionuclides from the ore so that the bulk of the solid residue is less hazardous and, consequently, requires less treatment for long-term storage (Sect. 4.4.2.8). A concentrated liquid radioactive waste is generated from the leach solution that can be converted to a form suitable for permanent storage. Pilot studies of the process have not been made. Consequently, the efficiency and cost for the process are subject to more uncertainty than for the other proposals. Leaching of radium from sulfuric acid-leached tailings with acid and salt solutions has been studied[30] but appears to be less attractive than the direct nitric leach of the ore, which removes uranium, radium, and the other radionuclides together in one step.

The nitric acid flowsheet is shown in Fig. 4.12. Ground ore is leached with 3 *M* nitric acid at 85°C in a series of agitated tanks. Countercurrent washing is accomplished in ten thickeners. The washing is done very thoroughly so that the losses of soluble radionuclides and nitrate with the discarded sands and slime tails are only 0.02% of that present in the leach solution. The leached and washed sand and slime tailings are deposited where they are unobtrusive and covered with 2 ft of earth topped by vegetation or coarse rock. The uranium-bearing solution is concentrated by evaporation, and the uranium is extracted with tributyl phosphate in a kerosene diluent. The vapor from the evaporator is fractionated into water and 13 *M* HNO_3, which are recycled to the wash and leach circuits. Uranium is stripped from the organic phase with water and, after evaporation, is shipped as a concentrated aqueous nitrate solution. The waste raffinate is treated in a continuous calciner to convert the metal nitrates (largely calcium, iron, aluminum, and radioactive elements) to oxides and to recover the oxides of nitrogen for recycle as nitric acid. Calcined solids are fixed in asphalt before burial by the method previously described. Most of the equipment is constructed of stainless steel to handle nitric acid.

4.4.2 Case Studies

Treatment cases for liquid and solid radwaste are summarized in Table 1.1. Case 1 represents current waste management methods and provides the base for the incremental cost analysis. Case 2 places primary emphasis on reducing windblown particulates from the active tailings area and increasing the probability that the permanent tailings cover will remain intact. Case 2 treatment methods are used currently on a limited basis. The middle cases emphasize reduction of radon emanation from the solid waste and reduction of the release of soluble radionuclides by seepage from the pond. The advanced cases emphasize the long-term integrity of the wastes. Case 7 demonstrates that it is possible to reduce the radon emanation to very low levels. Flowsheets for the treatment cases are shown in Figs. 4.3-4.14; the equipment requirements are listed in Sect. 6.0.

While the mill is active, the major concerns are windblown particulates and seepage. When the mill closes, liquids are no longer pumped to the pond and seepage ends. As the pond dries out, the movement of windblown sands and radon emanation increase unless the tailings are stabilized and covered with a radon diffusion barrier. After the mill is abandoned, the long-term integrity of the solid waste becomes a problem. The treatment cases were designed to alleviate both the short-term effects of the operating mill and the long-term effects of the solid tailings piles. The methods for handling the tailings while the mill is operating and after the mill is closed are presented for each case study in the following sections.

4.4.2.1 Model Tailings Impoundment Basin, Cases 1-4 and Case 7. – Cases 1-4 and Case 7 have in common a wedge-shaped tailings impoundment for all types of mills with a square surface formed by constructing a dam across a natural basin near the upper end of a drainage area (Sect. 4.4.1.1 and Fig. 4.15). Diversion dams and ditches minimize inflow of surface water. All liquid and solid process wastes are pumped together to this impoundment basin. During the early life of the mill, the slurry is spigoted on the upper face of the dam. This deposits the sand fraction close to the dam while the slimes and liquid flow "upstream" away from the dam. This separation is essential to the stability of the dam. The final stabilization of the tailings is facilitated by placing some sand in the slimes pond in the upper part of the basin during the later years of mill operation. Liquid disposal is by natural evaporation and varying degrees of seepage. The maximum height of the dam is arbitrarily set at 100 ft, including 5 ft freeboard. A minimum beach of 2 acres of dry tailings sand is maintained along the dam to protect it from wave action and avoid dam instability due to liquefaction. In Cases 1 and 2, the dam is constructed of tailings and there will also be exposed tailings on the face of the dam. Subject to the above restrictions, the impoundments were designed to keep the maximum area of tailings wet, since this minimizes the impact to the environment, and to provide adequate pond area for evaporation, including a 20% contingency for abnormal weather conditions. Liquids and solids are impounded together; i.e., there is no separate evaporation pond. The specific parameters of the tailings impoundment basins are given in Table 4.13. These depend upon the mill process, the net average annual evaporation rate, and the seepage loss.

At the model mills other than the Wyoming acid leach--solvent extraction mill, a wedge-shaped impoundment basin with a dam height of 97 to 100 ft (including 5 ft freeboard) and surface area of 116 to 121 acres contains all the tailings and provides sufficient area for the evaporation pond, including a 20% contingency for abnormal weather. During the early life of the mill, all solids are wet. As tailings accumulate, there is insufficient water to cover all the tailings and an exposed, dry tailings beach* forms which increases in area as a nearly linear function of time until the mill is shut down. The dry beach appears after 5 years of operation at the New Mexico alkaline-leach mill, and somewhat later at the other mills. Near the end of the 20-year life of these model mills, the dry beach varies in size from 2 to 66 acres, plus an additional 10 to 12 acres in the face of the dam in Cases 1 and 2. This dry beach is subject to wind erosion and represents a source of airborne radioactive solids. The rate of emanation of radon also increases as air replaces water in the voids between the solids. After mill operations cease, the pond evaporates, leaving 116 to 121 acres of tailings on the top surface, plus an additional 12 acres on the face of the dam in Cases 1 and 2, to be stabilized and covered.

The Wyoming acid leach--solvent extraction mill has a large volume of liquid effluent (1.5 tons per ton of ore vs 1.05 for the alkaline leach) and only 4.0 ft net average annual evaporation rate (vs 7.25 in New Mexico). This has a number of effects. The Wyoming solvent extraction mill must have a much larger evaporation area than the other mills — 174 to 193 acres, allowing 20% contingency for abnormal weather, vs 120 acres (Table 4.13). Therefore, it has a lower, longer dam to provide the necessary area. While the Wyoming solvent extraction mill is active, essentially all tailings are underwater, except for the tailings used to build the dam in Cases 1 and 2. Thus, the source terms for radon and wind-blown particulates from the active tailings area are quite low and little temporary treatment is needed. However, after mill operations cease and the pond evaporates, the tailings are distributed over a larger area so

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*Wet beach is equivalent to tailings covered by a pond in estimating the source terms and environmental impact.

that source terms for an untreated pile and stabilization costs are higher than for any of the other model mills.

Source term calculations and the estimated costs of temporary and interim cover on exposed beaches are based on the average size of the evaporation pond (open water and wet tailings), dry beach, and final tailings deposit. The design of the impoundment basin and the cost of final stabilization include the 20% contingency in the size of the pond for abnormal weather. It is assumed that, at times during the 20-year life of the mill, the additional land may be contaminated with liquid waste so that treatment is required; however, the amount of tailings deposited during high water is assumed to be small. These tailings are scraped into the main tailings deposit.

4.4.2.2 Case 1 (Current, Base Case). — Liquid and solid wastes are pumped as a slurry to the tailings impoundment basin described in Sect. 4.4.2.1, Table 4.12, and Fig. 4.15. A 10-ft-high starter dam is constructed of native soil across a natural basin near the upper end of a drainage area. Diversion dams and ditches minimize inflow of surface water to the tailings impoundment. The slurry is spigoted on the upper face of the dam, depositing the sand fraction close to the dam while the slimes and liquid flow "upstream" away from the dam. As required, the height of the dam is increased by adding tailings sand onto the dam with a bulldozer or dragline, or by pumping the slurry through a portable hydroclone. Ten percent of the radionuclides dissolved in the liquid waste are lost by seepage into the substrate and through the dam. Water disposal is achieved, for the most part, by natural evaporation from the retention pond. At the New Mexico site, where the net evaporation rate is 7.25 ft/year, the average pond areas required for evaporation are 80 acres for the acid leach--solvent extraction mill and 50 acres for the alkaline-leach mill. At the Wyoming site, where the net evaporation rate is 4 ft/year, the average evaporation area required is 145 acres for the acid leach--solvent extraction mill and 91 acres for the alkaline mill. Near the end of the 20-year life of the model mill, the area of dry beach and tailings in the face of the dam, which are a source of windblown particulates and radon, varies from 12 acres at the Wyoming solvent extraction mill to 78 acres at the

New Mexico alkaline mill (Table 4.13). No temporary treatment is applied to the dry beach while the mill is operating.

During the interim period after mill operations have ceased and while the pond is evaporating, a chemical spray (or, alternatively, 6 in. of earth cover) is applied to the exposed beach in Wyoming. Twenty-five acres was selected as a reasonable maximum for tailings subject to wind erosion. When the area of dry beach reaches 25 acres, the interim treatment is applied. Four applications are required at the alkaline-leach mill, and six at the acid-leach mill. No interim treatment is applied in New Mexico, where the average wind of 7 mph resuspends less tailings dust than does the 10-mph average wind in Wyoming.

As soon as possible (1 to 3 years) after mill operations have ceased, the pile is graded to provide a gradual slope with no low places where water might collect. Side slopes are stabilized with riprap, dikes, and reduction of grades. Drainage ditches are provided around the pile edges to prevent surface runoff from neighboring land from reaching the pile. The pile is then covered with 6 in. of earth topped by 6 in. of crushed rock. Vegetation could be used in place of the rock cover in areas, such as Wyoming, where sufficient rainfall occurs. This type of stabilization eliminates wind erosion of tailings as a source of airborne particulates and the migration of sand dunes. It also eliminates pollution of surface water by natural runoff from the pile, but has virtually no effect on the radon emanation. Access to the area is restricted by fencing and signs. Regular inspection and occasional maintenance are required in perpetuity to ensure the integrity of the cover.

4.4.2.3 Case 2 (Limited Current Use). — Liquid and solid wastes are pumped as a slurry to the same impoundment area described in Case 1 (Sects. 4.4.2.1 and 4.4.2.2). While the mill is active, all tailings are either kept wet, are controlled by the chemical spray, or alternatively, are covered temporarily with 6 in. of mine waste to prevent wind resuspension of tailings dust carrying radioactive materials. The costs shown are for the chemical spray. The area to be covered is a function of process, site, and age of the mill. During the early life of the mill, most tailings are underwater and little treatment is necessary. Near the end of the 20-year life of the model mill, the beach plus the dam face vary in size from 12 to 78 acres (Table 4.13). The cover is regarded as temporary.

After mill operations cease, periodic treatment of the tailings is required to minimize wind suspension of tailings dust as the surface dries. Ten acres has been selected as the maximum area of dry, exposed tailings that is permitted at any site. When the 10-acre maximum is reached, the chemical spray or, alternatively, a 6-in. cover of mine waste or earth is applied to the dry area. Since mill personnel are not readily available after the mill has closed, it does not seem reasonable to make more frequent applications of the cover.

About 2 years after mill operations have ceased, the tailings pile is stabilized in a manner similar to that described in Case 1, except that the final cover is 2 ft of earth topped by 6 in. of crushed rock rather than the 6 in. of earth used in Case 1. This increases the probability that the permanent tailings cover will remain intact. There is less probability of surface water eroding the cover or of vegetation or animals penetrating through the cover. A small reduction in the rate of radon emanation is also achieved.

4.4.2.4 Case 3 (Near Future). – General specifications of the tailings retention area are given in Sect. 4.4.2.1. In Case 3, the tailings basin is located over an impervious stratum such as shale or clay and the dam is constructed entirely of native materials with a watertight clay core. No tailings are used to raise the dam. This limits the seepage loss of water and dissolved radioisotopes to 2% of the liquid waste. It also eliminates the exposed, dry tailings on the face of the dam, which slightly lowers the rate of radon emanation (Table 4.20) and the cost of temporary cover to control blowing dust in the active tailings area. The area needed for the evaporation pond is larger in Case 3 than in Cases 1 and 2 because of the reduced seepage. At the New Mexico mills and the Wyoming alkaline mill, this has little effect on the size of the tailings basin. However, at the Wyoming solvent extraction mill, the increase in the size of the evaporation pond distributes tailings over a larger area of land than in Cases 1 and 2 (160 vs 147 acres, Table 4.13).

In Case 3, exposed beaches are coated temporarily with a chemical spray to control blowing dust. While the mill is active, all tailings are either coated or kept wet. During the interim period after the mill closes, a maximum of 10 acres of exposed tailings is permitted between applications of the coating or cover. Finally, the pile is graded and covered with 8 ft of earth topped by 6 in. of crushed rock. This stabilizes the pile against wind and surface water erosion as in Cases 1 and 2, eliminates most penetration of the tailings by vegetation and animals, and lowers the radon emanation rate by a factor of 5. Regular inspection and occasional maintenance are desirable.

4.4.2.5 Case 4 (Future). – General specifications of the tailings retention area are given in Sect. 4.4.2.1. A watertight, clay core dam is constructed; in addition, the retention area is lined with a 5/16-in.-thick asphalt membrane to seal the bottom and sides. No tailings are used to raise the dam. Since the pond is sealed, the geology is less critical than in Case 3. However, a firm foundation must be provided for the lining and dam. Acidic effluents are treated by neutralization to precipitate 90% of the radioactive materials. Alkaline waste is treated with copperas to remove 75% of the soluble and suspended radioactive materials. The combination of chemical treatment and use of a sealed pond results in a seepage loss of 0.1% of the water and contained radionuclides. Most water is lost by natural evaporation. The precipitation of soluble radium from the pond water and the decreased area of exposed beach cause a decrease in radon emanation from the active tailings area. The asphalt lining also improves the long-term integrity of the waste toward leaching which would occur if the water table should change. Beaches are coated temporarily with a chemical spray to control blowing dust. While the mill is active, all tailings are either coated or kept wet. During the interim period after the mill closes, a maximum of 10 acres of exposed tailings is permitted between applications of the coating or cover. After a 2-year drying period, the tailings pile is graded and stabilized by one of the following procedures. The alternative Cases 4a and 4b are designed to illustrate different geologic considerations and to produce the same impact (dose) to the environment, but have different monetary costs. Flowsheets are shown in Figs. 4.6 and 4.7.

In Case 4a, if the tailings are well above the water table, the pile is covered with 20 ft of earth topped by vegetation or rock after the mill closes. Twenty feet of earth has a radon attentuation factor of 0.022. Thus, the surface land might be returned to productive use, such as for grazing beef cattle. Restrictions relative to digging into the tailings or constructing residential buildings on the surface are recorded on the deed. Inspection might still be necessary following major natural events; in general, however, the waste is placed away from man's casual reach and will require minimal attention. In the case studies, all the solids are transferred to the landfill. Alternatively, the tailings could also be placed in a spent open-pit mine if the pit is first backfilled with mine waste so that the tailings are well above the water table.

Case 4b provides an alternative method for achieving a radon attenuation factor of 0.022. A 5/16-in. asphalt membrane is laid over the tailings, thus sealing them inside a tar box. The asphalt is then covered with 2 ft of earth topped by 6 in. of coarse rock to protect the asphalt from weathering. This method would be used if the water table is near the surface or if earth for cover is scarce. Access to the area must be restricted because the asphalt and earth covers are not designed to be load-bearing. Inspection and patching of cracks are required to maintain the integrity of the membrane.

4.4.2.6 Case 5 (Advanced). — All solids (slimes, sands, and precipitates) from the liquid treatment are mixed with Portland cement to form a low-strength cemented product (1 part cement to 20 parts tailings) and pumped as a slurry to a landfill for disposal above the water table. The landfill is lined with asphalt to minimize seepage of the excess liquid that drains from the slurry before the cemented product hardens. This eliminates the movement of windblown dusts, reduces the radon emanation rate, and lowers the long-term leach rate. The cemented solids are covered with 20 ft of earth topped by a 6-in. layer of rock. The 5/16-in. asphalt membrane covered with 2 ft of earth and topped with rock described in Case 4b could also be used as a final cover. The radon source terms and costs are calculated on the basis that the cover would not be placed until the mill has closed. If convenient, the cover could be placed while milling proceeds, which would lower the radon source terms for the active tailings area to some extent. In the advanced cases, there is no interim period after the mill closes while the tailings dry. The final cover can be laid at once.

Liquids are treated chemically either by neutralization (acidic effluents) or with copperas (alkaline effluents) and then pumped to a pond lined with 5/16-in. asphalt for natural evaporation as in Case 4. Since solids are not stored in the basin, a lower dam is required than for Cases 1 to 4 (Table 4.13). Some liquid will be incorporated with the solids in cement, but the bulk of the liquid radwaste is separated by washing and treated. All solids from the chemical treatment and the residue from evaporation in the asphalt-lined pond are incorporated in cement with the solid waste. Flowsheets are shown in Figs. 4.8 and 4.9.

4.4.2.7 Cases 6a and 6b (Advanced). — The sand fraction is washed to remove mother liquor and easily leached radionuclides, and is subsequently placed in a landfill. The slimes fraction and precipitates from neutralization of waste solutions, which together contain most of the radionuclides, are fixed by addition of either 1 part Portland cement to 20 parts of slimes (6a) or asphalt (6b), and then placed in a landfill above the water table. As milling proceeds, both the fixed waste and the sands are covered with 20 ft of dirt topped by coarse rock. The amounts of radioactive materials released in airborne particulates from the exposed sands and the amount of radon released from the incorporated products are unacceptably high for an advanced case, if the wastes remain uncovered while the mill is operating. Fixation in asphalt improves the resistance of the waste to leaching and decreases the rate of release of radon. However, the amount of radon released is higher than in Case 5, where both the sand and slimes are incorporated in cement. Case 6a is presented as an alternative which requires less cement than Case 5.

Acidic liquid wastes are first neutralized and then evaporated in a metal evaporator. The condensate is recycled to the mill. Alkaline effluents are evaporated directly. No liquid stream bearing radioactive material is discharged to the environment. There is no evaporation pond. Sands are washed free of mother liquor before they are discharged. Slimes and evaporator residues are incorporated in cement or asphalt before the cement or asphalt product is placed in the landfill. Flowsheets are shown in Figs. 4.10 and 4.11.

4.4.2.8 Case 6c (Advanced). — This case differs from all previous cases in that a nitric acid leach is substituted for the conventional sulfuric acid leach. The leached and washed sand and slime tailings are assumed to contain 1% of the radionuclides originally present in the ore, or about five times that of native soil in the uranium mining regions. Consequently, the disposal of these solids can be compared to that of mine wastes or overburden. It is deposited so that is is unobtrusive, and the surface is stabilized by 2 ft of earth topped by vegetation or coarse rock. The concentrated residue from the leach liquor contains about 99% of the radioactive materials present in the mill waste. This concentrate is incorporated in asphalt and buried under 20 ft of earth (similar to Case 6b).

The liquid wastes are evaporated and the pure overhead vapors fractionated into water and 13 *M* HNO_3, which are recycled to the mill. The evaporator concentrates, containing 99% of the radionuclides other than the yellow cake product, are fixed in asphalt. Ore sands and slimes are washed as free of mother liquor as possible before being discharged. The slimes fraction carries a small amount of soluble radionuclides (0.02% of the mother liquor) after the ten washing stages that are provided in the model plant. Unlike Cases 6a and 6b, where the slimes are incorporated in asphalt, a small amount of seepage occurs in Case 6c. Since all water used to transport solids is recycled to the mill, there is no pond in Case 6c. The flowsheet is shown in Fig. 4.12.

Ninety-nine % recovery has not been demonstrated for the nitric acid leach process. For example, Seeley recovered only 95.5% of the radium in three leaches of ore ground to -35 mesh.[30] However, Seeley did recover 97.8% of the radium in three leaches of the finer, -150 mesh slime tailings. Case 6c assumes that 99% recovery from ore is possible with finer grinding and more leaching stages. Even with this optimistic recovery, Case 6c is unattractive from a cost-benefit analysis (Sect. 8.0).

4.4.2.9 Case 7 (Advanced). — The purpose of Case 7 is to demonstrate that it is possible to decrease the radon emanation from a stabilized pile to a low level. Solids and liquids are managed as in Case 4, except for the final cover. A 1-in. asphalt membrane topped with 2 ft of dirt and 6 in. of coarse rock is used. This reduces the radon emanation by a factor of 1000. The 1-in. asphalt membrane could be applied equally well in Cases 5 and 6. The flowsheets are shown in Figs. 4.13 and 4.14.

4.4.3 Calculation of Source Terms

The tailings area where the liquid and solid effluents from the mill are impounded represents a source of gaseous, liquid, and solid radioactive materials. Airborne source terms for radon and windblown particulates while the mill is operating are summarized in Tables 4.6-4.9. The releases of airborne radioisotopes after the mill has been closed are summarized in Table 4.14 for (1) the interim period while the pond evaporates, and (2) the long term after the final stabilization. Losses of radioisotopes by seepage from the tailings basin are estimated in Table 4.15. In all case studies, it is assumed that the tailings area is properly sited for zero release of liquid effluents to surface streams, and that wind erosion is the only mechanism for moving solids off-site, i.e., removal of tailings does not occur by humans, animals, or accidental occurrences such as flash floods, avalanches, or other acts of nature. The long-term storage conditions are selected such that the tailings are expected to remain dry. The potential release of radioisotopes by leaching, if the solid tailings should accidentially be immersed in water, is estimated in Table 4.16. This is an indication of the long-term integrity of the stored waste.

The effectiveness of the liquid and solid waste treatment methods in reducing the release of radioactive materials from the tailings disposal area is assessed separately for the release of airborne particulates, radon gas, seepage, and leaching. Estimates of the treatment costs and radiological doses at 0.5 mile are also included for some of these releases. Considerations of the costs and doses for the total model plants in the case studies are presented in Sects. 6.0 and 7.0; the cost-benefit analyses are discussed in Sect. 8.0.

4.4.3.1 Windblown Particulates. — The fine slimes fraction (<200 mesh or <80 μ) of the tailings contains 85% of the radioisotopes (Table 9.7). The movement of these solids by wind action is not significant while the slimes are wet or under water. The slimes tend to form a crust as they dry so that the dry slimes are less readily moved by the wind than the sand fraction. However, slimes can become airborne by saltation, i.e., when airborne sand grains fall and impact the slime-dust (Sects. 9.6.3 and 7.2).[31] Once airborne, the fine slimes dust will move farther than the heavier sand particles, since the slimes can be ejected into the turbulent air stream while the sands merely creep along the surface. Variables affecting the amount of radioisotopes that are resuspended include the wind speed, the area of dry tailings exposed to the wind, and the concentrations of the radioisotopes in the dust. An average wind velocity of 7 mph is used in this study for the model New Mexico site* and 10 mph for the Wyoming site, based on the meteorological survey presented in Sect. 7.1. Estimates of annual dust movement caused by dust storms are not possible and are not included in this study. Consequently, the estimated source terms may be low, since, as indicated in Sects. 9.6.3 and 7.2, one 24-hr dust storm may transport as much dust as several months of average weather. Source terms for the amount of radioactive dust

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*The model New Mexico site has the meteorology of the first-order weather station at Albuquerque. The mountains may or may not cause perturbations. It should not be automatically assumed that this is the meteorology of the uranium milling district near Grants.

resuspended by the average 7- or 10-mph wind blowing 365 days a year (1) near the end of the 20-year life of the model mills, and (2) during the interim period after the mills have been closed and while the pond is drying are presented in Tables 4.6-4.9, 4.14, and 4.17. Some segregation of the sand from the slimes occurs when the tailings are spigoted from the dam. However, sufficient slimes (small particles) remain in the sandy beach to validate the wind suspension model, since only a small amount of slimes is required. It is assumed that most of the ^{234}Th in the tailings dust has decayed so that the ^{234}Th activity is the same as the ^{238}U activity. Source terms calculated from the theoretical resuspension model are in agreement with the limited data available from environmental monitoring (Sects. 9.6.3 and 7.2).

Dust Case 1, Active Tailings Area. — Source terms for the active tailings areas in this case represent the maximum impact from operating mills (Table 4.17), since they are based on the maximum dry beach area near the end of the 20-year life of the model mill. The average over the 20-year life of the mill will be significantly lower. In all case studies, the movement of airborne dusts is minimized by keeping as many tailings as possible covered by the pond. Consequently, separate evaporation ponds are not used in this study.

Dust Case 1, Inactive Tailings Area, and Cases 2-7, Active and Inactive Tailings Area. — In these cases, exposed tailings are covered with earth or otherwise treated in a temporary or permanent manner so that most of the time there will be no wind resuspension of tailings. Only Cases 1 and 2 are shown in Table 4.17, since this minimum treatment is sufficient to eliminate the problem. Cases 2-4 and Case 7 include the use of a chemical spray or, alternatively, a temporary 6-in. cover of earth on the beaches during operation of the mill (not used in Case 1). In Case 5, the cemented fixed wastes are not subject to wind erosion; in Case 6, the permanent cover is applied as milling proceeds. Permanent stabilization methods are used in all cases after the mill becomes inactive.

Dust Cases 1-4 and 7, Interim Period Between Mill Shutdown and Stabilization of Tailings. — In these cases, an interim period occurs between the time the mill is shut down and the time that the tailings pile can be stabilized. During this period of 1 to 3 years, the pond evaporates and the tailings dry to the point that heavy equipment can work on the surface to apply the permanent cover. In Case 1 at the Wyoming site and in Cases 2-4 and Case 7 at all sites, a chemical spray or, alternatively, a cover of mine waste or earth is applied periodically as the tailings dry. The maximum area of untreated dry tailings permitted during the interim period is 25 acres in Case 1 at the Wyoming site and 10 acres in Cases 2-4 and Case 7 at all sites. No interim treatment is used in Case 1 at the New Mexico site because the amount of tailings resuspended at the New Mexico site without interim treatment is lower than at the Wyoming site with interim treatment. This is the result of the lower average wind speed at the New Mexico site. Since particulate resuspension is a function of the cube of the wind speed, the small difference in average wind speed between the New Mexico site and the Wyoming site has a large effect on the source terms. Thus, the interim source term and dose in Case 1 for the untreated New Mexico tailings piles are lower than for the treated Wyoming piles (Table 4.17). There is no interim period for Cases 5 and 6 since the final stabilization and cover may be applied as soon as the mill closes.

4.4.3.2 Radon Emanation. — Gaseous radon from the decay of ^{226}Ra emanates from both the solid tailings and the pond. Primary emphasis in the treatment cases is to reduce the long-term release of radon from the tailings after the mill has been closed because (1) the long-term radon release rate is 2 to 20 times higher than the release rate from an active tailings area associated with an operating mill, and (2) the population density around currently operating mills is low so that the total population dose from the operating mill is low (Sect. 7.4), whereas long-term total population dose estimates are subject to more uncertainty because it is difficult to predict future population patterns.

Radon Cases 1-5 and 7, Inactive Tailings Area. — The long-term radon source terms for the tailings pile after the mill has been closed and the final cover placed over the tailings are shown in Table 4.18. Radon concentrations in the air as a function of distance from the stabilized tailings are given in Table 4.19 for Cases 1-4 at the New Mexico site.

In Case 1, the shallow 6-in. cover, which is applied to eliminate the movement of windblown particulates, has little effect on radon emanation. In Case 2, the 2-ft cover of earth also has little effect. In Case 3, an 8-ft earth cover lowers the radon emanation rate by a factor of 4. In Case 4, a 20-ft earth cover, or a 5/16-in. asphalt membrane topped by 2 ft of earth, reduces the radon emanation rate by about a factor of 40. In Case 5, incorporation of all solids in cement followed by burial under 20 ft of earth, decreases the radon emanation rate by a factor of about 1000. In Case 7, a 1-in. asphalt membrane topped by 2 ft of earth lowers the radon emanation rate by a factor of 50,000. In the source term calculations, it is assumed that the earth cover has the radon attentuation properties of coarse building sand containing 4% moisture (Fig. 4.16, Sect. 9.7.1). This is probably realistic for New Mexico, but the radon attenuation may be somewhat more effective than this in Wyoming where the soils may contain more moisture. Details of the calculations are given in ref. 20 and Sect. 9.7.1.

Radon Case 6, Inactive Tailings Area. — In Cases 6a, 6b, and 6c, the major objective is to reduce the long-term leach rate of the treated tailings. From the standpoint of reducing radon releases, Case 6 offers no advantage over Cases 5 and 7, i.e., the reduction in the radon emanation rate is about 300 in Cases 6a and 6b vs about 1000 and 50,000 for Cases 5 and 7. In Cases 6a and 6b, the slimes fraction, which contains 85% of the radioactive materials, is incorporated in cement (6a) or asphalt (6b). This lowers the radon emanation rate by a factor of about 6, and the untreated sands then become the major source of radon release. Thus, the 20-ft earth cover over the sands is the primary treatment for radon in Cases 6a and 6b. The radon emanation rate could be further reduced by an additional factor of 10 in Case 6a, or by 1000 in Case 6b, if the sands are covered with a layer of cement (6a) or asphalt (6b) containing the incorporated slimes. This treatment is not included in the case study, the estimated source term, or the cost estimate for Cases 6a or 6b. Since cementing or asphalting equipment is required in any event in Cases 6a or 6b, it is possible that application of the membrane might be accomplished within the costs listed or for a nominal increase in cost. In Case 6c, a different mill process is used wherein 99% of the radioisotopes are removed from the ore by a nitric acid leach. The uranium is then recovered and the liquid waste containing the bulk of the radioisotopes is concentrated in an evaporator. The evaporator concentrate is incorporated in asphalt and buried under 20 ft of earth. The removal of 99% of the radioactive materials from the tailings in the nitric acid leach reduces the radon emanation rate from the leached tailings by a factor of 100. Thus, deep burial of the leached tailings becomes less important. However, in Case 6c, the leached tailings are covered under 2 ft of earth. This reduces the radon emanation rate by an additional factor of 1.5 and results in an overall reduction in radon emanation rate for Case 6c of about 150, compared with base untreated tailings.

Radon Cases 1-4 and 7, Interim Period Between Mill Closure and Final Stabilization of Tailings. — In Cases 1-4, and Case 7, an interim period occurs between the time the mill is shut down and the time that the tailings pile can be stabilized. During this period of 1 to 3 years, the pond evaporates and the tailings dry to the point that heavy equipment can work on the surface to apply the permanent cover. The highest radon release rate occurs during this period (Table 4.14). Radon releases are calculated for the chemical spray treatment, which has no radon attenuation properties.[18] Radon releases are slightly lower if the 6-in. earth cover is used to control blowing dust. No interim period occurs in Cases 5 and 6, since the burial of the fixed wastes can be completed immediately after the mill is closed.

Radon from Cemented Tailings in Underground Mine. — The radon flux from cemented tailings appears to be somewhat lower than the natural flux in United States mines. The calculated flux on the surface of the cemented product (sands and slimes) is 2.0×10^{-15} Ci cm^{-2} sec^{-1}. The flux measured in underground mines varies from 5×10^{-14} to 5×10^{-16} Ci cm^{-2} sec^{-1}.[32] The low value is from the Elliott Lake region of Canada, where the rock porosity is probably less than 1%.[32] Since the rate of radon emanation from Grand Junction, Colorado, tailings sand is about 20% of the rate of radon formation,[33] the flux in a Colorado mine is probably about 20 times higher or 1×10^{-14} Ci cm^{-2} sec^{-1}. In the United States, the use of tailings as cemented backfill in an underground mine would probably not increase the radon levels in the mine, and may possibly reduce the radon levels somewhat by sealing old workings. Cemented backfill was not included as a case study because of the uncertainty concerning the possibility that water might contact the cemented tailings.

Radon Cases 1-7, Active Tailings Area. — Source terms are shown in Table 4.20 for radon emanation from the active tailings area near the end of the 20-year life of the mill when the tailings cover the maximum area and natural evaporation has concentrated the radium salts dissolved in the pond. Both a pond and a dry beach area are present at that time. These source terms represent the maximum release of radon from the operating mill. The average over the life of the mills is lower for all cases except the acid leach--solvent extraction mill in Wyoming. The dry beaches are the major sources of radon. The areas of the beaches increase over the 20-year life of the mill in every instance except the solvent extraction mill in Wyoming, where the area of dry tailings remains constant in Cases 3, 4, and 7 (Sect. 4.4.2.1). No treatments were evaluated which are specifically designed to reduce the radon emanation from active tailings areas; therefore, no cost estimates are given in Table 4.20. In Cases 5, 6a, and 6b, fixation in cement or asphalt lowers the radon emanation from a New Mexico acid leach--solvent extraction mill by a factor of about 15, as compared with Case 1, and from a New Mexico alkaline-leach mill by factors of 20 and 50, respectively, as compared with Case 1, but has less effect at Wyoming mills where the radon emanation is already low. In Case 6c, the nitric acid leach flowsheet, most of the radium is fixed in asphalt as milling proceeds so that very little radon is released from tailings. In Cases 2, 3, 4, and 7 the chemical spray treatment to control windblown dust has no radon attenuation properties.[18] There is no practical way to place the final radon diffusion barrier over the beach as milling proceeds because the grading necessary to eliminate low places can be done only after the mill has been closed. In Case 6, where there is no pond, the final 20-ft earth cover is laid as milling proceeds so that no more than 10% of the total solid waste is exposed. The cost estimates for Case 5, where all solid wastes are incorporated in cement, are based on the cement slurry being pumped to one asphalt-lined pit and the 20-ft earth cover being placed after the mill has been closed. Alternatively, laying the cover as milling proceeds would further reduce the radon emanation rate from the active mill by an additional factor of 45, at some increase in cost for forms to subdivide the asphalt-lined tailings basin.

Details concerning the source term calculations for the dry beach and fixed solids are given in ref. 20. Values for the beach may be slightly high because the calculations ignore capillary action and assume that all the beach sand is dry to a depth of 5 or 10 ft. A stirred-pond model is used which assumes that all radon diffusing to the liquid-solid interface from the tailings under the pond and all radon from the decay of radium dissolved in the pond water are released to the atmosphere. Wet beach is an equivalent source to tailings covered by a stirred pond. A quiet-pond model, where some of the radon decays as it diffuses through the pond, would yield somewhat lower radon releases. Since the dry beach is usually the major source, the assumptions used for the pond have little effect on the total radon release from the tailings area. The radon emanation from the tailings under the pond was calculated using Eq. (2) from Sect. 9.7.1.

Comparison of Radon Source Terms with Environmental Monitoring Data. — Radon gas concentrations in the air near the model New Mexico solvent extraction tailings pile have been calculated from the source terms using meteorology dilution factors in Fig. 7.2. As shown in Table 4.21, the calculated values based on the theoretical model are consistent with the environmental monitoring sampling and analysis studies performed by the Public Health Service. A rigorous comparison of the theoretical model with the monitoring program is not possible without knowing the area of exposed tailings and the meteorology for the sites sampled by the Public Health Service.

Natural Background Radon Levels. — Natural radiation levels can vary widely from site to site so that any comparison is site-specific rather than generic. However, such comparisons may still be useful in placing the radon source terms in perspective.

The limited data available indicate that the background radon emanation rate from native soils is about 1/500 that from ore tailings. The radon flux[34] from Yucca Flats soil is 1.6×10^{-16} Ci cm^{-2} sec^{-1} (2.04×10^{-1} Ci acre^{-1} year^{-1}) or about 1/400 the emanation from bare ore tailings in this study. Preoperational monitoring by the Exxon Company indicated a concentration of 3 to 7 ppm of U_3O_8 in the soils around their Highland mill site.[35] This is 1/700 to 1/300 the U_3O_8 content of the ore and, assuming secular equilibrium, would have roughly the same natural radon emanation as the Yucca Flats soil. Table 4.22 compares the surface flux over a stabilized tailings pile with these natural soil fluxes. In Cases 1 to 3, the flux is 300 to 450 times higher than the native soil flux, and only in Case 7 can the tailings flux be considered negligible.

In units of radon concentration in air rather than flux, the average of the natural background radon concentrations measured by the Public Health Service[36] near Salt Lake City, Utah; Monticello, Utah; and Durango, Colorado, is 0.41 pCi/liter. The probable natural radon concentration for the Grand Junction, Colorado, area is 0.79 pCi/liter.[36] In Case 1 at the New Mexico site, the maximum radon concentration at 0.5 mile from the stabilized model tailings deposit is 5 times the average background of 0.41 pCi/liter measured in three of the four milling cities by the Public Health Service; at 1 mile it is 1.5 times background; and at 5 miles it is only 0.15 times background. Thus, in Case 1, at 5 miles the stabilized tailings have a very low impact on these particular communities.

4.4.3.3 Seepage. – Estimates of the amount of seepage from the tailings basin while the mill is active are given in Table 4.15. The migration of this seepage through the ground is discussed in Sect. 7.6. Unlike the airborne releases which are distributed off-site, seepage does not migrate beyond the plant boundary at 0.5 mile according to the model described in Sect. 7.6, and should be regarded as the maximum potential release rather than the actual release from the mill site. Long-term seepage does not occur in an arid environment, since the production of liquid waste ends when the mill is closed and the pond dries out. Precipitation does not cause additional seepage, since the evaporation rate exceeds the rate of precipitation. In Cases 1 and 2, seepage losses are estimated at 10%. In Case 3, a watertight clay core dam is constructed and the tailings basin is sited in a suitable location such that seepage is reduced by a factor of 5. In Cases 4, 5, and 7, seepage is reduced by a factor of 100 by lining the basin with asphalt and precipitating soluble radioisotopes with lime or copperas. In Case 4, where solids and liquids are impounded together, a larger and more expensive dam is required than in Case 5 where the solids are incorporated in cement and buried in a landfill. In Cases 6a and 6b, no seepage occurs because all liquid waste is artifically evaporated and recycled to the mill. While most of the liquid is evaporated and recycled in Case 6c (the nitric acid mill flowsheet), a small amount of liquid containing soluble radioisotopes follows the slimes fraction to tailings, even after washing with 10 stages of CCD. This is not a problem in Cases 6a and 6b, where the slimes and sands are separated and the slimes are fixed in asphalt or concrete. The sand fraction can be washed virtually free of mother liquor. Artifical evaporation with complete recycle of all liquid, as used in Cases 6a and 6b, is both the most effective and the most expensive liquid waste treatment method.

4.4.3.4 Long-Term Leach Rate. — The long-term leach rate, if the tailings deposit is totally immersed in a flowing stream of water, is estimated in Table 4.16. These values give an indication of the long-term integrity of the waste. Since all case studies specify that the tailings are to be stored in dry locations, leaching does not occur in the case studies. Leaching presents a potential hazard only if (1) a drastic change from an arid to a wet environment should occur, and (2) the contaminated water communicates with water strata used in man's food chain. The leach rate is important if tailings are to be used as backfill in a wet mine. Radioactive materials can be readily leached from the solid wastes in Cases 1-4a. Encasing the waste in an asphalt box, Cases 4b and 7, lowers the leach rate by a factor of 10,000,000,000. In Case 5, incorporating the solids in cement lowers the leach rate by at least a factor of 100. The leach rates for materials incorporated in cement are based on scouting tests using a soluble ^{90}Sr salt in a cemented specimen made with tailings and cured for 1 month.[29] Actual leach rates for a slightly soluble radioisotope, such as thorium, fixed in cement with a longer cure time are likely to be much lower than the values in Table 4.16. Case 5 specifies that the cement-fixed waste is stored dry. However, there will probably be interest in using it as cemented backfill in the mines. Experimental data on the actual leach rate and a detailed knowledge of the geology of the particular mine are needed to evaluate the feasibility of using the cemented wastes as backfill. In Cases 6a and 6b, fixation of acid-leached slimes in asphalt or cement reduces the leach rate by a factor of about 6. The bare sands are the primary source of leachable radioisotopes. The use of the nitric acid leach in Case 6c lowers the leach rate of the bare tailings by a factor of about 2000. Completely encasing the solid wastes in an asphalt box, Case 4b, is the most effective method for controlling leaching and is also the least expensive way to lower the leach rate. Fixation of the slimes alone in Cases 6a and 6b does not solve the leaching problem completely, since the bare sands still present a potential leaching problem. In Cases 6a and 6b, the sands can be encased in a box of asphalt or cement at additional cost. However, such an alternative is not included in the present study. If this is done, then Cases 6a and 6b, where the slimes have been fixed, provide a margin of safety at considerable increase in cost over Case 4b. Details of the calculations are discussed in ref. 20.

4.5 References

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5.0 MISCELLANEOUS WASTES

The operation of a uranium mill will generate miscellaneous wastes in addition to the radioactive wastes. These wastes include sanitary waste, packaging materials from supplies, combustion products from the power plant, oils and greases from equipment maintenance, and chemicals in the main process waste streams. The sanitary wastes are disposed of in a septic tank and drain field facility. Nonradioactive solid wastes and oils are placed in a landfill. The combustion products that may contain SO_2 are dispersed through a stack.

The chemical composition of liquid wastes from the mill is shown in Table 4.11. Chemical wastes are not discharged to a surface stream, since they are sent to the tailings pond along with the radioactive constituents. In the first several case studies, where vertical seepage of liquid from the pond occurs, the chemicals will cause a corresponding contamination of the soil surrounding the pond. Several toxic chemicals, such as arsenic and fluoride, are present at very low concentrations and probably would be adsorbed in the soil either by ion exchange or by chemical reaction to prevent extensive penetration. Nitrate is present only in Case 6c for the acid leach--solvent extraction mill, and the nitrate concentration in the mill tailings effluent is less than 40 ppm. The concentrations of relatively nontoxic but undesirable salts, such as iron, aluminum, and sulfate, are significantly reduced by neutralization in the more advanced treatment cases.

6.0 COSTS FOR RADWASTE TREATMENT

Costs are presented for the radwaste treatment cases for the 2,000-ton*-of-ore-per-day model acid leach--solvent extraction and alkaline-leach uranium mills at two geographic sites, New Mexico and Wyoming. The capital costs, annual fixed charges, annual operating costs, total annual costs, the contribution to cost of uranium yellow cake, and the contribution to cost of electrical power are summarized in Tables 6.1 and 6.2 for the acid-leach mill and the alkaline-leach mill, respectively. These costs are the total costs for each case study and include the costs for treatment of gaseous and liquid radwastes and for stabilization or fixation of tailings wastes. The individual costs for treating liquid, gaseous, and tailings wastes are given in Sect. 4.0 as itemized below. The capital costs include all direct and indirect costs. Annual fixed charges are estimated at 24% of the total capital investment, typical of investor-owned, reprocessing plant cost estimates. Operating costs are based on estimates of labor, supplies, and maintenance costs. The cost per pound of U_3O_8 product is calculated directly from the annual production and total annual costs. The cost contribution to electrical power generation is derived from the amount of U_3O_8 required for power reactors. A model uranium mill processing 2,000 tons of ore per day and producing 1,329 tons of U_3O_8 annually can supply approximately eight 1,000-MW(e) LWR's (based on a requirement[1,2] of 5,000 tons of U_3O_8 over a 30-year life at a burnup of 33,000 MWd/metric ton of enriched uranium, 80% load factor, 32.5% thermal efficiency).[3] Costs are estimated in terms of 1973 dollars and do not include any allowance for inflation. The cost estimates were made by A. H. Ross & Associates,[4] consultants in the field of design of metallurgical processes.

Capital and total annual costs incurred in treatment of liquid waste and the corresponding source terms are shown in Table 4.15. Some cost items apply to the treatment of both liquid and solid wastes. In these cases, the costs have been proportioned between the liquid and solid

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*Short ton, 2,000 lb/ton.

treatment costs. The costs of fixation of solid waste and the source terms resulting from water leaching of the treated waste are shown in Table 4.16. The costs for stabilization or fixation of inactive tailings piles with earth or asphalt and the corresponding source terms for radon releases are shown in Table 4.18. The cost of treatment of airborne ore dusts, yellow cake dusts, and radon from the uranium mill and the corresponding source terms are given in Tables 4.3 and 4.5. The cost of controlling wind-resuspended tailings dust from the dry beaches in the tailings area and the corresponding source terms are given in Table 4.17.

6.1 Capital Cost

The capital cost of radwaste treatment is the sum of the direct costs of equipment, including installation, piping, instruments, and utility facilities and the indirect costs for design, engineering, construction expenses, and contractor's fee. The cost data are applicable only to the erection of the indicated process facilities. It is assumed that the various cases represent an incremental addition to a planned facility, and no allowance is included for offices, shops, warehouses, change houses, etc., or for bringing utilities and services, such as power, water, and roads, to the boundaries of the plant site. An interest charge of 20% of estimated capital cost is added to cover the construction period. An allowance of 20% of capital cost is for contingency. The major items of capital cost for liquid and solid radwaste treatment are shown in Tables 6.3 and 6.4 for the acid-leach mill and the alkaline-leach mill, respectively.

6.2 Annual Fixed Charges and Operating Costs

The total annual cost is the sum of fixed charges and operating costs. The fixed charges consist of an annual fixed rate of 24% of the invested capital plus an annual charge to accumulate capital to stabilize the solid tailings after the mill has been shut down. The charge rate corresponds to that reported in the Fuel Recycle Task Force,[3] using the same assumptions except for increased plant life (20 vs 15 years) and bond interest (8 vs

5%). The changes are offsetting and do not change the annual charge rate of 24% of invested capital. The basic assumptions of the Fuel Recycle Task Force are:

Plant lifetime, years	15
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 fixed charges to accumulate capital to pay for stabilizing the solid tailings are computed as the annual amount invested at 5% compound interest during the mill life (20 years) to yield the required capital. Also, where maintenance in perpetuity was provided, the cost is computed as the annual charge required to accumulate sufficient principal during mill life so that the resulting income from interest (5%) would cover the cost of perpetual care.

The annual operating cost was computed by estimating labor, supplies, and maintenance requirements of the waste treatment processes, based on the cost estimator's experience in the uranium milling industry. The estimates represent the direct cost of operating the facilities included in the capital cost estimates. The labor cost includes an allowance for burden and fringe benefits. Unit costs of labor and materials are listed in Table 6.5. The costs do not include any allowance for general services and administration such as accounting, warehousing, management, head office expenses, etc. The case studies represent incremental additions to an existing operation and, therefore, do not result in any increase in the indirect operating costs. The operating costs include an allowance of 15% for contingency.

Case 6c differs from the other cases. In Case 6c, the total plant processing flowsheet is revised to achieve an improvement in radwaste treatment; i.e., nitric acid is used for leaching instead of sulfuric acid and the aqueous waste is concentrated by evaporation. The additional radwaste treatment cost is calculated as the difference between the total capital and operating costs of Case 6c vs the same costs for a conventional plant which uses sulfuric acid leaching. The average capital cost of a complete conventional mill with a daily ore capacity of 2,000 tons is $13 million.[5]

6.3 References

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7.0 ENVIRONMENTAL IMPACT

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

Estimates of the dose per year of mill operation to both individuals and to the population within 55 miles, which may result from the expected radionuclide discharges during normal operation, are discussed below. Annual radiation dose commitments to individuals (in millirems) and to the population (in man-rems) are estimated from the release of airborne radioactive effluents. The atmospheric transport of radioactive materials released from the mill during normal operations in its twentieth year (i.e., the source terms, Sect. 4.0) is calculated. The resulting concentrations of radionuclides in the air and on the soil surface at various distances and directions from the model mill are then used to estimate the dose an individual might receive from this 1-year exposure of radioactive materials. Radioactive materials taken into the body by inhalation or ingestion (internal exposure) continuously irradiate the body until removed by processes of metabolism and radioactive decay. A dose calculated for 1 year of radionuclide intake (internal-exposure pathways) is an estimate of the total dose an individual will receive integrated over the next 50 years of his life as a result of that 1 year of exposure (i.e., dose commitment). All of the internal doses estimated in this report represent 50-year dose commitments. For those materials which either have short radioactive half-lives or those which are eliminated rapidly from the body, essentially all of the dose is received in the same year that the materials enter the body, i.e., the annual dose rate is about the same as the dose commitment. For example, most of the dose commitment for radon exposure (which includes the radon daughters) is received the first year. 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; i.e., approximately equal doses are received over a 50-year period. Thus, the average annual dose rate is only 1/50 the dose commitment. If an individual is exposed to mill effluents for the 20-year operating life of the plant, his annual dose rate during the twentieth year is about 20 times the annual dose rate for one year of exposure (i.e., ~2/5 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 20 years that apply in the 20th 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 (ORNL-4992).

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

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

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

No dose calculations are presented for liquid releases. The model mills have no liquid releases to surface streams. The potential for underground migration of radioactive materials is recognized, and treatments are proposed in Sect. 4.4. The available data indicate that no detectable horizontal underground movement of radioactive materials beyond the mill boundary has occurred from properly sited tailings ponds (Sect. 9.5.2), and a sample calculation (Sect. 7.6) indicates that none is expected.

7.1 Meteorology

The release of airborne effluents to the atmosphere is one mode of environmental contamination from uranium milling. Atmospheric transport of radioactive materials released from the mills to the terrestrial environment is calculated according to the Gaussian plume model.[4] A computer code[5] has been modified to calculate the approximate annual average concentrations in air for short- and long-lived nuclides in the atmosphere at various distances and directions from the source. For particulate releases, the meteorologic X/Q' values are used in conjunction with deposition velocities to estimate air concentrations and steady-state ground concentrations. 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, result in additional dose via the food chain pathway.

The meteorologic data required for the calculations are joint frequency distributions of velocity and direction, and these data are summarized by stability class. Meteorologic data from representative New Mexico and Wyoming regions[6] are used to calculate average values of X/Q' ($\mathrm{sec \cdot m^{-3}}$), i.e., factors that are used to calculate the concentration of radioactive substances at a reference point per unit of source strength. The X/Q' values are calculated for sectors in the 16 principal compass directions bounded by radial distances of 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 10.0, 15.0, 25.0, 35.0, 45.0, and 55.0 miles from the point of release. The X/Q' values are based on a ground level release. Maximum and minimum annual

X/Q' values in sectors at successive distances from the release point are given in Figs. 7.2 and 7.3 for the New Mexico and Wyoming sites, respectively. Direction is not specified in the maximum-minimum values at a given distance (Figs. 7.2 and 7.3), but all values, irrespective of direction, range between the maximum-minimum values. For equivalent source strengths at a given distance, the average annual air concentrations are lower in Wyoming than in New Mexico. The maximum X/Q' at the Wyoming site is 57% of the maximum in New Mexico, while the minimum X/Q' in Wyoming is 22% of the New Mexico minimum. Directions at which maximum-minimum values are attained are different at the two sites. For a ground-level release, the maximum concentration of radioactive substances in air occurs at the point of release. Air concentrations decrease according to a power function of distance from the source. Although a site boundary is not specified for uranium mills, the X/Q' values, which reflect variable air concentrations at 0.5 mile, for example, range from 2.3 to 8.7×10^{-6} $\text{sec}\cdot\text{m}^{-3}$ for the New Mexico site. Values for the same distance range from 5.1×10^{-7} to 5.0×10^{-6} $\text{sec}\cdot\text{m}^{-3}$ for the Wyoming site. The values decrease by approximately three orders of magnitude at a distance of 55 miles from the source.

Radioactive materials from the atmosphere are deposited on the ground surface through mechanisms of dry deposition and washout. Dry deposition, as used in this analysis, represents an integrated deposition of radioactive materials by processes of gravitational settling, adsorption, particle interception, diffusion, and chemical-electrostatic effects and is calculated from deposition velocity,[7] Vg, for a 1-year time interval. Deposition velocity values for particles and reactive gases commonly range from 0.1 to 1.0 $\text{cm}\cdot\text{sec}^{-1}$,[7,8] and for micron-sized particles, Vg's may approach 10 $\text{cm}\cdot\text{sec}^{-1}$. A value of 1.0 $\text{cm}\cdot\text{sec}^{-1}$ is used for calculation of ground concentrations of all radioactive particles which originate from both mill and tailings sources. Although many variables influence the washout of radioactivity from the atmosphere,[9] Cowser et al.[8] showed that washout would cause only a negligible decrease in annual air concentration based on a washout weight of 0.038 (Oak Ridge, Tennessee) and a washout coefficient of 10^{-1} sec^{-1}. The annual increase in ground concentration from washout would likewise be nominal, especially in arid climates where rainfall averages 6 to 12 in. per year. Thus, for model uranium milling sites, total transfer of radioactive materials from the atmosphere to the ground surface is included in the dry deposition rate term.

7.2 Suspension of Tailings Particles and Transport of Dust

Suspension of particles from tailings piles and entrainment in the atmosphere constitutes an important mode of transport and pathway of exposure in arid environments. Persistent wind and localized convectional turbulence acting on dry surfaces suspend dust particles, and the entrained aerosols are transported to sites of human occupancy. Although windblown dust is a common phenomenon in arid environments, the mechanisms of suspension and transport have not been investigated in great detail. A model based on physical principles and limited field data was developed for this survey. Using this model, the dispersion of dust from an idealized uranium mill tailings pile is calculated from saltation and particle suspension data coupled with atmospheric transport using the Gaussian plume model. Air concentrations of radioactive substances are calculated for respective distances following suspension from a surface source.[10] Particle suspension is focused on the <80-μ size class (i.e., the -200 mesh slime fraction) because surface creep is the major transport mechanism for larger particles, while those particles that are <80 μ in diameter are ejected into the turbulent air stream and are then dispersed beyond the mill boundary.

1. Suspension of dust is related to processes of saltation as described by Bagnold.[11] Silt-sized particles are not suspended from horizontal surfaces by wind forces alone, since the drag forces on such small particles are spread over a large area rather than an individual particle. However, larger sand-sized particles are readily suspended by aerodynamic forces. Consequently, the saltation mechanism, whereby large airborne particles (>50 μ) impact on smaller particles (<50 μ) and cause their suspension from the tailings surface, is considered the principal method for inducing airborne movement of the fine particles.

The vertical flux suspension factor (k) for the smaller particles is based on agricultural studies of soil erosion by wind.[12] Vertical flux constitutes the source strength from a level, ground, surface area.

2. Given the source strength, atmospheric transport is calculated using the Gaussian plume model.[4]

The particle size distribution of uranium ore tailings is determined from samples provided by mill operators (Table 9.7). The fraction of tailings in size classes (<80 μ) that is used as parent material in the calculation of source strength is given in Table 7.1. Ore processed in the alkaline circuit is ground to a finer size than acid leach tailings. Approximately 30% of the alkaline leach particles and 10% of acid leach particles are <10 μ in diameter, the upper limit of respirable particles.

Particle suspension as a result of the saltation process is directly related to the cube of wind velocity.[10] Thus, wind characteristics are important in the calculation of particle flux from a surface plane. The frequency distribution by velocity classes is summarized in Table 7.2. Because of substantially higher frequency in the 11- to 21-mph velocity class at the Wyoming site, the average velocity is nearly 4 mph greater at Casper, Wyoming (10.7 mph) compared with Albuquerque, New Mexico (6.9 mph). The data are based on a 5-year observation period. A 1-day storm with a wind velocity of 30 mph is a credible occurrence at Albuquerque (Table 7.3), based on an annual summary of hourly and daily data for a 12-month period. Hourly wind data for Casper, Wyoming, are not available for similar analysis, but the frequency of wind velocities which are >21 mph is six times greater for Casper than for Albuquerque (Table 7.2). Thus, the frequency of 1-day storm events with 30-mph wind velocity or greater would probably exceed the one event per year observed at Albuquerque. As many as six 30-mph events per year may conceivably be expected at the Wyoming site.

Particle suspension of airborne dust has been calculated for 7-, 10-, and 30-mph wind velocities (Table 7.4). Suspended dust is expressed in terms of the quantity of particles moving from the ground surface into a horizontal wind stream per unit of time (g/sec). The flux from a tailings beach is computed for a square meter of dry tailings surface,[10] and the results are expressed as the source strength for a standard 100-acre area. In practice, the source strength is then adjusted for the actual acreages of dry tailings (Tables 4.13 and 4.17) and the radionuclide concentration in the slime fraction of the tailings (Table 4.12) which are applicable in each case study. The adjusted suspension flux constitutes the source-strength input to the Gaussian transport model. The suspension rate (source strength) is 13 times higher for a 10-mph wind than for a 7-mph wind and about 300 times higher for a 30-mph wind than for a 10-mph wind because suspension is approximately dependent on the cube of the wind velocity.

Winds blow at variable velocities; however, for the purpose of this assessment, the annual average air concentration of radioactive substances from tailings is based on the suspension caused by constant 7- or 10-mph winds, i.e., the annual average velocities for Albuquerque, New Mexico, or Casper, Wyoming, respectively. Once suspended, the particles are dispersed into the 16 sectors based on actual wind frequency-velocity distributions obtained for the respective sites. For purposes of calculating atmospheric transport, the tailings area is considered to be a point source with all the resuspended tailings dust being released from the center of the pile. Dispersion calculations modeled on an area source rather than a point source would give slightly higher air and ground concentrations near the pile. At 1000 m (0.6 mile) from a 100-acre tailings source, the bias is less than 10%. Therefore, the simpler point source dispersion model is considered valid for this study. For an annual, average, wind velocity of 10 mph, the concentration of radioactive dust does not exceed 18 $\mu g/m^3$ at 100 m from the tailings pile, and the concentrations decrease by orders of magnitude with increasing distance from the source. Dust from a 100-acre tailings source contributes less than 2 $\mu g/m^3$ to the air concentration at distances greater than 1000 m from the source. By comparison, the ambient airborne dust concentration in many cities[13] consistently exceeds 50 $\mu g/m^3$. Most of the dust particles in city air are <1 μ in diameter. Wind gusts and dust devils of seconds or minutes duration are also important processes which inject particulates into the ground-level layer of the atmosphere,[14] but there are insufficient data to estimate their contribution to the ambient dust levels.

Systematic studies of suspension and dispersion of particles from tailings piles have not been made; consequently, there is no basis for verifying the air concentrations which are calculated using the saltation-suspension-dispersion model. However, the calculated concentrations are in reasonable agreement with ambient concentrations of radioactive materials observed in the vicinity of tailings piles. For example, for a 10-mph wind, the total dust concentration in the air 100 m from a 100-acre tailings pile is calculated as 18 $\mu g/m^3$. This represents a ^{226}Ra concentration of 2.8×10^{-14} µCi/ml for acid-leached tailings dust or 1.7×10^{-14} µCi/ml for alkaline-leached dust based on the radium concentration in the slime fraction (Table 4.12). Measurements of radium concentrations in the air in a crosswind direction at Tuba City, Arizona,[15] ranged from 1 to 7×10^{-14} µCi/ml at locations around the tailings pile (Table 9.26). In a 3-month period at Grand Junction, Colorado (Table 9.25), the average concentrations of ^{226}Ra in the air at locations around the tailings pile ranged from 0.4 to 2.7×10^{-14} µCi/ml for an average wind velocity of 8.8 mph.[16] The calculated values based on the saltation-suspension-dispersion model are 1.7 or 2.8×10^{-14} µCi/ml vs 0.4 to 7.0 $\times 10^{-14}$ µCi/ml for the observed values.

The concentrations of ^{226}Ra in air have also been measured during periods of high wind velocities at Tuba City[15] (Table 9.26). Concentrations of 5.6×10^{-12} µCi/ml were measured while the wind was blowing at estimated velocities of 15 to 30 mph at a point outside the site boundary in a downwind direction (50 m from the boundary and 335 m from the center of the tailings pile). For comparison, the calculated concentration of ^{226}Ra at a distance of 100 m, using the saltation model, is 2.3×10^{-12} µCi/ml for a 30-mph wind velocity. The calculation is based on a comparable 65-acre tailings pile and the concentration of ^{226}Ra in the Tuba City tailings as listed in Table 9.26, assuming that the exposed tailings are alkaline tailings* and that the <80-µ fraction (i.e., the slimes) is 50% by weight and contains 85% of the radium.

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*The Tuba City mill used an acid-leach process from 1956 to 1962 and an alkaline-leach process from 1963 to 1966.[17]

The agreement between the calculated values and the observed values is surprisingly good considering the uncertainties involved, i.e., the unknown differences in meteorology, site location, and tailings characteristics. The calculated values for dust suspension at the model sites, based on average wind velocities of 7 mph at the New Mexico site and 10 mph at the Wyoming site, may be low, since high-velocity wind events of short duration are not considered. Wind storms and dust devils can suspend large amounts of dust from tailings piles, since the amount of suspension increases with the cube of the wind velocity. However, meteorological data do not exist which could be used to model this type of occurrence. The estimated annual total body dose does not increase greatly as the result of a single 30-mph windstorm (Sect. 7.4.2).

7.3 Population

A population distribution was derived which is representative of western regions where uranium milling facilities are located. Distributions for five actual sites of uranium mills (Table 7.5) were summarized from 1970 Census Bureau tape records to obtain representative data. An average population distribution (Table 7.6) was compiled from these data sets. The computer code PANS[18] 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 X/Q' values are calculated. The computer code summaries of population data from census tapes are accurate beyond a 5-mile radius. Within 5 miles, where sectors represent relatively small areas, distributions are somewhat disconnected because census enumeration districts encompass several sectors while the population records are reported in only a single sector. Averaging data from five locations smooths the major discontinuities.

Population distributions in rural areas of western United States vary. Average data for five sites (Table 7.6) show population in only 6 of 16 sectors to a distance of 10 miles. No individuals are reported at distances of less than 1 mile. With such an irregular population distribution, standard deviations of mean population estimates are six to nine times the mean value at distances greater than 10 miles and are three to four times the mean from 10 to 55 miles from the model site. The population density around mill sites is low. Maximum estimated density is 10 individuals per square mile in the 5- to 10-mile annulus. From 1 to 5 miles, the density is 4 individuals per square mile, and only 3 individuals per square mile reside in the 10- to 35-mile annulus from the site. Although several small cities are included in the 35- to 55-mile zone, the averaged population density is only 7 individuals per square mile. Cumulative population in the area encompassed by the 55-mile radius is estimated to be 53,000 people.

7.4 Radiation Dose from Airborne Effluents from Model Uranium Mills and Tailings Piles During Operation

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 mill. The doses resulting from submersion in the airborne effluent, exposure to contaminated ground surface, and intake of radionuclides through inhalation and ingestion are calculated with computer codes[19] which use dosimetric criteria of the International Commission on Radiological Protection and other recognized authorities. Estimates of intake of radionuclides by man through terrestrial food chains are made with a model and a computer code[20] which consider 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 is being prepared as Appendix B.

Many of the basic environmental parameters used in this model are conservative, i.e., 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, i.e., the twentieth year of mill operation when releases from the tailings area are maximum and there is a 20-year accumulation of deposited radioactive materials on the ground surface outside the mill property. Doses are calculated for two extreme ingestion patterns, i.e., the case where none of the food is produced locally and the case where 100% of the food is produced at the reference location. The area around a typical western uranium mill is used for beef or sheep ranching; however, because of the arid environment, little if any vegetable crops, milk, pork, or chicken are produced locally. An individual living near a uranium mill could obtain all his meat intake from cattle grown locally, but would have to import most of his other food. Most of the dose, other than to the lung, is caused by the ingestion of radioactive materials. If vegetables and milk are not produced and consumed around the mill site, the maximum doses actually experienced for the total body and organs excluding lungs are only about 40% of the values shown for 100% ingestion. If only half the meat intake and none of the other food is produced locally, the maximum doses other than to lung are only about 20% of the values shown for 100% ingestion. The lung dose is based on inhalation of radioactive materials and is affected less by the pattern of food intake.

7.4.1 Radiation Dose from Airborne Effluents from Uranium Mill Processes

The radiation doses from the effluents from the operating mills are calculated for the mill alone, i.e., exclusive of the tailings pile, using the source terms given in Tables 4.3 and 4.5 for a mill processing a dusty, 6% moisture ore.

Dose to Total Body and Organs for Individuals. — The maximum annual total body dose and the dose to organs of individuals from airborne effluents at 0.5 mile from operating mills are shown in Tables 7.7 and 7.7c for sites in New Mexico and Wyoming, respectively, assuming that 100% of the food consumed is produced locally. Contributions of each mill process (ore or yellow cake handling) to the maximum dose to individuals are shown in Tables 7.7a and 7.7b for the New Mexico site and in Tables 7.7d and 7.7e for the Wyoming site. These dose estimates are for the mill processes only and do not include the contribution from tailings (Sect. 7.4.2). In Tables 7.8-7.8e, comparable dose data are presented based on the assumption that none (0%) of the food consumed is produced locally. Appropriate dose reduction factors* can be applied when the food production and consumption pattern is known. The average dose to the individual at 0.5 mile is 47% of the maximum dose, and the maximum dose to the individual at 1.0 mile is 18% of that given for 0.5 mile.

The total body dose, as shown in Table 7.7, decreases from 20.2 millirems in Case 1 to 2.1×10^{-4} millirem in Cases 6 and 7 for the solvent extraction plant at the New Mexico site, and decreases from 25.3 millirems in Case 1 to 3.3×10^{-4} millirem in Cases 6 and 7 for the alkaline plant, assuming that all of the food consumed is produced locally. The relative contributions of radionuclides and exposure modes to total body dose from airborne effluents are shown in Table 7.9. Internal exposure from inhalation and ingestion accounts for about 98% of the total body dose. Radionuclides which contribute less than 0.1% of the total dose are not included. Only organs receiving doses greater than those to the total body are listed in Tables 7.7-7.8e. The doses to the bone (in Case 1, 232 and 266 millirems, respectively, for the New Mexico solvent extraction and alkaline mills) are approximately six to ten times higher than for the other organs. Seventy percent of the bone dose and 85% of the total body dose come from the ingestion of ^{226}Ra in the food chain and its subsequent concentration in the bone (Tables 7.9 and 7.10).

The radiation doses summarized in Tables 7.7 through 7.8e are based on the meteorology of the first-order weather station at Albuquerque, New Mexico, or at Casper, Wyoming. The meteorology is similar at both sites, with average wind velocities of 7 mph in New Mexico and 10 mph in Wyoming; however, the frequency distribution of wind direction is different at the two sites. Simply stated, the wind blows in the same direction for longer periods in New Mexico than in Wyoming; consequently, the maximum dose occurs in that segment of the plant boundary. The 10-mph wind moves the dust out faster from the mill with less fallout from the plume than does the 7-mph wind. The net effect is that the

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*The dose due to 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 percent food produced in the area and added back to the dose from other sources (0% ingestion) to obtain the total dose.

maximum doses at the Wyoming site are about 82% of those at the New Mexico site (Tables 7.7-7.8e).

Population Dose from Mill Effluents. — The annual total body dose commitment to the cumulative population as a function of the distance from the model mill is presented in Table 7.11 for the Case 1 study. The annual dose to the total population living within 55 miles of the model mill is presented in Tables 7.7-7.9e for all of the cases studied. In all cases, the dose to the population is less than 1 man-rem. The total dose to the population is expected to be low at most uranium ore mills because the mills are located in areas of relatively low population density.

7.4.2 Radiation Dose from Airborne Effluents from Tailings Piles

Radiation exposures from tailings result from inhalation of ^{222}Rn gas, which is continuously released from these wastes and from windblown (resuspended) tailings particles which are carried off-site. Moreover, the tailings represent a source of radiation exposure from ^{222}Rn after a mill is closed. Dose due to resuspension of tailings particles can be essentially eliminated by coating the exposed tailings beaches with a chemical spray or covering with earth (Sect. 4.4). Dose due to radon release can be reduced after the mill closes by applying a radon diffusion barrier, but it is difficult to control while the mill is operating (Sect. 4.4). The radiation doses from the airborne radioactive materials from the tailings piles at the model mills are calculated based on the source terms given in Tables 4.6 through 4.9, 4.14, 4.17, 4.18, and 4.20. The areas of the pond and beach at the end of 20 years of operation are presented in Table 4.13.

Radiation Dose to Lungs from ^{222}Rn. — During operation and after closure of the mill, the maximum annual dose to the lungs from ^{222}Rn emanating from the model tailings piles at the New Mexico and Wyoming sites is presented in Table 7.12. The treatments of the tailings piles and assumptions for radiological source terms are described in Sect. 4.4. For calculation of maximum dose to lungs from ^{222}Rn, it is assumed that the ^{222}Rn gas released from tailings piles takes 3 min to reach the site boundary (0.5 mile) at the Wyoming model mill and 4 min at the New Mexico model mill site. This transport time, although brief, would allow for buildup of ^{218}Po and ^{214}Pb. At the New Mexico site, 0.597 pCi of ^{218}Po and 0.034 pCi of ^{214}Pb would be produced from the decay of each picocurie of ^{222}Rn. At the Wyoming site, 0.494 pCi of ^{218}Po and 0.021 pCi of ^{214}Pb would be produced. Thus, radiation doses to lungs of individuals exposed to ^{222}Rn at 0.5 mile from the tailings piles are the result of exposure to ^{222}Rn and its first two daughters. Average doses to the lungs at 0.5 mile are 44% of the maximum values given in Table 7.12. At 1.0 mile the maximum doses are reduced by a factor of approximately 5; at 50 miles they are reduced about three orders of magnitude. In Case 1, the doses range from 7 to 68 millirems per year at 0.5 mile for the active tailings area near the end of the 20-year life of the mill when tailings cover the maximum area. While the mill is active, part (and sometimes all) of the tailings are either wet or are incorporated in cement or asphalt so that there is a radon diffusion barrier over at least part of the tailings. The maximum radon dose averaged over the 20-year life of the mill will be lower in Cases 1 to 4 and 7 than the values in Table 7.12. This is because the tailings beach, which is the principal radon source, increases in size over the life of the mill (Sect. 4.4.2.1). Variations in the size of the tailings beach (which result from differences in the mill processes and natural evaporation rates at the sites) cause wide variations in the radon doses. These variations and their effect on the source terms are discussed in Sects. 4.4.2 and 4.4.3.1. The annual doses increase in Cases 1 and 2 after the mill is shutdown because the radon diffusion barrier, i.e., the pond, evaporates. In Case 1, the maximum annual dose at 0.5 mile is 59 millirems in Wyoming and 100 millirems in New Mexico after the mill has been shut down and the tailings covered with 6 in. of earth (Table 7.12). In Cases 3, 4, and 7, the annual dose at 0.5 mile during the interim period following mill closure and before the radon diffusion barrier is applied will also be about 59 millirems in Wyoming and 100 millirems in New Mexico. A cover of 20 ft of earth reduces the annual dose from ^{222}Rn to about 2.5 millirems for the New Mexico mill and 1.5 millirems for the Wyoming mill (Table 7.12, Case 4).

Radiation Dose from Resuspended Airborne Tailings During Operation of the Mill. — The maximum doses to individuals and organs of individuals at 0.5 mile from model tailings areas are estimated for both sites and both processes for cases where all food is grown locally (Table 7.13) and for cases where no food is grown locally (Table 7.13a). Only particles 10 μ or less in diameter are considered in estimating inhalation doses, since larger particles are not considered to be in the respirable range. All particle sizes are considered in making estimates of doses from submersion in air, contaminated ground, and food ingestion. In Case 1, the annual maximum total body doses from the active tailings area vary from about 16 to 82 millirems at 0.5 mile when it is assumed that 100% of the food is grown and consumed locally (Table 7.13). As in the case of estimating the dose from the particulate effluents of the operating mill (Sect. 7.4.1 and Table 7.9), the dose to the bone is ten times higher than to the other organs. The estimated annual bone doses range from 168 to 841 millirems at 0.5 mile in Case 1. A wide variation in the dose from resuspended tailings occurs for both the active tailings area (Table 7.13) and for the interim period following mill shutdown before the final cover is laid (Table 4.17). This is the result of the character of the source terms, which are a complex function of the cube of the windspeed, the area of exposed tailings (process and climate variable), and the radionuclide concentration in the slime fraction of the tailings (process variable). These effects are discussed under source terms, Sect. 4.4.2 and 4.4.3.1. In Cases 2 to 6, the tailings beach is covered or otherwise treated to eliminate tailings resuspension while the mill is operating. In all cases after the mill closes, the tailings are covered with earth to prevent wind transport of tailings dust, although radon gas will still emanate from the pile. In Cases 1 to 4 and 7, there is an interim period of 1 to 3 years following mill shutdown before the final cover can be applied. Total body doses of 26 to 92 millirems per year and bone doses of 273 to 933 millirems per year are estimated for Case 1 during the brief (1 to 3 years) interim period following mill shutdown before the final cover is applied (Table 4.17). In Cases 2 to 4 and 7 total body doses of 2 to 37 millirems and bone doses of 21 to 373 millirems are estimated for the interim period.

The percent of total body dose from resuspended airborne tailings as a function of exposure mode is listed in Table 7.14. Ninety-eight percent of the total body doses are the result of ingestion of food containing radioactive materials, with ^{226}Ra contributing the major dose. The conservative aspects of these estimates, which result in maximizing the estimated doses, are discussed in Sects. 7.4 and 7.4.1. Regardless of the conservative assumptions, however, mill tailings are an important source of the total radiation dose to man for a given mill during mill operation and during the interim period following mill closure before the final cover is applied. Covering or otherwise stabilizing the tailings serves to prevent resuspension of tailings particles and decreases the maximum and average dose to individuals living close to the tailings pile.

The dose calculations are based on the resuspension of tailings by average wind velocities of 7 mph for New Mexico and 10 mph for Wyoming using the resuspension model described in Sect. 7.2. The amount of tailings resuspended are then apportioned according to the directional frequencies of the winds characteristic of the meteorology of the two sites. Since the rate of resuspension of tailings increases with windspeed by a power function, about ten times more tailings are resuspended for a given area of tailings with a 10-mph wind than with a 7-mph wind. Resuspension of tailings may be greater than that estimated using the annual average wind speeds. A 30-mph wind (i.e., a dust storm) blowing for one day, for example, resuspends about 300 times more tailings than a 10-mph wind and about 4000 times more than a 7-mph wind (Sect. 7.2). In terms of radiation dose, however, a single 30-mph wind does not add greatly to the annual radiation doses calculated for average windspeeds. For the New Mexico mill (solvent extraction process), a 30-mph wind would resuspend tailings particles such that a concentration of 1.37×10^{-3} g/m^3 would be in the air at 0.5 mile from the tailings area. Exposure to this concentration for 1 day (breathing) and deposition for 1 day, with subsequent incorporation into the food chain and exposure to individuals from contaminated ground, would add 2.6 millirems per year to the annual total body dose from mill effluents of 36.8 millirems calculated for Case 1 on the basis of the average wind velocity (Table 7.15).

7.4.3 Total Radiation Dose from the Combined Operating Model Mills and Tailings Piles

Maximum radiation dose to individuals and organs of individuals from all operating mill sources are summarized for Case 1 in Tables 7.15 and 7.16 for the New Mexico and Wyoming sites, respectively. The total dose to the lungs during operation of the mill and tailings areas is presented in Table 7.17 for all cases. These doses are the sum of the doses presented in Tables 7.7 or 7.7c, 7.12, and 7.13 or 7.13a and represent the total doses received during the 20th year of operation when the tailings area has reached the maximum size. In Cases 2 to 7, no resuspension of tailings occurs; consequently, the total dose in these cases is the sum of the doses from the airborne mill effluents (Table 7.7 or 7.7c) and the radon from the tailings area (Table 7.12). The contribution of radon to the total body dose and doses to organs other than the lung is negligible. Thus, the doses listed in Tables 7.7 and 7.7c for the mill effluents for total body and organs (other than the lung) are also the total maximum doses for the complete mill installation in Cases 2 to 7. The population doses for total body and organs exposed to both mill and tailings airborne effluents at the Case 1 model mills are presented in Table 7.18.

7.4.4 Radiation Dose to Biota Other than Man

The estimated maximum doses to man (total body) in Case 1 range from 37 to 102 millirems/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, also would be subjected to exposures via immersion in air, contaminated ground, and inhalation. These animals would receive additional exposure via their particular food chains.

Although the model mills do not have a liquid radioactive release, it would be possible for aquatic organisms to receive small doses of radiation from process dusts or tailings that might be deposited from the atmosphere into their habitats. These deposits, depending on the surface area of a particular aquatic habitat, would be small and subsequent dilution in the volume of receiving water would reduce concentrations available to aquatic biota. Doses to aquatic organisms from atmospheric deposits would be only several percent of the doses estimated for terrestrial organisms.

7.5 Radiation Dose from Long-Lived Radionuclides After the Mill Is Closed

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 mill 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.[21]

7.5.1 Source Term

The model mill (Case 1) releases radon gas, dusts from the mill, and airborne tailings during 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 from 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 long after the plant has ceased operations. The total quantities of radionuclides released in Case 1 from the model alkaline leach mill sited in Wyoming are listed in Table 7.19. This is the worst case (i.e., the highest release) studied. The longest-lived radionuclides (^{234}U, ^{238}U, ^{226}Ra, and ^{230}Th) will remain in the environment for generations.

The distribution of these radionuclides around the mill 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 50-mile radius of the mill. This follows from consideration of the meteorology at the model plants and from the use of a settling rate for particles of 1 $cm \cdot sec^{-1}$ from a source which is released at ground level. The same assumptions are used in estimating the dose to the population from releases from the operating mill and the tailings area. Other estimates of the deposition of these materials indicate that as much as 70% of the materials are deposited within 50 miles, even though the release point is the top of a 100-m-high stack.[22]

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

In calculating the dose from ^{222}Rn gas, it is assumed that the 128-acre tailings pile with a 6-in. earth cover would release 8.4×10^3 Ci of ^{222}Rn each year after the mill is closed. The average X/Q' value for a distance of 25 miles from the mill (5.5×10^{-9} $sec \cdot m^{-3}$) is used to calculate the concentration of ^{222}Rn at that distance. This ^{222}Rn concentration is used, in turn, to estimate the annual dose to the lungs of the average individual within the 50-mile radius of the mill. It is further assumed that the ^{222}Rn is in secular equilibrium with its daughter products.

7.5.2 Pathways of Exposure

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

A resuspension factor can be estimated from measurements made above aged contaminated soil and from consideration of natural tracers such as ^{238}U. Resuspension factors of 10^{-9} and 10^{-10} m^{-1} were obtained from recent measurements of ^{239}Pu made at the Nevada Test Site in an area contaminated 17 years previously.[21] 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}.[21] Discounting airborne material of industrial origin, it appears from the data concerning movement of natural ^{238}U that a realistic estimate of the resuspension of aged radioactive material in surface soil lies between 10^{-8} and 10^{-10} m^{-1}.[21] 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 milling 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 redisposition on foliage of crops and pastures. For estimating intake via inhalation of resuspended radionuclides, the expression is:

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

Ingestion. — The radionuclides that are not inhaled by man remain in the environment for times proportional to their radiological half-lives. During this time they may be ingested by man. Plants may be contaminated by direct deposition of airborne particles onto foliar parts and by root uptake of isotopes leached from, or exchanged with, particles deposited in soil. Plant uptake studies show that uranium, radium, and thorium are strongly excluded from plant uptake and poorly translocated by plant systems. The general findings from experiments indicate that the concentration factors (ppm dried plant material/ppm 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. Several competing processes can influence the changes, including downward movement of radioactive materials in soil, which can 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 plant material accumulates a concentration, C_f, of radionuclides in the soil in which the plants grow, that there is no downward movement of the radionuclides in the soil beyond the root zone (15 cm), and that 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 2.25×10^5 g of soil. The following expression is used to estimate the intake via ingestion of plants:

$$\text{Ci yr}^{-1}\text{ ingested} = \frac{\text{Ci m}^{-2}}{2.25 \times 10^{5}\text{ g cm}^{-2}} \times C_f \times 9.12 \times 10^{4}\text{ g plant ingested yr}^{-1},$$

where 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.[20]

Contaminated Ground. — Exposure via contaminated ground is also estimated. It is assumed that there is no loss of deposited radionuclides from the soil surface except through radioactive decay.

7.5.3 Dose Estimates

The radiation dose to an individual residing within the uniformly contaminated area of 7.85×10^3 square miles is estimated for total body, bone, and lungs. No additional population assumptions are made, and population doses are expressed as man-rems per 53,000 persons. All radiation doses from ingestion and inhalation are 50-year dose commitments from 1 year of exposure, i.e., the dose an individual will accrue over a 50-year period from 1 year of intake of radionuclides. External doses (exposure to contaminated ground) are annual doses from 1 year of exposure. It is conservative to call a dose commitment an annual dose in the case of a single year's intake of long-lived radionuclides. However, for assessing a situation where people are continually exposed over long periods of time and radionuclides have reached steady-state conditions in the environment, dose commitments may approximate annual doses.

Individual and Organ Doses. — As a result of the deposition of long-lived radionuclides, persons living within a 50-mile radius of the model mill 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 50-mile radius of the mill for the various radionuclides and exposure modes are shown in Table 7.20. Forty-nine percent of the total body dose of 1.4×10^{-3} millirem results from exposure to contaminated ground and 48% from the ingestion of radioactive materials. Forty-nine percent of the total body dose is from ^{226}Ra, and 45% is from ^{238}U and ^{234}U. The actual dose to any one individual will vary as a function of distance from the mill. For example, during operation, the total body dose to an individual from ^{226}Ra at a distance of 1 mile is about 1100 times higher than the dose to an individual at 50 miles. The average doses per year of exposure to the organs resulting from the various radionuclides and for the major internal pathways are shown in Table 7.21. The lung receives the highest organ dose (0.34 millirem) which is about 50 times the dose to the bone (6.7×10^{-3} millirem) (Table 7.21).

Population Doses. — The annual population total body dose is 7.4×10^{-2} man-rem per 53,000 persons after the mill closes and until there is significant decay of the long-lived radionuclides (Table 7.22). The annual dose to the population (total body and organs) is again primarily due to ^{226}Ra, ^{238}U, and ^{234}U, with ^{226}Ra contributing 48% and the uranium isotopes 45% of the total. The lung receives the highest organ dose, 18 man-rems per year per 53,000 persons.

7.6 Movement of Radioactive Materials in Underground Seepage from Tailings Ponds

Radioactive materials can be transported by water. As a requirement for licensing, suitable precautions must be taken to prevent the release of radioactive materials to surface streams (Sects. 9.5.2, 9.5.3, and 9.6.2). Therefore, these case studies deal only with the underground seepage from the tailings pond. Estimation of the amount of radioactive materials which seep, and of the distances that these materials move through the earth in both vertical and horizontal directions, is difficult in a generic study because of the lack of data and the diverse geology of the various tailings sites. Core drillings and analyses of core samples have not been made underneath tailings piles or evaporation ponds to determine the actual rate of movement of radioactive materials. However, monitoring wells are placed around tailings areas to detect the horizontal movement of radioactive materials. Available data indicate that no detectable horizontal underground movement of radioactive materials beyond the plant boundary has occurred from tailings ponds sited by current licensing standards (Sect. 9.5.2); i.e., the amount of radioactive materials found in a given monitoring well remains constant over a period of years. Consequently, it is assumed in this survey of model plants that, even in Case 1, no detectable amounts of radioactive materials are released to the environment beyond the plant boundaries in either surface or underground waters during plant operation or for any foreseeable period thereafter. The advanced cases provide treatment to reduce the already low seepage rate (Table 4.15), and to lower the leachability of the solid waste (Table 4.16), in the improbable event that a major climatic change occurs from an arid to a wet environment.

A limited theoretical analysis of the transport of radioactive materials in ground water is presented. This supports the conclusion that radioactive materials which seep from the bottom of the tailings pond do not pass beyond the plant boundaries in detectable amounts. The analysis is necessarily limited because of the small amount of data available.

A typical cross section showing a small seepage pond and its relationship to a surface stream is shown in Fig. 7.4, top. In Case 1, water seeps from the pond into the sandy soil below at a steady-state rate of 4.0×10^{-7} cm/sec. This flow rate is very low due to clogging of the pond bottom by the fine sediment contained in the mill tailings. The magnitude of the flux is selected to result in a 10% loss of soluble radionuclides from the pond by seepage and is greater than any rate reported for an existing pond. Two computer codes are used to analyze the transport of radionuclides into the sandy soil below the pond. The first code[23] provides a numerical solution to the equation that governs the flow of water through the medium. The velocity output from the first code is then used in the second code,[24] which provides a numerical solution to the equation which describes the transport of the radioactive ions. The medium below the clogged bottom is assumed to be an unconsolidated sand that has an intrinsic permeability of 5.6×10^{-8} cm^2 and a porosity of 30%. To simplify the calculations, steady-state fluid velocities in the medium below the pond (i.e., water-saturated soil) were used in the solution of the transport equation (Fig. 7.4, bottom).* All the above assumptions maximize the transport of radioactive materials. Radium[25] has a distribution coefficient, k_d, of 100, while ^{234}U, ^{238}U, ^{230}Th, and ^{210}Pb have distribution coefficients greater than 1000. The distribution coefficient is defined as the equilibrium concentration of a radionuclide adsorbed on the sand divided by the concentration in the water, i.e., Ci ^{226}Ra/g of sand divided by the Ci ^{226}Ra/ml of water.

The solution of the transport equation for the movement of ^{226}Ra from the pond in 5- and 20-year periods using a k_d of 100 is shown in Fig. 7.5. The two concentration contours represent the positions where the concentration of ^{226}Ra in the water is 10 and 50% of that in the seepage pond. The 10% contour is only about 3 m (10 ft) below the bottom of the pond after 20 years. These results indicate that no detectable amount of ^{226}Ra reaches the stream in the 20-year lifetime of the plant. Figure 7.6 shows the movement of radionuclides from the seepage pond toward the stream when the k_d is 1000. The 10% contour for a k_d of 1000 is only about 2 m (6 ft) below the bottom of the pond. Thus, radionuclides, such as ^{230}Th, ^{234}U, ^{235}U, ^{238}U, and ^{210}Pb, which have distribution coefficients greater than 1000,do not reach the stream in detectable concentrations during the 20-year lifetime of the plant.

After the mill has been closed, no water other than precipitation enters the pond. In the arid regions, where most mills are located, the evaporation rate exceeds the rate of precipitation. The tailings pond evaporates, and there is very little net flow of water. Additional movement of the radionuclides, which are adsorbed on the sands under the seepage pond, becomes extremely slow in the absence of a flow of water. Thus, it is assumed that the additional movement of radioactive materials after mill shutdown is nearly zero in the absence of climatic changes that might raise the water table.

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*Calculated penetration of seepage liquid into dry soil of 30% porosity is about 28 ft in 20 years, assuming no ground water present or capillary action.

The solution of these problems was obtained by numerical solution of the governing partial differential equations for a specific set of boundary conditions and coefficients. Because of the complexity of groundwater problems, the results obtained apply only to the problems presented. Thus, the rate of movement of radioactive materials estimated for these specific conditions may not be applied in other problems.

7.7 References

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8.0 CORRELATION OF RADIOLOGICAL DOSE WITH COST OF WASTE TREATMENT

The relationships between the impact of radioactive releases (dose commitment) presented in Section 7 and the annual costs of the radwaste treatment systems described in Sections 4 and 6 are discussed in this section. The accuracy of the cost estimates is about ±30%. Uranium mills are located in arid regions where agricultural use of the surrounding land is limited. Therefore, dose commitments to the individual are presented for the two extremes of food consumption, i.e., where none (0%) or all (100%) of the food that is consumed by an individual is grown at the reference location where the individual lives. The actual doses for a specific mill location, where the food consumption pattern is known, can be estimated from these values by applying appropriate factors. Doses, other than to the lung, are approximately a factor of 10 lower than the maximum doses if none of the food consumed is produced at the reference location, or approximately a factor of 5 lower if half of the meat but none of the other food is produced locally. Some of the advanced treatment systems are in an early stage of development and their technical feasibility has not been verified in a plant installation. Models for the movement and concentration of radionuclides in the environment are receiving additional study to increase their accuracy. Internal mill flowsheets are based on actual operating experience of mills today. The ore composition selected is the average processed by the industry over the past five years. The mill processes a dry, 6% moisture ore which yields a relatively large amount of dust and a relatively high dose to the surrounding population. Factors are provided in Table 4.4 which can be used to estimate the dose when ores with a higher moisture content are used (wetter ores produce less dust). In the base case, estimates of the release of radioactive wastes (the source terms) are realistic for airborne releases from the tailings area, and conservative (i.e., maximum) for airborne releases from the mill, seepage losses, and leach rates. In all cases, conservative assumptions (i.e., those that maximize dose or cost) are made in selecting treatment efficiency ratings for equipment, in estimating costs, in defining the movement of radionuclides in the environment, and in selecting food and liquid consumption patterns.

Cost-benefit correlations are presented in the following sections for an acid leach—solvent extraction and an alkaline-leach uranium mill sited in New Mexico and in Wyoming for three time periods: (1) the period while the mill is operating, (2) the interim period following mill closure while the tailings dry and before they are stabilized, and (3) the period after final stabilization of the tailings. The annual costs of treatment systems which would reduce the amount of radioactive materials released in airborne effluents are correlated with the doses to individuals and to the population out to a distance of 55 miles. The dose to the surrounding population is not estimated for the release of radioactive seepage or the potential release of leach waters because of the lack of the detailed information required to calculate the underground movement of liquids and dissolved solids and because of the diversity of the sites to be considered. This corresponds to the current state of knowledge where there is no evidence of underground movement of radioactive materials beyond the plant boundary from tailings areas sited in the semi-arid western states by current standards (Sect. 9.5.2) and little movement is predicted in a sample calculation (Sect. 7.6). Liquids or solids are not released directly to surface streams at operating mills (Sects. 9.5.2) and none is released in the case studies. However, selected amounts of radioactive materials are released through the bottom of the tailings area in seepage in the case studies and these amounts along with the amounts of radioactive materials that, potentially, could be released in leach waters, rather than dose to the population, are correlated with the annual costs of treatment systems which would reduce the amount of radioactive materials released in seepage or potentially in leach waters. These treatments provide additional safety in the storage of the wastes and are effective in reducing potential doses. The leach rate has application in defining the potential movement of radioactive materials in water (1) at sites with high rainfall; (2) in wet storage areas, such as spent mines; and (3) at sites where geologic or meteorologic changes may occur, which could form a fissure under the tailings pile or cause the water table to rise into the tailings, although these considerations are not variables in this study.

Cost-benefit comparisons are presented first in summary form for the combined waste treatment packages for each case (Sect. 8.1), and then separately for the major components (Sects. 8.2 to 8.7). The gross comparisons of Sect. 8.1 mask many features including the relative cost-benefit of alternative procedures. It is difficult to make broad generalizations. In essence, the study deals with four different model uranium mills, because the natural evaporation rate and the wind speed at the sites are variables which affect the amount of radioactive materials released from the tailings area and the cost of waste treatment. Consequently, the solvent extraction mill sited in Wyoming has a different impact than the solvent extraction mill sited in New Mexico even though the same internal mill process is used at both sites.

8.1 Airborne and Liquid Effluents from Mill and Tailings Area During Mill Operation and After Mill Closure

The total annual costs for reduction of the radiological dose to the population surrounding the model mills during mill operation and after mill closure are summarized for Cases 1 to 7 in Table 8.1 and Fig. 8.1 for the model acid leach--solvent extraction mill at New Mexico and in Fig. 8.2 for the alkaline-leach mill at New Mexico. Similar summaries for the Wyoming site are presented in Table 8.2 and Figs. 8.3 and 8.4. The total annual costs include all costs for treatment of airborne and liquid effluents from the mill and tailings area during mill operation and after mill closure and include the amounts required to reduce the release of radioactive materials in seepage or potentially in leach waters, even though the liquid releases do not contribute to the calculated dose. These annual costs vary from about $175,000 in Case 1 to nearly $10,000,000 in Case 6c.

The maximum annual individual doses are shown in Tables 8.1 and 8.2 for whole body and organs at a distance of 0.5 mile from the operating model mills and their associated tailings impoundments near the end of the 20-year life of the mills when the tailings cover the maximum area. The doses for whole body and bone drop from Case 1 to Case 2. For example, near an operating New Mexico solvent extraction mill, the doses to an individual assuming that 100% of the food is produced locally drop from about 37 mrem for total body and 400 mrem for bone in Case 1 to about 6 and 73 mrem, respectively, in Case 2 at a total annual cost increment of $27,000. About 45% of this dose reduction is the result of covering the tailings beach to prevent wind resuspension of tailings at an annual cost of $7,000 (Sect. 8.3). At the Wyoming solvent extraction mill the 100% food ingestion dose drops from 61 mrem for total body and 640 mrem for bone in Case 1, to 5 and 59 mrem, respectively, in Case 2 at a total annual cost increment of $26,000. At the Wyoming alkaline-leach mill the 100% food ingestion dose drops from 102 mrem for total body and 1057 mrem for bone in Case 1, to 6 and 66 mrem, respectively, in Case 2 at a total annual cost increment of $25,000. If no food is produced near the mill, the doses drop from about 2 mrem in Case 1 to 0.4 mrem in Case 2 for total body and from about 60 to 10 mrem for bone. Case 1 is the only case in which tailings dust becomes airborne from an exposed beach during operation of the mill. In subsequent cases, the tailings beach is coated with a chemical spray to prevent resuspension of the tailings by the wind. Consequently, in Cases 2 to 7, radon is the only radioactive material that is released from the tailings area. The decrease in the total body and bone dose in Cases 2 to 7 is the result of the improved dust removal systems applied to the gaseous effluent from the mill. The mill dusts contain ^{226}Ra which is a major contributor to total body and bone dose.

After the mill is closed, the tailings pile is stabilized to prevent the movement of airborne tailings particles and to decrease the emanation rate of radon. Thus, radon is the only radioactive material released from the tailings pile after mill closure (with the exception of the interim period, Sect. 8.4). The radon lung dose from the stabilized tailings area after the mill is closed is higher in Cases 1 and 2 than the radon lung dose from the combined mill and tailings area during operation of the mill because the radon is attenuated by the pond water which covers a fraction of the tailings during operation of the mill. In later cases, the stabilization treatment lowers the radon dose. Overall, the radon dose from the stabilized tailings pile in New Mexico decreases from 100 mrem in Case 1 to 2×10^{-3} mrem in Case 7 and the total annual costs increase from $175,000 for Case 1 to nearly $10,000,000 for Case 6. In addition to the lung dose from the radon, which is continuously released from the tailings after the mill closes, there is also a long-term dose from the long-lived radioactive materials which were dispersed while the mill was operating. The long-term total body dose to an average individual living within 50 miles is 1.4×10^{-3} mrem/yr and the bone dose is 7.6×10^{-3} mrem/yr at the model mill that released the greatest amount of radioactive materials (Sect. 7.5). Since these doses are small compared to the background dose, no cost correlations are made for the long-term period for the dose received from the particulates dispersed by the operating mill and the active tailings area.

In Sections 8.2 to 8.7, the total costs are separated into costs for reduction in release of airborne radioactive materials, and costs for treatment of liquid wastes to reduce the amount of radioactive materials released in seepage or potentially in leach waters and these costs are compared with the maximum dose to the individual or the amounts of materials released in seepage water. While the mill is operating, the total whole body dose to the population out to a distance of 55 miles is 1 to 3 man-rem in Case 1 and less than 0.2 man-rem in Cases 2 to 7 (Tables 8.1 and 8.2). After the mill is closed and tailings have been stabilized, the total annual whole body dose to the population out to 50 miles is less than 0.01 man-rem in Case 1. Therefore, no cost correlations are made with the population dose.

8.2 Airborne Effluents from the Operating Mill Excluding the Tailings Area

The radiological doses and annual costs for the treatment of airborne effluents from the mill process buildings (excluding the tailings area) are presented in Tables 4.3 and 4.5 and Fig. 8.5. The radioactive materials in this effluent consist of radon, ore dusts, and uranium concentrate (yellow cake) dusts. The annual costs are those for the treatment of the mill effluent, exclusive of the tailings area, and are the same for both types of mill at both sites. The waste treatment case studies illustrate an increasing efficiency for dust removal for

Cases 1 through 6. The treatment system in Case 7 includes a bed of charcoal which retains the radon and allows it to decay to very low levels before release (Sect. 4.3.1.4). The doses for the New Mexico model mills are presented in Tables 4.3-4.5 and 7.7-7.7b and in Fig. 8.5 assuming that 100% of the food is produced locally, and in Tables 7.8-7.8b assuming no (0%) local food production. The doses for the Wyoming model mills (Tables 7.7c-7.7e and 7.8c-7.8e) are 81% of the New Mexico doses because of differences in the wind velocity and frequency distribution (Sect. 7.1).

The maximum annual whole body dose (100% food ingestion) at 0.5 mile distance from the mill decreases exponently with increased treatment cost from about 20 mrem in Case 1 at an annual cost of $43,000 to 0.3 mrem in Case 6 where the annual cost is $265,000 (Tables 4.3 and 4.5 and Fig. 8.5). This corresponds to an incremental cost-benefit ratio of about $11,000/mrem reduction in total body dose. No further reduction of total body dose is obtained by the large increase in cost to $1,432,000 in Case 7 where the relatively expensive charcoal bed is used to decrease the release of radon. Radon contributes only a minor fraction to the total body dose, and hence the removal of radon in Case 7 has a negligible effect on the total body dose. The major fraction (85%) of total body dose (100% food ingestion) is contributed by ^{226}Ra (Table 7.9) which is contained in the ore dust. Thus, the decrease in total body dose is primarily a function of the efficiency of the removal of the ore dusts from mill effluents. If no food is produced locally, the total body dose decreases from about 2 mrem in Case 1 to 3×10^{-6} mrem in Case 6 (Tables 7.8 and 7.8c), and the incremental cost-benefit ratio is about $110,000/mrem reduction.

The bone dose changes with treatment cost in the same manner as the total body dose (Tables 4.3 and 4.5, Fig. 8.5) because it is also mainly dependent on the amount of ^{226}Ra in the effluent (Table 7.10). The maximum annual bone dose (100% food ingestion) at 0.5 mile distance from the mill decreases from roughly 200 mrem for Case 1 to 3×10^{-3} mrem for Case 6 as the annual cost increases from $43,000 to $265,000. If no food is produced locally, the bone dose decreases from about 40 mrem in Case 1 to less than 0.001 mrem in Case 6 (Tables 7.8 and 7.8c).

The lung dose is contributed predominately by ^{226}Ra and U_{nat} (Table 7.10). Therefore, the lung dose is a function of the efficiency for removal of ore dusts (U_{nat}, ^{226}Ra) and yellow cake dusts (U_{nat}) from the airborne mill effluents. The maximum annual lung dose at 0.5-mile distance from the mill decreases sharply from about 30 mrem for Case 1 at an annual cost of $43,000 to 2 mrem for Case 3 at an annual cost of $84,000 (Tables 4.3 and 4.5, Fig. 8.5). An inflection in the curve occurs between Cases 3 and 4 showing a lower rate of decrease of dose with increase in annual cost for Cases 4 to 7. In Case 7, where radon is removed by the charcoal bed, the lung dose is less than 0.01 mrem and the annual cost is $1,432,000. Although the charcoal bed is effective in reducing the lung dose from mill sources, the use of a charcoal bed does not seem justified because the lung dose from the active tailings area in Case 7 is 10 to 100 times higher than the lung dose from the mill effluents without the charcoal trap in Cases 5 and 6 (Table 7.17, Sect. 8.3).

8.3 Airborne Effluent from the Tailings Area During Operation of the Mill

During operation of the mill, the liquid and solid ore tailings are pumped as a slurry to a tailings impoundment area. A beach of variable area forms which becomes a source of airborne radioactive particulates. In the model plants, the maximum area of beach is formed near the end of the 20-year life of the mill. A dry beach exists in Case 1, ranging in area from 12 acres for a solvent extraction mill in Wyoming to 78 acres for an alkaline-leach mill in New Mexico (Table 4.17). In subsequent cases (2, 3, 4, 7), the beach is coated with a chemical spray to prevent the resuspension of tailings dust by the wind. This reduces the airborne release of tailings dust (containing ^{226}Ra) to nearly zero and causes a sharp decrease in total body and bone dose between Cases 1 and 2. Radium-226 is the major contributor to these doses. The maximum annual doses to individuals and organs of individuals at a distance of 0.5 mile from the tailings pile for Case 1 are shown in Table 7.13 for 100% food ingestion and Table 7.13a for 0% food ingestion. The total body dose (100% food ingestion) from the tailings area is 44 mrem for the acid leach--solvent extraction mill and 82 mrem for the alkaline leach mill in Wyoming and 16 mrem for the New Mexico mills. The bone doses vary from 166 to 842 mrem for the mills at the two sites. The maximum annual cost for the temporary cover in Cases 2, 3, 4, and 7 is $9,000 (Table 4.17). The incremental cost-benefit ratio between Cases 1 and 2 varies from $73 to $562/mrem reduction in total body dose. Temporary cover is not required for Cases 5 and 6 where the tailings are incorporated in either cement or asphalt and hence are not susceptible to resuspension by the wind. If no food is produced locally, the total body doses range from 0.3 to 2 mrem in Case 1 and the bone doses from 7 to 62 mrem (Table 7.13a).

The maximum annual individual dose to the lung at a distance of 0.5 mile from the tailings area is a function of the rate of emanation of radon which generally occurs at two levels, i.e., high for Cases 1, 2, 3, 4, and 7, where the tailings are bare or covered with only 6 inches of earth, or low for Cases 5 and 6 where the tailings are incorporated in cement or asphalt which act as barriers to the diffusion of radon. The variation of lung dose is the result of the variation of area of dry beach for the two sites and two types of mills (Table 4.20). Diffusion of radon occurs more readily from dry tailings than from wet tailings and, consequently, the lung doses from tailings during mill operations are about five times higher at the New Mexico site (large dry beach area) than at the Wyoming site for the corresponding Cases (1, 2, 3, 4, and 7) (Table 7.12). For these same reasons, a greater reduction in dose is achieved at the New Mexico site when the tailings are incorporated in cement or asphalt (Cases 5 and 6) than at the Wyoming site. For example, the radon dose to lungs at the alkaline-leach mill in New Mexico is reduced from 53 mrem in Case 4a to 4 mrem in Case 5 (incorporation in cement) compared to the alkaline-leach mill in Wyoming where the dose is reduced from 7 mrem in Case 4a to 2 mrem in Case 5. The annual cost for incorporating all tailings in cement in Case 5 is $1,747,000 (Table 4.18). This corresponds to an incremental cost-benefit ratio of about $35,000/mrem reduction in lung dose for the alkaline-leach mill in New Mexico. Incorporation of the tailing slimes in asphalt (Case 6b) is less effective in reducing the radon emission and is 3 times as costly. The radon dose is primarily due to inhalation and is independent of the food ingestion pattern.

8.4 Airborne Effluent from the Tailings Area During the Interim Drying Period

After the mill is closed, a 2- to 3-year interim period ensues wherein the tailings dry out sufficiently to permit the use of earth-moving equipment for application of the final stabilization cover. An interim period does not occur in Cases 5 and 6 because the tailings are incorporated in either cement or asphalt during operation of the mill. In the other cases (1, 2, 3, 4, and 7), surveillance is maintained and the chemical spray or a cover of earth or mine waste is applied in increments as the tailings dry out, so that in Case 1 the area susceptible to particle resuspension by the wind does not exceed 25 acres at the Wyoming site and in Cases 2, 3, 4, and 7 it does not exceed 10 acres at either site. Interim treatment is not applied at the New Mexico site in Case 1 because the doses produced by the uncovered, dry tailings piles at the mills in New Mexico (128 acres), which are subject to wind erosion, are lower than for the tailings piles in Wyoming (25 acres uncovered) which receive interim treatment. This is the result of the higher wind velocity in Wyoming. For example, the maximum doses (100% food ingestion) at 0.5 mile from the interim treated tailings area at the acid leach--solvent extraction mill in Wyoming are 92 mrem for total body and 933 mrem for bone compared to 44 mrem for total body and 448 for bone from the untreated tailings area in New Mexico (Table 4.17). Interim treatment is applied in New Mexico in Cases 2, 3, 4, and 7. Doses are approximately a factor of 10 lower if no food is produced locally.

Interim treatment is especially beneficial for the large tailings area (157 acres) present at the acid leach--solvent extraction mill at Wyoming. The maximum annual individual total body dose (100% food ingestion) at 0.5 mile downwind would be 580 mrem, if the entire area were allowed to dry and become a source of dust and radon. The annual cost of the chemical spray for interim treatment amortized over the 20-year life of the mill is $2000 in Case 1, when the equipment is used only for interim treatment, and $1000 in Cases 2, 3, 4, and 7 where the equipment is also used to coat the beaches while the mill is operating.

8.5 Airborne Effluent from the Tailings Area After Final Stabilization

The tailings pile which remains after the mill is closed contains a large amount of hazardous radioactive materials. The release of these materials is reduced by siting the tailings area above the water table, by providing protection from surface waters, and by covering the tailings with earth and rock and in some cases by incorporating the tailings in cement or asphalt. Since the tailings are covered (stabilized) in all cases, resuspension of tailings dust does not occur. Consequently, only one radioactive material, radon gas (^{222}Rn), is released as an airborne effluent. The ^{222}Rn is the daughter of ^{226}Ra which has a half-life of 1,620 years and, thus, ^{222}Rn will be released for thousands of years. The amount of radon released is decreased by placing a diffusion barrier over the tailings.

The annual cost of the earth and/or asphalt cover which is applied to reduce the maximum annual individual dose to the lung (the only organ which receives a significant dose from ^{222}Rn) is shown in Table 4.18 and Fig. 8.6 for model mills in New Mexico and Fig. 8.7 for model mills in Wyoming. The annual costs include the costs for the final cover and the incorporation of tailings in cement or asphalt. The construction of the tailings basin, the asphalt membrane liner, and the dam are not included since their purpose is to impound liquid waste (Table 4.18). The lung dose decreases exponentially with the increase in annual cost of the earth cover. A dose of 100 mrem in Case 1 is reduced to 2 mrem for Case 4a and 4b with an increase in annual cost of $22,000 at the New Mexico site. This is equivalent to an incremental cost-benefit ratio of about $224/mrem reduction in lung dose. Comparison of Cases 4a and 4b shows that a 5/16-in. asphalt membrane with 2 ft of earth cover is equal in cost and reduction in dose to 20 ft of earth. Increasing the asphalt membrane thickness to 1 in. in Case 7 reduces the dose an additional three orders of magnitude to less than 0.01 mrem at an additional annual cost of $43,000. A comparison of Cases 4a and 4b with Case 7 shows an incremental cost-benefit ratio of $21,000/mrem reduction in lung dose. The 2×10^{-3} mrem lung dose achieved in Case 7 is well below the dose from natural radon in areas of the country not involved in uranium mining (Sect. 4.4.3.2, Table 4.22). Comparison of the rate of release of radon at the surface of the unstabilized tailings pile with the very limited data available on native soils indicates that the release from the tailings pile must be reduced 500-fold to be comparable to native soil. This reduction corresponds to a lung dose of about 1 mrem and occurs between Cases 4 and 7 in Figs. 8.6 and 8.7. The doses and costs of cover for tailings piles are higher for the acid leach--solvent extraction mill in Wyoming because of the larger tailings area, i.e., 174 acres in Wyoming vs 116 acres in New Mexico (plus the tailings in the face of the dam in Cases 1 and 2). The lung doses for Case 5, in which all of the tailings are incorporated in cement and then covered with 20 ft of earth, are about 1/30 of the dose for Case 4a in which untreated tailings are covered with 20 ft of earth. This decrease in lung dose by a factor of 30 is achieved at an increase in annual cost by a factor of 60, i.e., the annual cost is about $1,700,000 in Case 5 compared with $27,000 for Case 4a at the New Mexico site. Incorporation of the slimes in either cement (Case 6a) or asphalt (Case 6b) is less effective than incorporation of all of the tailings in cement (Case 5) for reducing the lung dose and the annual cost of incorporation in asphalt (Case 6b) is higher, i.e., $6,300,000. The major fraction of the cost for incorporation of the tailings in cement or asphalt should not be assessed to the reduction in radon emission and lung dose, since the principal objective in incorporating tailings in cement or asphalt is to immobilize the tailings and to reduce the leach rate of radioactive materials from the tailings in case large amounts of water should unexpectedly contact the tailings (Sect. 8.7).

8.6 Release of Soluble Radioactive Materials in Seepage Water

Liquid wastes from the model mills are evaporated in ponds of sufficient area for natural evaporation, or as in Case 6, in metal evaporators. The residue from evaporation remains with the solid tailings from the mill. During operation of the mill and until the tailings pile becomes dry, seepage of liquid containing radioactive material from the pond to the soil under the tailings pile occurs. The loss of soluble material is

10% in Cases 1 and 2, 2% in Case 3, 0.1% in Cases 4, 5, and 7, and none in Cases 6a and 6b. The migration of soluble salts in soils is a complex process and is dependent on the properties of the soil, such as permeability and ion exchange capacity. The detailed information required to estimate the underground movement of seepage water and the dissolved radioactive materials is not available and, consequently, the dose to the surrounding population is not estimated. Available data indicate that no detectable underground horizontal movement of radioactive materials has occurred from tailings areas sited by current standards. Little movement is predicted in a sample calculation where the model tailings pond was sited on homogeneous soil with the properties of porous sand (Sect. 7.6).

The efficiency of the treatment methods in preventing the release of radioactive materials in seepage water is used as a parameter for comparison with annual costs, since these releases represent potential doses to the population surrounding a mill. For example, an impact on the population could occur if the earth under the tailings areas contains (or should develop at a later time) geologic faults or other formations, such as a fissure, which would permit the rapid movement of water and radioactive materials beyond the boundary of the mill.

The annual cost for treatments to reduce the amount of radioactive materials released from the tailings pond in seepage water are presented in Figs. 8.8 and 8.9 and Table 4.15. These costs include the costs for physical and chemical treatment of the wastes, the asphalt membrane liner for the tailings area, and the construction of the tailings basin and dam. The costs for the earth cover to stabilize the tailings and for incorporation in cement or asphalt are excluded because their principal purpose is to minimize the release of airborne radioactive materials and to decrease the long-term leach rate of the tailings. Radium-226 is used as an example in characterizing releases in seepage, since it is the most hazardous material. In the acid leach--solvent extraction mill, the annual loss of ^{226}Ra is reduced from 5×10^{-2} Ci for Cases 1 and 2 at an annual cost of $92,000 to 5×10^{-4} Ci for Case 4 at an annual cost of $1,500,000. In Case 6, the waste liquid is evaporated in metal evaporators and the condensate is recycled to the mill thereby reducing the loss to the soil to zero at an annual cost of \$2,600,000. Similar trends in reduction of losses from alkaline leach mill waste liquids are obtained at slightly lower annual costs.

Although the benefits from the more expensive treatments appear small for the semiarid sites of the model mills, the need and benefits would be much greater at sites where some of the environmental characteristics are different, such as rainfall is high, soil has poor ion exchange properties, the water table is near the surface, or the earth under the tailings pile contains geologic faults or fissures. In practice, however, these environmental factors would be evaluated in site selection so that potential hazards will be minimized.

8.7 Leach Rate of Radioactive Materials from Tailings

Although the tailings from the model mills are carefully placed above the ground water table and protected from surface streams, leachability of radionuclides, particularly ^{226}Ra, is important if the tailings are to be used as backfill in mines (most mines are wet) or if the tailings disposal site is near the water table. In addition, the meteorologic conditions may change over a long period of time such that water might contact the tailings. Doses to the population cannot be calculated as a result of leaching and, consequently, the potential leach rate of ^{226}Ra is correlated with the treatment costs for reducing the leach rate. The annual costs for reducing the leach rate of ^{226}Ra from tailings are presented in Table 4.16 and Figs. 8.10 and 8.11. These costs include the costs for incorporation of the tailings in asphalt or cement in Cases 5 and 6 and for providing asphalt membranes in Cases 4, 5, and 7.

The potential, annual leach rate of ^{226}Ra from the tailings from the acid leach--solvent extraction mill is reduced from 2.6×10^2 Ci in Cases 1, 2, and 3, where the tailings are not treated to reduce the leach rate, to 3.1×10^{-8} Ci in Case 4b where the tailings are completely encased in a 5/16-in.-thick asphalt membrane. The annual cost for the asphalt membrane is \$254,000 in New Mexico. Incorporating the tailings in cement in Case 5 reduces the annual leach rate to 2.1 Ci for an annual cost of

\$1,919,000. Encasing the slime fraction, which contains 70% of the ^{226}Ra in the tailings in asphalt reduces the annual leach rate to 76 curies at an annual cost of \$6,338,000 (Case 6b). The total leach rate in Case 6b is higher than in Case 5 because the sands are not encased in asphalt in Case 6b and the sands are assumed to have the same leach rate for ^{226}Ra as the slimes. Removing 99% of the radionuclides by strong acid leaching and incorporation of the concentrated waste in asphalt yields an annual leach rate of 0.012 curie of ^{226}Ra at an annual cost of \$7,863,000 (Case 6c). Although the treatments using incorporation in cement or asphalt show higher leach rates and higher costs than treatment by encasement in an asphalt membrane, they probably are more conservative in that they would not be subject to a sudden change in leach rate which would occur if the asphalt membrane were ruptured. The same trends apply to the leach rates for tailings from the model alkaline-leach mill. However, at alkaline-leach mills, the costs are slightly higher for treatment of the slime fraction because of the higher proportion of slimes in alkaline-leach tailings.

The protection of the solid tailings against potential leaching by water by incorporation with cement or asphalt, or by encasement in an asphalt membrane, probably should be considered as a conservative, alternative treatment for the semiarid sites of the model mills. At other sites, where high rainfall, high water tables, or geologic faults under the tailings area may occur, such treatments become much more beneficial and necessary.

8.8 Contribution of the Cost of Radwaste Treatment to Yellow Cake and Total Nuclear Power Costs

The capital cost of the model uranium mill is estimated at \$13,000,000. The capital costs of radwaste treatment added to the model mill range from \$357,000 for Case 1 to \$10,577,000 for Case 7 (Tables 6.1 and 6.2). In the special case where the conventional sulfuric acid leach is replaced with a nitric acid leach, the net increase in capital cost is \$29,959,000. For current practice (Case 1), the maximum annual cost of radwaste treatment is \$180,000 which is equivalent to \$0.07/lb of U_3O_8 and 0.003 mills/kWhr. The annual costs increase from this base case to a maximum of \$9,900,000 for Case 6b for the alkaline-leach mill which is equivalent to \$3.65/lb U_3O_8 and 0.173 mills/kWhr. This highest cost is less than 3% of an estimated total power generation cost of 7 to 10 mills/kWhr.

The maximum radwaste treatment cost which does not involve the use of expensive HEPA filters, charcoal delay trap, and incorporation of tailings in cement or asphalt is \$1,778,000. This is equivalent to \$0.66/lb U_3O_8 and 0.032 mills/kWhr. It contributes less than 0.4% to the total cost of nuclear power. This cost will cover high-efficiency, reverse jet, bag filters and high-energy venturi scrubbers on the airborne effluents from the mill (Case 4), neutralization or copperas treatment of liquids, an asphalt-lined tailings basin with a clay core dam, and a 1-in. asphalt membrane topped by 2 ft of earth stabilized with 6 in. of crushed rock (Case 7). This combination of Case 4 treatment for airborne mill dusts and Case 7 treatment of liquid and solid wastes reduces the maximum individual total body dose and most organ doses to less than 1 mrem/yr (100% food ingestion), the maximum bone dose to less than 7 mrem/yr, and the long-term radon lung dose to less than 0.002 mrem/yr. It reduces loss by seepage to 0.1% and provides some protection against future leaching of radioactive materials from the tailings by complete encasement in an asphalt membrane. The radon dose from the active mill and active tailings area can be reduced only by the use of expensive additional treatments.

9.0 OVERVIEW OF URANIUM MILLING

Present practices in the uranium milling industry, with particular emphasis on effluent control and waste management, have been surveyed. A questionnaire was distributed to all active uranium mills in the United States. Replies to this questionnaire were received from about 75% of the mill operators. The study team visited six operating uranium mills representing the different flowsheets in use today and the newest, most modern mill designs. Three stabilized tailings piles were inspected, and discussions were held with members of the Region IV Office of AEC Regulatory Operations and the Grand Junction Office of the AEC. _Nuclear Science Abstracts_ through April 1973, as well as other sources, were searched for literature pertinent to uranium mill processes and waste management. Over 200 publications have been abstracted and catalogued. There has been relatively little recent work in this field, and literature references are generally ten or more years old. Some historical problems which were corrected long ago have been included both to make the survey complete and to emphasize the need for continued care in these areas.

9.1 The Uranium Milling Industry

In the spring of 1973 there were 15 uranium mills operating in the United States with a combined processing rate of 22,500 tons of ore per day. One mill, which expected to close for major process modifications, asked to be omitted from the survey. A second mill was inactive except for a small program involving treatment of mine water by ion exchange. Two mills are on standby (Table 9.1).* No new mills are under construction in the United States at present. The industry is currently in a depressed condition, with some mills operating at less than full capacity — for example, 10 days out of 14. During 1972 the average daily tonnage of ore processed was 17,500.[4] The 15 active mills vary in size from 350 to 5,000 tons/day, with the majority (12 mills) in the range between 900

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*The Union Carbide mill at Rifle, Colorado,[1] and the Susquehanna-Western mill at Edgemont, South Dakota,[2] are on standby. The Susquehanna-Western mill at Falls City, Texas, was closed permanently in early 1971.[3]

and 2,000 tons/day. As the grade of ore drops, mills must process larger quantities of ore in order to maintain a profitable yellow cake* production rate.

The active mills are located in six western states. There are three in New Mexico (8,800 tons/day), seven in Wyoming (8,950 tons/day), two in Texas (3,000 tons/day), two in full operation (1,450 tons/day) and two in partial operation in western Colorado and eastern Utah, and one in Washington (350 tons/day). Future producing areas are in New Mexico and Wyoming, with $8.00/lb reserves estimated at 49,064,315 and 55,547,228 tons of ore respectively.[5] Texas is third with 10,668,742 tons and Colorado-Utah fourth with 5,637,034 tons.[5] All other areas combined have reserves of 7,393,229 tons.[5]

Some uranium mills began operations in the late 1950's and have adequate reserves to continue milling for many years, but other mills were abandoned after 10 or 15 years. An industrial consultant estimates the average life of a mill to be about 20 years.[3] There are 22 abandoned or inactive uranium mill sites in the United States. Rio Algom and Exxon expect to stop milling when their ore reserves are exhausted in 10 and 12 years, respectively.[6,7]

9.2 Mill Processes

The process of uranium extraction varies among the mills, due partly to differences in the chemical composition of the ore.[8] Steps basic to all mills are crushing, grinding, chemical leaching (wherein the uranium is dissolved from the ground ore), and recovery of the uranium from the leach solutions. The mill processes fall into three general types: acid circuit--solvent extraction (10,100 tons/day), acid circuit--ion exchange (9,100 tons/day), and alkaline circuit (3,350 tons/day) (Table 9.1).

Acid Circuit Mills. - In acid circuit mills, ore is ground to sand size (-28 mesh) and leached with sulfuric acid. An oxidant such as

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*The term yellow cake is used loosely in this report to mean the uranium concentrate product, although strictly speaking it refers only to the product formed by precipitation with sodium hydroxide.

sodium chlorate or manganese dioxide must be added. Otherwise, conditions are relatively mild, i.e., temperatures between 80 and 140°F and a pH of 0.5 to 2.0. Mills processing vanadium ores use higher leaching temperatures (~180°F) and more-concentrated acid (pH, 0.15 to 0.5).* Uranium is recovered and separated from impurities in the sulfuric acid leach solution either by solvent extraction with an amine or by an ion exchange resin. A purified and concentrated uranium solution is then stripped from the organic solvent or eluted from the ion exchange resin by a variety of reagents (Table 9.1). Uranium is finally precipitated (usually with ammonia as the diuranate), dried (usually at ~300°F), although occasionally it is calcined at 750 to 950°F), and packaged.

There are almost as many variations in acid mill processes as there are acid mills (Table 9.1). In a limited survey, it is not possible to consider in depth all possible variations, even though some of these differences can affect the volume and chemical composition of the liquid wastes and, consequently, the cost of waste treatment and the environmental impact. However, the selection of a model acid circuit plant, which uses amine solvent extraction with countercurrent decantation (CCD) in thickeners for the solid-liquid separation after leaching, and an ammonium sulfate strip, serves the purpose of this survey (Sect. 9.2). The use of this type of plant appears to be the trend of the future, as four out of five new acid circuit mills constructed in the western world in the last five years are of this type.[3] Many items affecting the radwaste are the same for both solvent extraction and ion exchange plants:

1. The ore crushing, grinding, and leaching system.
2. The volume and composition of airborne effluents.
3. The volume and composition of solid wastes.
4. The total amount of radionuclides leached from the ore, and the total amount in the liquid effluents.
5. The methods used for treatment and disposal of gaseous, liquid, and solid wastes.

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*The salt roast process is not used today for vanadium recovery at uranium mills.

Alkaline Circuit Mills. — Alkaline circuit mills must grind the ore much finer (25 to 80% -200 mesh) than acid circuit mills. The ground ore is leached with a sodium carbonate--sodium bicarbonate solution at ~250°F and 50-psi pressure using air or an oxygen-air mixture as an oxidant. The carbonate leach is more selective than the acid leach so that it is not necessary to purify the alkaline leach solutions. Uranium is precipitated directly with sodium hydroxide, and the liquid recarbonated with carbon dioxide (from flue gas) and recycled to the process. Because the chemicals are expensive, alkaline circuit mills have always practiced solution recycle within the plant, with only a small bleed stream being routed to waste. In recent years some alkaline circuit mills have had to purify their yellow cake product by dissolving it in sulfuric acid and reprecipitating with hydrogen peroxide or ammonia in order to meet the specifications with regard to sodium concentration in the product.

A model alkaline circuit plant is selected for use in this survey since alkaline mills represent a significant fraction of the total industry (3,350 tons/day) and the wastes differ both in chemical composition and in the distribution of radioisotopes from the acid circuit wastes (Sects. 9.3, 9.5, and 4.4). Alkaline leaching is used on ores which cannot be readily leached with acid. The model alkaline plant uses the same process as that used by three of the existing alkaline plants (Table 9.1). The fourth alkaline plant, the Atlas mill at Moab, Utah, is expected to convert to the conventional alkaline flowsheet in the near future.[3]

9.3 Radioactive Materials

9.3.1 Source and Relative Hazard of Radioactive Materials

The function of uranium mills is to extract uranium in concentrated form from naturally occurring ore deposits which generally contain 3 to 6 pounds of U_3O_8 per ton of ore (0.15 to 0.30% U_3O_8). The average grade of ore processed during the period 1967 through 1972 was 0.20 to 0.21% U_3O_8.[9] The radioactive material comprising uranium waste has been naturally present in the crust of the earth for thousands of years. It does not come from artificial acts of man. The milling process has no effect on the total amount of radioactivity; i.e., the total amount of radioactive materials leaving the plant in the uranium product and in various waste effluents is the same as the amount entering in the ore. There is no danger of criticality accidents. The principal in-plant hazards are inhalation and ingestion of radioactive materials. Shielding from radiation is not necessary.* Direct maintenance of equipment is standard practice. The uranium is present as uranium-238 and uranium-235, both of which are naturally occurring parents of long chains of radioactive daughters. Since natural uranium contains 99.28% uranium-238, it is the uranium-238 decay chain that is of primary concern. The parent element, uranium-238, which has a half-life of 4.5 billion years, decays by alpha emission to thorium-234, which has a half-life of 24.1 days and, in turn, decays by beta emission to protactinium-234. The decay chain continues until stable lead-206 is reached (Fig. 9.1). Most ores are in secular equilibrium; i.e., the daughter products are being formed at the same rate as they are decaying (Table 9.2). One ton of ore containing 4 lb of U_3O_8 has about 515 µCi of activity from each member of the decay chain, with a total combined alpha and beta radioactivity level of about 7,200 µCi. About 85% of the total activity ends up in the mill waste, and about 15% is in the uranium product.[11] With no parent remaining, the thorium-234 and protactinium-234 decay out of the mill wastes so that, after a year, the wastes contain about 70% of the activity originally present in the ore. The uranium ore processing industry is thus characterized by tremendous tonnages of solid wastes containing relatively low levels of radioactivity.

The concern with the wastes from the milling industry stems from the large amounts of these wastes, the potentially hazardous nature of the long-lived radium-226 and other associated radioactive materials should they become distributed in the environment, and the ability of radon gas to diffuse into structures where the daughters plate out on room surfaces. From 1948 through 1972, the uranium milling industry processed 103,078,023 tons of ore containing 243,715 tons of U_3O_8.[12] This represents an accumulation of over 100 million tons of solid waste (tailings) containing

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*One exception is the Dawn mill, which utilizes shielded ion exchange columns. In the process used at this mill, radium concentrated in the columns and radiation levels exceeded 5 mR.[10]

about 62,000 Ci of radium-226, plus nearly ten times this amount of radioactivity from other members of the decay chain. The maximum permissible concentration in drinking water (MPC_w) for soluble radium-226 is about 100 times lower than for soluble plutonium-239 (Table 9.3).[13] This is because approximately 30% of the radium passes from the alimentary canal to the blood and thence to the bones, vs only about 1/30,000 of the plutonium.[14] Other hazardous daughters in the decay chain with MPC values comparable to plutonium-239 or strontium-90 are thorium-230, polonium-218, polonium-214, lead-210, and polonium-210 (Table 9.3). Thorium-230 has a half-life of 8.3×10^4 years and, since it is near the top of the decay chain, it will produce radium-226 and all the other daughters below it in the decay chain. The radon-222 from the decay of radium-226 is a gas which diffuses out of the waste piles and then decays to hazardous nonvolatile daughters. When uranium mill tailings were used for construction at Grand Junction, it was the diffusion of the radon into the buildings that caused most of the radiation exposure.[15]

9.3.2 Distribution of Radioactive Materials in the Milling Process

The milling process causes some redistribution of radioactive materials in addition to recovering the uranium. About 50% of the thorium[16] and 0.4 to 6.7% of the radium[16,17] are dissolved in acid-leaching circuits. Most of this is rejected to the liquid waste by the purification process so that the final yellow cake product contains 0.9% (ion exchange) to 5.3% (solvent extraction with alkyl phosphoric acid) of the thorium[16] and 0.02 to 0.22% of the radium.[16,17] It should be noted that these surveys were made on RIP* ion exchange, fixed-bed ion exchange, and the now obsolete alkyl phosphoric acid solvent extraction processes. Surveys have not been made on the amine solvent extraction process used for the "model" flowsheet. The leaching behavior will be the same, and presumably the extraction behavior is not markedly different or the effect would have been observed in the yellow cake. The amount of thorium in the yellow cake may be lower than 5% with amine solvent extraction since the amine

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*RIP: resin-in-pulp.

probably extracts less thorium than the alkyl phosphoric acid. Thorium is virtually insoluble in the alkaline circuit, but 1.5 to 2.2% of the radium dissolves and is precipitated with the uranium product.[16,17] Radioactive nuclides other than uranium, radium, and thorium are apparently rejected to tailings since radiation measurements do not indicate their presence in the yellow cake.[18]

9.3.3 Distribution of Radioactive Materials as a Function of Particle Size

Uranium is not uniformly distributed throughout the ore or the tailings. For example, at two mills, the -200 mesh fraction of the leach feed, which was 20 to 30% by weight of the ore, contained 55 to 60% of the uranium (Table 9.4). After leaching, the -200 mesh fraction contained about 45% of the uranium not dissolved by the milling process. Analysis of the dust in one mill showed that the uranium, radium, and thorium concentrations increased with decreasing particle size across the particle size range from 119 μ (approximately 115 mesh) to 5 μ (Table 9.5). Radium and gamma-emitting isotopes concentrate in the slimes tailings, with 70 to 90% appearing in the -200 mesh fractions which usually comprise 20 to 30% of the weight of acid-leached tailings and about half the weight of alkaline-leached tailings (Tables 9.6, 9.7, and 9.8). Presumably the other daughter products in the decay chain also concentrate in the fines. Thus, the slimes tailings are considerably more hazardous than the sands. In addition, when the mill ceases operations and the pile dries out, the dissolved radioactive materials in the pond water will crystallize and become part of the slime fraction.

9.4 Airborne Radioactive Dusts from Mill Processes

Numerous opportunities arise for the formation of airborne radioactive dusts in the milling processes — ore crushing, screening, transferring, etc., and the yellow cake drying and packaging. Dust-producing activities are essentially the same in all mills and are unrelated to the chemical flowsheet. The intermediate milling steps of grinding, leaching, and uranium purification are wet steps. With good housekeeping and cleanup of spills, no dust should be generated in these operations.

9.4.1 Sources and Treatment of Ore Dusts

Ore is delivered to the mills by truck or rail* and dumped into small piles. Soon after it is received, a front-end loader moves it to the grizzly feed for the crusher. Ore is not ordinarily stockpiled in the mill receiving yard unless the mine is some distance away. The desired mill feed is obtained by adjusting the shipments from the mine and blending from the fine ore bins. The ore is generally moist so that only a small amount of dust is generated in the ore receiving yard. Some mills dump ore into three-sided concrete bins, which provide some protection against wind erosion in addition to their primary function of separating the ore piles. The trend of the future is toward deeper mines, i.e., wetter ores. Even in Colorado, which historically is known for its dry underground mines, new mines are wet, and the industry expects to be mining mostly wet ores in the near future.[19]

Once the ore passes the grizzly feed to the crusher, dust-producing activities are enclosed in buildings. Until the late 1950's, there was little or no ventilation of ore-handling operations, which, in turn, meant that the ore dusts were contained inside the buildings. Ventilation was installed in the late 1950°s when surveys showed that some workers were being overexposed to silica dust.[20] (Note that it is the silica and not the uranium which was judged to be the primary hazard from ore dusts.[20]) Dust control practices in the industry today are summarized in Table 9.9. The amount of ventilation varies from none to 37,000 cfm normalized to a standard crushing rate of 100 tons/hr. There is considerable variation in the nature of the ores and the design of the dust control systems so that the air flow alone cannot be regarded as a measure of how clean the mill air is. Mills with no ventilation process ("muck" through) very wet ores which create little dust. Mill D has a tight system around the crusher and screens, and all conveyor transfer points are completely hooded. Mill D processes a relatively moist ore and is able to maintain good internal dust control with only 2800 cfm of ventilation air. Other mills use high air flows either because they handle dusty ores (limestone

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*Anaconda hauls ore by railroad.

being the worst) or because the collecting system is less efficient, as for example the use of open screens and/or conveyor transfer points. The newest mills are conservatively designed with relatively tight systems and high airflows. Records kept by both AEC and industry indicate that dust levels in the mills are well below the MPC in terms of radioactive materials for all of the dust control methods.* The dust-laden air is generally passed through a wet scrubber or bag filter, which removes the bulk of the dust before the air is exhausted through a roof vent to the environment (Table 9.9). In practice, there will be at least two ore dust collectors, one on the ore bins which operates 24 hr per day and from one to four for the crusher, screens, conveyors, etc., which operate for one to two shifts per day. Many mills prefer to use several scrubbers rather than design elaborate duct systems with the associated problems of balancing airflows.

9.4.2 Sources and Treatment of Yellow Cake Dusts

Airborne dusts are also released to the environment from the yellow cake area of the mill. The dryer off-gas is an essential part of the mill process which removes the moisture and any ammonia from the wet uranium precipitate. In addition, the yellow cake handling rooms must be ventilated to protect the health of the workers. Airflows from the yellow cake areas vary from a low of 170 cfm to a high of 1,140 cfm normalized to a standard U_3O_8 production rate of 1,000 lb per 24 hr (Table 9.10). The weighted average is about 620 cfm total, with 200 to 250 cfm coming from the dryer off-gas and the remainder from packaging and room ventilation. Considerable variation occurs in the amount of dust-laden air that leaks into the room from the equipment; in turn, this leakage is reflected in the amount of ventilation required. One mill, for example, built a hood around the dryer to control the leakage that was experienced with the initial unit. All mills pass the dryer off-gas through a wet scrubber, and the dust-laden air from the packaging room through either a wet scrubber or a bag filter, to recover at least 98%

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*Raw data on air samples inside the mills are available in the mill files but have not been tabulated.

of the yellow cake dust before the air is exhausted through a vent in the roof (Table 9.10).

9.4.3 Dust Losses in Stack Effluents and Particle Size of Dusts

The mills do not routinely take isokinetic samples of stack effluents, relying instead upon environmental monitoring for compliance with the 10 CFR 20 regulations. In the early 1960's, some grab samples were taken (Table 9.11) which exceeded MPC, indicating that dilution in the atmosphere was necessary to comply with the regulation. Most of the mills listed in Table 9.11 are now closed, and there is no information available on the airflows or types of dust collectors which were used. Several mill operators have supplied estimates of their current dust losses based on metallurgical sampling programs or occasional grab samples of stack effluents (Tables 9.12 and 9.13). These estimates probably provide a more realistic assessment of present-day particulate emissions than do the older stack analyses. Yellow cake dust losses average about 0.02% except at one mill which has a very efficient venturi scrubber and loses only 0.002% (Table 9.13). Ore dust losses vary from about $5 \times 10^{-4}\%$ for a "dry" (6% moisture) ore and a wet scrubber to $7 \times 10^{-5}\%$ for a "wet" (9 to 10% moisture) ore with no scrubber (Table 9.12). The ore dusts exhausted from the stack contain approximately 2.4 times as much uranium as the mill feed (Table 9.12). This is to be expected since the -10 μ particles, which are rich in uranium, are the major particles to pass through the dust collector.

The dust load to the collector and the particle size distribution (which affects the efficiency of the dust collector) must be known in order to design the advanced gas treatment cases for this survey. Neither has been measured experimentally. Surveys in the operating areas of the mills (Table 9.14 and 9.15) indicate that the mill dusts are typical industrial dusts. Thus, it is assumed that the efficiencies of the dust collectors as determined by Stairmand[21,22] on a standard industrial test dust (Table 9.16) are valid, and these efficiencies are used in this survey. The dust load to the collector can be calculated from the dust losses using these efficiencies (Tables 9.12 and 9.13). The efficiencies given by

Stairmand are the result of long-term plant and laboratory investigations of a number of types and commercial models of dust collectors.[22] Stairmand's data have been widely quoted by air pollution control experts and, short of an actual pilot-plant test, are considered the best for estimating performance.[23] Accurate dust sampling is difficult, and errors usually result in the dust being judged too coarse; hence the predicted efficiencies are too high. Almost any wet scrubber will do a good job of removing particles larger than 10 μ.

9.4.4 Environmental Monitoring

The concentration of uranium in the air at the boundary of the site or unrestricted area downwind from active uranium mills is generally 2 to 15 x 10^{-14} μCi/ml, or 1 to 8% of MPC (Table 9.17). This, of course, includes dust from the tailings pile (Sect. 9.6.3), and may also include dust from the mine if it is nearby. Tailings have a low uranium content and,in addition, may be wet while the mill is operating, and the mines are generally wet; thus most of the airborne uranium dust comes from the mill. The environmental uranium levels at Mill F were a factor of 10 lower than at most other mills, i.e., only 0.55 x 10^{-14} μCi/ml. This mill uses bag filters and venturi scrubbers, which are a factor of 10 more efficient than the dust collectors used by most of the industry.

9.4.5 Other Dust Sources — the Ore Dryer and the Roaster

The ore dryer and the roaster are two additional sources of dust which are occasionally encountered. Most fine ore bins are housed in an enclosure which can be heated in winter to prevent freezing and are equipped with specially designed 60° cone bottoms, wide discharge openings, belt feeders, and an air injection manifold so that ore drying is unnecessary. Ore dryers are used as little as possible because of the expense. Exact dust losses from an ore dryer are unknown. The airflows are high, i.e., 20,000 to 45,000 cfm. The dust concentration in the ore dryer off-gas could vary from 10 (Table 9.11) to 30 times that of the crusher complex (extrapolating the data in Table 9.12 to 4% moisture in the dried ore). It is thus apparent that an ore dryer could easily release 10 to 60 times as much dust as the crusher complex. Occasionally, an alkaline or an ion exchange circuit mill will have to roast the yellow cake in order to remove vanadium or molybdenum impurities. Roasting is similar to yellow cake drying, and dust losses of perhaps 0.01% of the yellow cake might be expected. Roasting is not necessary with the solvent extraction circuit.

9.5 Liquid Effluents from Mill Processes

9.5.1 Quantity and Chemical Composition

Uranium mills generate large volumes of acidic or basic liquid wastes which contain high concentrations of chemicals in addition to dissolved radioisotopes (Tables 9.18, 9.19, and 9.20). The exact volume and composition of the wastes are variable, depending on the mill process. In general, a solvent extraction or moving-bed ion exchange mill will produce about 1.5 tons of liquid effluent per ton of ore processed, a resin-in-pulp ion exchange mill about 2.5 tons of liquid per ton of ore, and an alkaline leach mill from 0.3 to 0.8 ton of liquid per ton of ore (Table 9.18). Untreated wastes from an acid leach mill have a pH of 2 to 3; those from an alkaline leach mill have a pH of about 10 (Table 9.18). The uranium concentration in untreated wastes generally varies from 0.01 to 0.03 g/liter (3 to 10×10^{-6} μCi of U_{nat}/ml, Table 9.18); the radium concentration from 360 to $11{,}000 \times 10^{-9}$ μCi/ml in acid effluent and 20 to 100×10^{-9} μCi/ml in alkaline effluent; and the thorium from 11,000 to $500{,}000 \times 10^{-9}$ μCi/ml in acid effluent (Tables 9.18 and 9.20). Thorium does not dissolve appreciably in the alkaline circuit. Most modern mills analyze the liquid effluents for SO_4^{2-}, and some also check for Cl^- and Na^+; additional chemical data are not available. Table 9.21 lists the chemical usage in mills today. This gives some indication of the waste composition, although all of the chemicals will not necessarily appear in the liquid effluent.

The chemical analyses of mill effluents in 1959-1962, along with Public Health Service drinking water standards, are shown in Table 9.19. Numerous changes have been made in mill processes since 1962. For example, at many mills, ammonia is used instead of sodium hydroxide to precipitate the yellow cake, and sodium chlorate has replaced manganese dioxide as the oxidant. There is also less extensive use of chloride and nitrate in stripping circuits. Solvent extraction mills and ion exchange mills which use Eluex solvent extraction to concentrate the uranium from the ion exchange circuit will have effluents containing dissolved organics, i.e., an amine (Alamine 336 or Adogen 364), an alcohol (isodecanol or tridecanol), and kerosene. Toxicity figures on these amines are not available; however, the organic raffinate from the old process which used di(2-ethylhexyl)phosphoric acid was toxic to fish.[24,25] Other chemicals which have been found in mill effluents include fluoride, boron, selenium, lead, arsenic, cadmium, chromium, molybdenum, vanadium, zinc, and phenolic compounds.[3,26]

9.5.2 Total Impoundment and Disposal by Natural Evaporation and Seepage

Fourteen of the mills operating in 1973 impound all liquid wastes in the tailings area or in evaporation ponds and depend on natural evaporation and seepage for liquid disposal. Since liquids are not released, pollution of surface water does not occur.[27,28] Most of these impoundment areas are sited a considerable distance from any major stream; consequently, the risk that seepage or accidental releases would reach the stream is decreased. The long-term risk that seepage may contaminate underground water supplies is more difficult to evaluate. Mill operators routinely sample monitoring wells sited where the geologists predict that seepage would first appear and, to date, have not observed any change in their samples. Some environmentalists are concerned that liquid disposal by seepage merely postpones, rather than solves, the water pollution problem and that, in time, the radioisotopes and chemicals will migrate through the soils and irreversibly contaminate the underground aquifers.[29] The tests needed to resolve this question have not been made. For example, analysis of core drillings underneath abandoned tailings areas would provide information about seepage. Little information exists relative to the exchange capacities of the soils, and the monitoring well data have not been rigorously analyzed. Base-line well data were not taken for the older mills, and the new mills that have base-line data have not been operating for a significantly long period; i.e., the extent of operations is only about one year. Although there is no proof, seepage is probably not a serious problem if the tailings area is properly sited.

Most ponds in the United States are located on clay soils in an arid environment with little rainfall, and the water table is well below the surface. Consequently, the environment provides a considerable safety margin. The fine mill tailings usually seal the bottom of the pond so that most seepage occurs during the early life of the pond[30] and does not continue indefinitely. Alkaline leach tailings can be expected to seal the pond more rapidly than acid tailings because the particle size of the tailings is much smaller (ore is more finely ground). Tailings from a clay-type ore should form a seal more rapidly than a sandy ore. If the pond is sited on a clay soil, the highly acid effluent from an acid leach mill will disperse the soil particles which, in turn, clog the void spaces and stop further seepage.[31] Conversely, the acid effluents can dissolve a limestone soil, causing channeling and an increase in the seepage rate.[31] The soils under many tailings areas contain montmorillonite clay, which has a cation exchange capacity of about 100 meq/100 g of clay[32] and can adsorb considerable quantities of radioisotopes. For example, an estimate for the Exxon mill indicates that one ton of the soil around their tailings area is theoretically capable of adsorbing 2000 g of radium.[33] Many soils contain cations, such as calcium, iron, or heavy metals, which will form insoluble salts with the sulfate ion and stop the migration of sulfate.

Older mills often have dams or dikes constructed of tailings through which liquids seep. The seepage is collected in catch basins and pumped back into the pond. The newest mills have clay core dams,[34,35] and seepage has not been observed.

9.5.3 Release from Impoundment Ponds

In the 1950's, radium contamination in the Colorado River Basin was attributed to releases of untreated liquid (and solid) wastes from some tailings impoundments located on stream banks in the Colorado plateau.[36-40]

By 1962 the industry had generally solved the liquid effluent and seepage problem,[41] and by 1966 the number of accidental releases from dike failures had been reduced by the establishment of structural requirements for dikes.[42] Most of the old mills are now closed; however, as of early 1973, two mills were releasing treated effluents to rivers because they had insufficient pond area for evaporation. One, the Atlas mill at Moab, plans to make process modifications which will reduce the volume of liquid effluents such that their pond area will be adequate.[3] The second, the Union Carbide mill at Uravan, has no ready solution. The most obvious is to lease additional adjoining land from the Forest Service, but that agency is not amenable to this procedure.[19] It is expected that the mill will continue to (1) release a barium chloride-treated effluent from the yellow cake precipitation circuit plus tailings dike seepage to the river, (2) dispose of organic raffinate and high-salt-content wastes in seepage ponds which dip away from the river, and (3) impound acidic effluents for recycle to the mill.[19,43] Seepage is visible on the canyon walls below the Uravan tailings area. Although Mines Development, Edgemont, South Dakota, impounded all liquid effluents, the tailings failed to seal the bottom; and, as recently as 1966, they had some seepage to the river.[44] Seepage collected from the bank of Cottonwood Creek contained 32×10^{-9} μCi/ml of radium and 58×10^{-9} μCi/ml of uranium.[44] Dissolved iron salts precipitated in the creek, producing a red coloration.[44] Seepage also apparently flowed upward into the Cheyenne River bed via an underground spring.[44] Cottonwood Creek contained 2×10^{-9} μCi/ml of radium, but this was rapidly diluted to background after the confluence with the Cheyenne River.[44]

9.5.4 Deep-Well Injection

The Anaconda mill uses a deep well for disposal of excess liquid in the winter since the geologic conditions will not permit expansion of the ponds.[45-48] Bulk solids are removed from the tailings effluent by settling in the pond, and the supernate is filtered to produce a clear effluent suitable for injection. Experience has shown that chemical treatment for bacteria, fungus, etc., is unnecessary.[45] Operations have been satisfactory for 11 years.[45] The use of deep well disposal requires special geologic conditions; consequently, this method is not suitable for the Uravan mill.[49]

9.5.5 Disposal of Nitrate-Bearing Wastes

Nitrate from uranium ore processing facilities has been detected in underground wells.[50,51] Nitrate ion is much more mobile than sulfate ion because its salts are more soluble and because the nitrate ion is less readily adsorbed by the natural minerals in the earth. Nitrate is not used in mills at present (1973).

9.5.6 Chemical Treatment

Chemical treatment of liquid wastes is not widely practiced in the United States. The wastes are neutralized at the Dawn (Ford, Washington) plant[52] and are treated with barium chloride to precipitate radium at Uravan (Colorado)[19,43] and at Atlas (Moab, Utah).[53] The Canadians mill uranium ores in a wet environment and have considerable operating experience with liquid waste treatment. Neutralization of acidic effluents has been compulsory in the province of Ontario, Canada, since 1960,[54] and by 1968 all Ontario mills were also treating their tailings pond overflow with barium chloride.[55] In the future, new Canadian mills will be restricted to a limit of 1 ppm of NH_3 in liquid releases.[3] To meet this requirement, the mills will probably have to treat and recycle most of the pond water to the mill. A small bleed stream would be discharged with the solid tailings.[3]

Neutralization. — Neutralization is effective in reducing the pollution potential of acid leach mill wastes. In addition to eliminating the excess acidity, it causes the precipitation of ~90% of the radium,[16] almost all the thorium, and much of the iron, copper, cobalt, arsenic, uranium, vanadium, and other heavy metal ions as insoluble oxides or hydroxides. When lime is the neutralizing agent, sulfate, phosphate, and similar anions are precipitated as insoluble calcium salts. Lime is somewhat more effective than ammonia or sodium hydroxide in removing radium because the radium coprecipitates with the calcium sulfate.[56] Lime is also the least expensive. The treated solutions must be clarified before their release to streams since suspended solids can carry considerable amounts of radium.[16] The effect of neutralization is quite striking, i.e., neutralized effluents (pH ~7) contain 0.25 to 500 x 10^{-9} μCi/ml of radium and 0.95 to 130 x 10^{-9} μCi/ml of thorium compared with 500 to 81,000 x 10^{-9} μCi/ml of radium and 1,100 to 477,000 x 10^{-9} μCi/ml of thorium in acidic effluents (pH 1.5 to 3.0) (Tables 9.18 and 9.20). Seepage from neutralized, compacted tailings covered by a pond, or runoff from neutralized tailings, carries very little radium,[54,57] in contrast to seepage or runoff from unneutralized tailings which does carry dissolved radium.[29] However, the radium in neutralized tailings can be dissolved by vigorous agitation with large quantities of water, i.e., 1000 parts water to 1 part fines.[57] Gypsum ($CaSO_4$), formed during lime neutralization, can be a problem due to scaling on tanks and in tailings pipelines. Several methods for minimizing scale buildup are:

1. Combination of liquids with solid ore tailings prior to neutralization, as the gypsum then tends to precipitate on the sand particles rather than on the equipment.[58]
2. Use of aeration rather than mechanical agitation.[58]
3. Holding slurries in the mixing tank for a period of 2 hr[59] to several hours.[58]
4. Applying a heavy coat of grease to the neutralization tank for easier removal of the scale.[58]

Scale has been cleaned from pipelines using high-pressure air[58] and various kinds of mechanical "pigs", "bugs", or "hedgehogs" equipped with spikes, teeth, cutting vanes, or wire brushes.[58,59]

Neutralization is of limited value in treating alkaline wastes since most of the species removed in treating acid wastes are not present in alkaline solutions. Neutralization removes a fraction of the radium, but the results are erratic, probably because the mechanism is the adsorption of soluble radium on precipitates or other solid surfaces.[16]

Barium Chloride Treatment. — Barium chloride is an effective agent for removing radium from sulfate-containing wastes by coprecipitating radium sulfate with barium sulfate.[43,54,57] The efficiency is dependent on the radium concentration in the stream to be treated, i.e., 99% radium removal was obtained from streams containing ~400 pCi/liter (~400 x 10^{-9} μCi/ml),[43] while the more recent Uravan experience has been removal of 93 to 96% of the radium from more dilute streams of ~28 pCi/liter.[19] It is effective on either acidic or neutral wastes. The barium chloride must be added to a clear solution, such as the decant from a tailings pond, and the small particles of radium-bearing precipitate must settle before the treated effluent is released to the environment.[19,43,54,57] If barium chloride is added to a typical waste slurry, radium can be leached from the fine suspended solids.[54,57] It is advisable to use a "tailings free" settling basin. In a test program, the Canadians used a clear, neutral overflow solution containing ~30 pCi/liter, added 0.01 g/liter of barium chloride which lowered the soluble radium concentration to ~1 pCi/liter, and pumped the treated liquid to an old tailings pond to settle. The decant from the pond contained ~13 pCi/liter from the stirring of old tailings where the pipeline ended.[54,57] After a month the settling basin overflow contained ~3 pCi/liter; after 2 months it contained ~2 pCi/liter.[54,57] They then extended their pipeline into open water to prevent any further leaching.[54,57] The precipitate formed by the barium chloride treatment is less hazardous than the ore tailings and contains less radium in a less leachable form.[19] Solids which collect in the settling basin can be pumped to the tailings area.[19] Other barium compounds such as barium carbonate and barium sulfate (barite) have been tried, but are neither as effective nor as convenient for sulfate-containing wastes as barium chloride.[19,43]

Copperas Treatment. — Alkaline effluents may be treated with either copperas ($FeSO_4 \cdot 7H_2O$, a flocculating agent) or barite ($BaSO_4$).[16] The barium chloride treatment is not effective on alkaline wastes which contain no sulfate. A single-stage copperas treatment will remove 78% of the radium; two stages of copperas, 89%; neutralization followed by barite treatment, 95%; and copperas followed by barite, 97%.[16] Reagent costs are lower for copperas followed by barite than for neutralization followed by barite.[16] These processes were tested in a pilot plant at the AEC Monticello mill, but they have not been used commercially.

Lime-Steam Strip with Recycle of Water and Ammonia. — A completely different approach would be to recycle all water and have no liquid effluents. There are now designs for two foreign mills which are basically similar to the "model" acid leach mill (amine solvent extraction, NH_4SO_4 strip, NH_3 precipitation) used in this survey, except that they include a lime-steam stripping circuit to recover ammonia from the strip liquors.[3] One mill will be built in an isolated part of Australia, where they believe they can recover ammonia cheaper than they can buy it. The other mill expects to recover ammonia and recycle at least 75% of the water to the mill in order to meet the 1-ppm ammonia limit in discharges set by the province of Ontario. A lime-steam stripping circuit for the recovery of ammonia from ammonium sulfate has been operated at a Canadian paper company for 2 to 3 years.[3]

9.6 Tailings

9.6.1 Quantity and Composition

Uranium ores contain only 3 to 6 lb of U_3O_8 per ton of ore (0.15 to 0.30% U_3O_8), which means that one ton of solid waste tailings will be generated for each ton of ore processed. The tailings consist primarily of silica with some silicates (i.e., sand), and in the case of an acid leach mill will contain insoluble sulfates, such as calcium sulfate, from the milling process. Liquid and solid wastes are commonly stored together, and as the water evaporates, soluble salts crystallize from the pond and become part of the solid tailings. The tailings generally contain 50 to 400 μg U/g (20 to 130 x 10^{-6} μCi U_{nat}/g), and 150 to 1000 x 10^{-6} μCi/g each of radium-226, thorium-230, and lead-210, depending on how rich an ore was processed (Table 9.22). In the Spring 1973 survey, seven mill operators reported that their tailings contain 0.005 to 0.015% uranium (20 to 50 x 10^{-6} μCi U_{nat}/g) while two reported >0.015% uranium (>50 x 10^{-6} μCi/g). Mills do not ordinarily analyze tailings for anything but uranium. Three mills reported radium-226 and thorium-230 contents that are consistent with Table 9.22. Other radioisotopes which may be expected are discussed in Sect. 9.3, but there are no tailings analyses for them. The maximum gamma radiation level measured 3 ft above the surface of the pile is usually about 0.5 to 1.6 mR/hr, although higher values are known (Tables 9.23 and 9.24). The surface of the tailings pile is not uniform. The tailings are spigoted from the dam or dike, with the heavier sands settling near the dam and the slimes moving toward the center and upper end of the impoundment. It is essential for the stability of the dam to place the slimes well away from the dam.[30] Since the radioisotopes are concentrated in the slimes fraction (Sect. 9.3), this results in a widely varying level of radioactivity over the surface of the pile. For example, the radium concentration at Mexican Hat varies from 27 to 860 pCi/g (27 to 860 x 10^{-6} μCi/g), and the gamma radiation at Tuba City from 0.02 to 6 mR/hr (Table 9.24). A careful sampling program is thus required to obtain a representative picture of an entire pile. The settled tailings contain 30 to 40% water initially.[3] When the mill becomes inactive, the tailings dry to 10 to 20% moisture.[60] The weight varies from 123 lb/ft^3 with 20% moisture to 140 lb/ft^3 with 10% moisture.[60] A ton of mill feed will occupy a volume of 0.63 to 0.66 cubic yard as "dry" tailings.[60]

9.6.2 Waste Retention Systems

The liquid and solid effluents are combined in the mill, and the slurry is pumped to the tailings area. The tailings are often dumped inside dikes made of coarse tailings sand, thus forming a pile which can grow to 30 or 40 ft high and as much as half a mile long. This is the general practice in New Mexico, Colorado, Utah, and the abandoned sites in **Arizona**. In some cases, low earth starter dams were used initially, but the overall effect is a gigantic sand pile. At Wyoming mills[34,61] and also at the new Rio Algom mill in Utah,[35] the tailings are impounded in a natural basin with an earth-fill dam or dike across the opening. Exxon,[34] Rio Algom,[35] and Utah International at Gas Hills[62] have clay core dams which are keyed either to shale or to an underlying natural clay formation to minimize seepage through the dam. The AEC Licensing Guide of 1963 lists a number of criteria for retention systems such as permanent diversion of any natural watercourse and runoff, minimum distance of 200 ft from any permanent flowing watercourse at flood stage, design and construction parameters for the embankment, minimum freeboard of 3 ft at the high water mark, and a program for maintenance and inspection.[63] Tailings are deposited with the sands near the dam and the slimes and pond away from the dam, as a water-saturated dam is likely to be unstable.[30]

The area of exposed dry tailings is variable, depending on the volume of liquid effluent from the mill, the natural evaporation rate, and the design of the retention system. In the spring of 1973, all tailings at the new Exxon and Rio Algom mills were submerged in water. In contrast, the New Mexico mills have many acres of dry tailings.

9.6.3 Wind Erosion of Tailings*

The blowing dust and moving sand dunes from dry tailings, especially from an inactive pile which has completely dried, can be a nuisance to the surrounding community. Complaints about the blowing dust were the primary impetus behind the Colorado regulation requiring stabilization of uranium mill tailings.[28] Theoretically, the amount of airborne radioactive dust should be highly dependent on the meteorology. The fine slimes fraction, which contains most of the radioisotopes, is not directly transported into the air by turbulent diffusion since the drag force on such small particles is spread over a large area rather than over an individual particle.[64] Instead, the process of dust suspension is thought to take place by saltation when sand grains impact dust on the ground.[64] Maximum winds and gustiness are more important factors in moving dusts than is the average wind speed. Other factors are the area and radioisotope concentration of the exposed, dry tailings.

Examples of airborne radioactive dust concentrations are given in Tables 9.25 and 9.26. Radium-226 and thorium-230 values of 0.5 to 4 x 10^{-14} μCi/ml of air are common around tailings piles. From the standpoint of inhalation, the radium dust levels are generally low, i.e., ~1% of MPC.

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*For other sources of airborne particulates, see Sects. 9.4 and 9.7.

It is unfortunate that there is little information available on the movement of thorium-230, because the MPC for airborne thorium is 100 times lower than for radium (Table 9.3). Assuming that radium and thorium are in secular equilibrium in the airborne tailings dust (which is not necessarily true), then the thorium may approach MPC about 30% of the time. The data in Table 9.25 summarize 3 months' continuous monitoring in Grand Junction and Durango during the windy, gusty season of the year. The period was an unusually wet spring with 60% more precipitation than normal; hence the dust levels would be lower than for a typical spring. The other studies were all short term and merely indicate conditions at the time of the surveys. At Tuba City, Arizona, the radium-226 concentration from resuspended tailings dust averaged 560×10^{-14} μCi/ml of air for four days at a station 1200 ft downwind from the tailings pile and outside the fence (Table 9.26). This is twice the MPC for radium. If thorium-230 and radium-226 were in secular equilibrium, the thorium concentration would have been ~200 times MPC. Although Tuba City does not have dust storms 365 days a year, the importance of long-term continuous monitoring in determining the annual atmospheric transport must be emphasized. Upwind and crosswind from the Tuba City pile, the radium concentrations were much lower, i.e., only 1 to 7×10^{-14} μCi/ml during the same four days.

Although silicosis is recognized as the primary hazard in the inhalation of ore dusts,[20] no records of silica analyses in the vicinity of tailings piles could be located.

Little information could be found regarding the fraction of the airborne dust that is respirable. Preliminary analysis of grab samples taken from the top 1/4 in. of a pile which has been inactive for 10 years indicated that 78% of the particles were <2.5 μ and 91% were <5.0 μ; i.e., most of the particles remaining on the surface sampled are respirable.[65] This implies that the wind has blown away the coarser fraction of the slimes.

In general, the concern of Public Health authorities has been the long-term atmospheric transport of tailings off-site over the 1,620-year half-life of radium-226 and the 83,000-year half-life of thorium-230, rather than any immediate hazard from inhalation of airborne dusts.[29]

Both EPA and AEC-Regulatory have taken soil samples in the vicinity of tailings piles.[66] No detectable increase has been noted in the off-site activity except where there has been visible migration of sand dunes.[66]

9.6.4 Water Pollution*

Solid tailings potentially represent a large radium reservoir from which soluble radium may be slowly dissolved simply by water leaching.[16,67,68] If tailings enter a stream or contact surface runoff, radium can be leached to the overlying water. Historically there was one case where the concentration of radium-226 in a river increased by 12×10^{-9} μCi/ml as it passed a mill – 5% from radium dissolved in the mill effluents and 95% from the leaching of solid tailings in the stream bed.[37,38] After pollution-control measures were instituted in the early 1960's, the spring floods transported most of the radium-bearing solids in the stream beds downstream to Lake Powell and Lake Mead reservoirs, where they have since been buried under later sediments.[29,37] The slimes, which contain most of the radium (Sect. 9.3.3), are easily carried by surface runoff from the piles, and in the middle 1960's were considered the major contributor (other than natural sources) to the dissolved radium in streams.[29] Total impoundment (Sect. 9.6.2) and stabilization (Sect. 9.6.6) have virtually eliminated tailings as a source of water pollution today.

9.6.5 Use of Tailings for Construction Purposes

Prior to 1966 there was no evidence that radon from uranium mill tailings would readily diffuse into enclosed structures.[69] Tailings-sand compacts easily and makes good fill for construction projects. In the particular case of Grand Junction, Colorado, it was available at no cost from a pile in the center of the city. An estimated total of 50,000 tons was used around structures in Grand Junction.[70,71] Gamma surveys in the Grand Junction area indicated the probable presence of tailings around ~4,800 structures.[15] Of these, ~1,100 had indoor radon levels of 0.05

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*For water pollution from liquid effluents, see Sect. 9.5.2 and 9.5.3.

WL* or higher above background and ~2,000 had levels of 0.01 to 0.05 WL.[15] The cost of remedial action has been estimated at $10,000,000[72] to $15,000,000.[71] In addition, an estimated 250,000 tons of tailings was removed from the Grand Junction pile for use as a subbase under roads, driveways, and sidewalks and as packing around culverts, sewers, and waterlines.[70] Tailings have been found around structures in other uranium milling towns,[15,73-75] but Grand Junction is the only community where widespread use of tailings occurred.

9.6.6 Stabilization of Tailings Piles

In 1966 Colorado adopted a regulation requiring stabilization of all uranium and thorium mill tailings piles and ponds from inactive mills against wind and water erosion.[76] The regulation requires written notice to the State Department of Health before the site can be transferred to another party, and written approval before the surface of the land is put to use or tailings are removed for purposes other than reprocessing. Stabilization shall be conducted in the following manner:

"1. Ponds shall be drained and covered with materials that prevent blowing of dust. Water drained from the ponds shall be dispersed of in a manner approved by the Water Pollution Control Commission.

2. Taking into consideration the types of materials at each site, piles shall be leveled and graded so that there is, insofar as possible, a gradual slope to ensure that there shall be no low places on the pile where water might collect. Side slopes shall be stabilized by riprap, dikes, reduction of grades, vegetation, or any other method or combination of methods that will ensure stabilization.

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*WL = Working Level; 1 WL is defined as any combination of short-lived radon progeny in one liter of air that will result in the ultimate emission of 1.3×10^5 MeV of alpha energy by decay to lead-210. The occupational limit for a uranium miner is 0.3 WL.[15]

3. If pile edges are adjacent to a river, creek, gulch, or other watercourse that might reasonably be expected to erode the edges during periods of high water, the exposed slopes shall be stabilized and the edges shall be diked and riprapped sufficiently to prevent erosion of the pile.

4. Drainage ditches shall be provided around the pile edges sufficient to prevent surface runoff water from neighboring land from reaching and eroding the pile.

5. The pile shall be stabilized against wind and water erosion. The method of stabilization may consist of vegetation or a cover of soil, soil containing rock or stone, rock or stone, cement or concrete products, petroleum products, or any other soil stabilization material presently recognized or which may be recognized in the future, or any combination of the foregoing as may be required for proper protection from wind, or water erosion."

Arizona has passed a law similar to that in Colorado,[77] while Wyoming is including tailings piles under their land reclamation law for open pit mining.[78] The Environmental Protection Agency is encouraging the other ore processing states to adopt regulations patterned after Colorado's, with the additional provision for long-term maintenance of the pile cover and safeguards against water pollution if irrigation is used to establish vegetation.[79] In licensing new mills, the Atomic Energy Commission requires the mill operator to describe procedures for stabilization and long-term control of tailings, and to post a bond which is increased each year as the tailings grow to guarantee that funds will be available to cover the expected cost.[80]

The first extensive uranium mill tailings stabilization project at the AEC Monticello, Utah, site has been successful. Approximately 900,000 tons of solid tailings in four separate areas covering about 40 acres were graded to facilitate drainage and covered with a 12- to 24-in.-deep rock and soil surface.[81] Barnyard manure and commercial fertilizer were spread, and the area was seeded with native grasses. Cost of the project was $190,000. The principal difficulty was covering an area where wet slimes had accumulated to a depth of 20 ft. The slimes were covered with 2 to 4 ft of tailings sand (6 ft over extremely fluid areas) before putting on the soil and rock cover. The vegetation cover is well established, and only minor maintenance has been necessary.[82] Problems associated with wind and water erosion of tailings and the physical hazards of the quicksand-like slimes were eliminated. Three years after the project was completed, surface soil, water, and vegetation samples showed no evidence of leaching or uptake of activity from the subsurface tailings.[83] The average gamma dose rate of the covered pile was 0.044 mR/hr on the surface and 0.040 mR/hr 3 ft above the surface, compared with an average background in the town of 0.036 mR/hr on the surface of the ground and 0.032 mR/hr 3 ft above the ground.[83] In contrast before stabilization, the radium-226 content of South Creek downstream from the property averaged one to two times MPC, the gamma radiation levels along the perimeter of the tailings ponds ranged from 0.35 to 0.40 mR/hr and were probably as high as 1 to 2 mR/hr in the slimes areas.[81] In addition, the radon concentration over the covered Monticello tailings pile was two to four times lower than the concentration over unstabilized piles (Sect. 9.7.1).

Uranium tailings piles at Grand Junction, Gunnison, Naturita, "old" Rifle, and Slick Rock, Colorado, and Green River, Utah, have been covered and vegetation established.[19,43,84] Stabilization of the Maybell, Colorado, pile should be completed in August 1973.[19] Generally, the covers are 6 in. thick,[19] although 1 ft was used at Grand Junction.[85] The 1-ft cover on the Grand Junction pile reduced the gamma radiation by about one order of magnitude.[28] No radiological surveys have been made over the 6-in. covers. The radium concentration in the grass on the old Rifle pile (6-in.-deep cover) is higher than background, indicating that the roots penetrate the tailings.[19] Cost of the initial stabilization varies according to the amount of grading required and the distance that rock and riprap must be hauled.[29] Union Carbide calculates their costs at $850 to $3500/acre for a cover with a minimum depth of 6 in. and varying up to 8 to 12 in.[19] Unlike Monticello, where maintenance has been low and annual precipitation is 14 in.,[82,86] regular sprinkling is often required for at least several years[19,43,85] and possibly in perpetuity. At Grand Junction, where the annual precipitation is 8 in.,[86] irrigation is required for six months of the year.[85] Power costs alone for the irrigation pumps amount to $400 per month, and the system requires 80 man-hours of labor per week in addition to annual reseeding of winter-killed areas.[85]

Attempts have been made to establish vegetation directly on tailings to avoid the expense of earth or rock covers. Problems encountered include blowing sands, low water holding capacity, deficiency of plant nutrients, acidity or basicity, salinity, toxic chemicals, and steep slopes and soft spots that cannot be worked by machinery.[86-89] In addition, tailings piles are mostly located in arid climates with short growing seasons.[86] Vegetation has been established directly on uranium mill tailings at the "new" Rifle pile, Grand Junction, and Durango, and on tailings from other types of ore processing activities.[43,55,84,86-88] Frequent fertilizing, watering, and sometimes liming are required.[28,55] Establishment of vegetation directly on tailings may be useful for temporary dust control at an operating mill, especially if the operator is sprinkling anyway. It will have no effect on radiation hazards other than blowing dust. To date, results by both agricultural experts and mining companies indicate that it is not possible to develop directly on tailings a plant community which will maintain itself indefinitely without further attention or artificial aid such as irrigation, and that other methods must be used for long-term control.[55,84]

Succulent grasses will attract wildlife;[87] deer (Rifle),[19] antelope (Exxon), prairie dogs (Grand Junction), and gophers (Monticello)[90] are seen regularly in tailings areas. Presumably, other animals such as rabbits and field mice native to the area are also present. Burrowing animals can dig up covered tailings.

At Shiprock, New Mexico, the main tailings pile has been covered with rock. While this may not be as esthetically pleasing as green grass, a rock cover seems to be a more permanent solution in a desert environment than a vegetative cover which requires irrigation in perpetuity. Atlas Minerals at Moab, Utah, has stabilized the sides of its active tailings area with a crushed, local red rock which blends well with the surroundings.[43]

Chemical stabilization of tailings by spraying petroleum derivatives has been tried, but is expensive and only lasts about a year.[28,55,91-93]

The stabilization methods used at the present time are regarded by Public Health authorities as interim control measures rather than a permanent disposal method.[28,29] All require regular inspection and maintenance when necessary to ensure that the cover remains intact.[28]

9.6.7 Chemical Treatment

Tailings can be made less hazardous by removing the radium. Laboratory tests have shown that 97 to 98% of the radium can be removed by three leaches with 3 *M* HNO_3 at 85°C,[94] and 90 to 93% by leaching with versene (tetrasodium ethylenediaminetetraacetate).[94,95,96] It has been reported that 95 to 100% of the radium can be recovered from Czechoslovakian tailings by leaching with 1 N KCl or 1 N NaCl;[97] however this was ineffective on Ambrosia Lake tailings.[94] The nitric acid leach appears to be the most promising. Chemical costs alone for the versene treatment would more than double the cost of uranium.[96] Large quantities of leaching solution are required because the radium is associated with the sparingly soluble calcium sulfate which must also be dissolved.[94] Nitric acid can be purified by distillation and recycled, but the removal of calcium sulfate from a potassium or sodium chloride salt solution does not seem practical. Without recycle, the disposal of large volumes of contaminated salt solution would itself have a serious environmental impact.

9.7 Radon and Other Gaseous Effluents

9.7.1 Radon from Tailings

Radon-222 gas will emanate from the tailings pile for thousands of years unless both the radium-226 parent (half-life, 1,620 years) and the thorium-230 grandparent (half-life, 83,000 years) are removed or a radon diffusion barrier is placed over the pile. The solid, particulate daughters from radon-222 (half-life, 3.83 days) deposit on dust particles in the air and are a significant part of the total airborne radioactive particulates. The concentrations of individual radon daughters (polonium-210, polonium-218, lead-214, lead-210, and bismuth-214) in airborne particulate samples range from 2 to 100,000 times the radium concentration from wind erosion of tailings (Tables 9.25 and 9.26). Even if the pile is covered with 6 in. to 2 ft of soil to prevent wind and water erosion, the radon emanation from the pile and subsequent diffusion through the soil cover will provide a perpetual source of both radon gas and airborne, particulate radon daughters.

The radon-222 concentration 3 ft above a tailings pile generally ranges from 1 to 34 pCi/liter* (1 to 34 x 10^{-9} μCi/ml) (Tables 9.26, 9.27, and 9.28). The concentration at 3 ft is highly variable, depending on the amount of wind available for atmospheric dilution. For example, at Station 4 at Mexican Hat, the 24-hr sample collected during light wind contained 5.7 pCi of radon-222 per liter, while the sample collected during 10- to 20-mph winds contained only 0.7 pCi/liter (Table 9.26). With the wind constantly moving radon and daughter products away from the pile, the radioactive materials do not reach secular equilibrium (Table 9.26). Radon and the upper members of the chain are expected to predominate close to the pile. At greater distances from the pile, the short-lived upper members of the chain will have decayed, leaving predominantly lead-210, bismuth-210, and polonium-210 as the residual activities. Most of the data is based on grab samples; however, Shearer and Sill[98] determined an annual average by collecting samples at regular intervals for a calendar year (Table 9.27). The radon concentrations 3 ft above active tailings piles at Grand Junction and Salt Lake City were 7.8 and 7.2 pCi/liter, respectively. The radon concentration was 16 pCi/liter over dry, unstabilized tailings at Durango, and 3.5 pCi/liter over tailings at Monticello, which had been covered with 2 ft of soil. The radon concentration at four stations located one-half mile from the Grand Junction pile averaged 1.9 pCi/liter. One station at Durango, located one-fourth mile from the pile, averaged 1.4 pCi/liter. All other off-pile stations averaged approximately background, which was about 0.4 pCi/liter at Durango, Salt Lake City, and Monticello, and probably 0.83 pCi/liter in Grand Junction. Unfortunately, Shearer and Sill did not

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*MPC for radon-222 leaving the boundary of a restricted area is 3 pCi/liter (3 x 10^{-9} μCi/ml) above background. The ICRP recommends a 1 pCi/liter limit for continuous exposure to individuals in the general population.[98]

measure several important parameters, such as the areas of wet and dry tailings at the active mills and the radium concentration in the upper layers of the pile. Consequently, their data cannot be extrapolated to other tailings piles by using the diffusion theory.

Other than the environmental monitoring, no studies have been made concerning the diffusion of radon in tailings piles. However, related work has been done on the diffusion of radon through the ground because of interest in the radon emanation method of uranium prospecting in the Soviet Union.[99] Kraner et al.[100] have shown that the steady-state diffusion of radon from natural sources in alluvium soil at Yucca Flats can be described mathematically by an equation derived from diffusion theory. In the model, the soil is viewed as a matrix of impermeable solid particles containing a maze of capillaries through which the diffusion takes place.

$$J_{(x)} = -D_e C_v \sqrt{\frac{\lambda}{D_e/v}} \; e^{-\sqrt{\lambda/D_e/v}\; x} \qquad (1)$$

At x = 0, i.e., the surface, the equation reduces to

$$J_o = -D_e C_v \sqrt{\frac{\lambda}{D_e/v}} \, , \qquad (2)$$

where*

$J_{(x)}$ = radon flux across a spatial area or total section of the bulk medium,

D_e = effective diffusion coefficient for radon through the fluid (air, water, etc.) in the void spaces between the solid particles,

λ = decay constant of radon-222 = 0.692/half-life = 2.1×10^{-6} sec,

v = void fraction; the fraction of the total volume which is not occupied by solid particles (this is often called the porosity[99-101] and should not be confused with the porosity of an individual particle),

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*Some of the symbols used by Kraner et al.[100] have been changed to clarify the meaning of the terms.

C_v = concentration of radon in the voids (interstices) between the particles, and

x = distance from the interface into the medium containing the radon source.

The negative sign means that the diffusion proceeds in the opposite direction from the measurement of x.

The term "D_e", as it has been defined here, is the same as the k_e used by Culot et al.[101] As they have pointed out, the diffusion coefficient in the review article by Tanner[99] includes the porosity (i.e., void fraction) so that

$$D_{\text{Tanner}} = \frac{D_e}{v} = \frac{D_{\text{Kraner}}}{\text{porosity}} = \frac{k_{e\ \text{Culot}}}{\text{porosity}} .$$

This has caused some confusion, especially when the Tanner and Kraner papers were published consecutively in the Proceedings. The effective diffusion coefficient for a fluid in the voids of a solid matrix will be lower than for the same fluid as a continuous medium because of the many "blind alleys" in the capillary structure. For example, the D_e/v of radon in dry sand is about 2/3 the value in air (Table 9.29). The diffusion coefficient for air is 10^4 times the coefficient in water. Even small amounts of moisture cause a considerable decrease in the effective diffusion coefficient for sands and soils. For example, the D_e/v for dry sand is 6.8×10^{-2} cm^2/sec. In sands containing 17% moisture, it is 5.0×10^{-3}; for soil with 37% moisture (mud), it is 5.7×10^{-6} (Table 9.29). Since the radon flux on the surface is directly proportional to the square root of the effective diffusion coefficient [Eq. (2)], it is important to know the moisture content. Dry uranium ore tailings can be expected to release ~100 times as much radon as wet tailings. Shearer and Sill[98] attributed the high radon values over the Durango pile to the fact that the pile was sited against a mountain so that all the radon emanated from one side. It is also possible that the Durango values are high because the pile had been inactive for 4 years at the time of the survey and may have had a larger area of dry tailings than either the Grand Junction or Salt Lake City piles, where the active mills were pumping liquid effluent to the tailings area.

The term "C_v", the concentration of radon in the voids between the particles, is related to the radium content of the tailings by:

$$C_v = \frac{E\ C_t}{v} ,$$

where

E = emanation coefficient (the fraction of the total radon that escapes the solid particles and is free to migrate),

C_t = activity of radium in the solid tailings per unit volume of the bulk medium = activity of radium per gram tailings x gram tailings per cm^3 of the bulk medium, and

v = void fraction.

The emanation coefficient is a measure of the probability that a recoil radon atom will enter a void where it is free to migrate, rather than being trapped in a solid particle. Since the number of fissures and pores in the tailings particles could vary from ore to ore, there is no reason, necessarily, to expect the emanation coefficient to be the same for all tailings piles. The emanation coefficient, E, for the sand fraction of Grand Junction tailings has been measured experimentally as 0.2.[101] Congo ore tailings processed by Mallinckrodt retained an estimated 50 to 90% of the radon based on gamma surveys.[102] Typical void fractions and weights of solid tailings per unit volume of the bulk medium are shown in Table 9.30. The finer alkaline tailings have a higher void fraction than do the coarser ground acid leach tailings.

The surface of a tailings pile is not at steady state. Kraner has fitted the steady-state Eq. (1) to the experimental data for soil depths of 3 ft and greater, but in the upper 6 to 12 in. of soil the apparent distribution coefficient was 3 times higher.[100] Equation (2) for determining the flux at the surface must, therefore, be regarded as a crude approximation. Solutions have been developed for estimating the radon emanation under nonsteady-state conditions;[101,103] however, there are meteorological variables whose effects can only be determined experimentally. Kraner[100] observed that strong winds or a thermally unstable atmosphere with convective overturning will deplete radon from upper soil layers, i.e., increase the radon emanation. Precipitation will reduce the radon diffusion. Freezing moist ground to a depth of 6 in. will reduce the surface radon flux by 40% compared with stable summer conditions, while an ice cap will trap almost all the radon in the soil.[100]

The diffusion of radon from a plane source (an ore body or a tailings pile) through a medium which does not contain a source (an earth cover) can be described by:[99,101]

$$C_{(x)} = C_p \, e^{-\sqrt{\lambda v/D_e x}} \quad , \qquad (3)$$

where

$C_{(x)}$ = radon concentration at a distance x from the plane source,
C_p = radon concentration in the plane source, and
x = depth of the cover.

The constants were defined earlier.

Diffusion theory predictions of the attenuation in the radon emanation by covering the tailings pile are given in Table 9.31. Columns 1 or 2, building sand with 4% moisture or Yucca Flats soil, are probably the best models for a near desert environment (6 to 8 in. annual precipitation) like New Mexico or Grand Junction, Colorado. Column 3, fine quartz sand with 15% moisture,provides a reasonable fit with the experimental data for the pile at Monticello, Utah (annual precipitation, 14 in.; 7,050-ft elevation)[86] and may also be representative of piles in Wyoming where the annual precipitation is about 14 in. It is obvious from Table 9.31 that the 6-in. soil cover commonly used today does little to reduce the emanation of radon. To reduce the radon release by a factor of 10 would require at least a 5-ft cover in Wyoming and a 10-ft cover in New Mexico. Reduction by a factor of 100 would require at least a 10-ft cover in Wyoming and 20 ft or more in New Mexico. Clay is superior to soil or sand. The figures for mud show the beneficial effect of water, i.e., 6 in. of mud is roughly equivalent to 20 ft of soil in Wyoming or 40 ft of soil in New Mexico.

A rough correlation for the Monticello pile between the attenuation calculated from diffusion theory and the environmental monitoring data of Shearer and Sill can be made.[98] The annual average radon concentration over the stabilized Monticello pile was 3.5 pCi/liter. While no data are available for the Monticello pile before stabilization, a rough estimate can be made from the three uncovered piles since the radium concentration was about the same in each case. The radon concentration over the dry, unstabilized Monticello pile must have been greater than the 7.5 pCi/liter measured at the active piles in Grand Junction and Salt Lake City, which would have had large areas of wet tailings. It was probably less than the 16.0 pCi/liter measured at the Durango pile, which is sited in a narrow valley where atmospheric dilution would be less. Therefore, the radon attenuation achieved by stabilizing the Monticello pile was:

$$\frac{3.5}{7.5} > \frac{C_{(x)}}{C_p} > \frac{3.5}{16.0} \text{ , or } 0.47 > \frac{C_{(x)}}{C_p} > 0.22 \quad .$$

Actually there were two covers placed on the Monticello pile. The first was a 2- to 4-ft cover of tailings sand over the slimes, followed by a 2-ft soil cover over the entire pile.[81] Assuming that the tailings composition in Table 9.6 is representative of the Monticello pile,* then before stabilization 65% of the surface would have been covered with +325 mesh sands containing an average of 933 dpm/g of radium and 35% of the surface would have been a -325 mesh slimes pond containing 5,957 dpm/g. Covering the slimes with 3 ft of tailings sand containing 15% moisture would give a radon attentuation of 0.42 in the slimes area and 0.67 for the overall pile. The 2-ft soil cover with 15% moisture provides an additional attentuation of 0.51. Therefore, the net radon attentuation estimated from diffusion theory for the two-step stabilization of the Monticello pile is 0.27, which is in agreement with the $0.47 > C_{(x)}/C_p >$ 0.22 estimated from environmental monitoring.

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*While the reference for Table 9.6 does not explicitly state that these were Monticello tailings, most of the other work in the report was done in cooperation with the Monticello mill.

9.7.2 Radon from the Mill

The amount of radon gas released during milling operations has not been reported. Tsivoglou and O'Connell postulated that 24% of the gross alpha is lost during milling as radon and subsequent short-lived daughters.[104] However, their material balance did not close, and this value appears to be high. Seeley has estimated very roughly that probably about 10% of the radon is lost during milling by comparison of the bismuth-214 growth curves for crushed uranium ore and leached ore samples.[105] Seeley points out that in order to accurately determine the radon loss he would need samples of freshly crushed ore, ground ore, and tailings sealed at the mill. Analysis for radon daughters in air samples collected inside one mill in September 1967 showed 0.27 WL at the top of the ore bins, 0.26 WL near the rod mill, 0.16 ML near the classifiers, and 0.03 WL around the leach tanks.[106] The other 13 samples were less than 0.01 WL.[106] As might be expected, most of the radon was released during the crushing and grinding operations, and from the ore bins.

9.7.3 Nonradioactive Gases

The usual effluents from burning fuels for heat and vehicle exhausts will be released. Some ammonia is released if the mill uses an ammonia precipitation circuit, and some sulfur dioxide if it has a sulfuric acid manufacturing plant. Mills processing vanadium ores use higher leaching temperatures and may release traces of sulfuric acid mist; in general, however, there is very little acid mist as evidenced by the absence of corrosion.

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Table 1.1. Summary of Variables of Radwaste Treatment Systems for Model Uranium Mills*

Radwaste Case No.	1 (Current, Base Case)	2 (Limited Current Use)	3 (Near Future)	4 (Future)		5 (Advanced)	6 (Advanced)			7 (Advanced)
				a	b		a	b	c (Not applicable to alkaline leach mill)	
Airborne (mill processes only)										
Objective	Control process dust	Reduce ore dust release by 3 and yellow cake dust release by 4	Reduce ore dust release by 13 and yellow cake dust release by 10	Reduce ore dust release by 65 and yellow cake dust release by 20	Same as Case 4a	Reduce ore dust release by 65 and yellow cake dust release by 10^4	Reduce ore dust release by 10^5 and yellow cake dust release by 10^4	Same as Case 6a	Same as Case 6a	**Reduce radon release from the mill by 10^2; ore dust release by 10^5, and yellow cake release by 10^4**
Treatment										
Ore dusts	Orifice	Wet impingement	Low energy venturi	Reverse jet bag filter; windbreak around ore yard	Same as Case 4a	Same as Case 4a	Reverse jet bag filter; HEPA filter; windbreak around ore yard	Same as Case 6a	Same as Case 6a	**Bag filter; HEPA filter; charcoal delay trap; windbreak around ore yard**
Yellow cake dust	Wet impingement	Low energy venturi	Medium energy venturi	High energy venturi	Same as Case 4a	High energy venturi; HEPA filter	Same as Case 5	Same as Case 5	Same as Case 5	**Same as Case 5**
Liquid										
Objective	Zero liquid release to surface waters; 10% seepage from the tailings pond of radioisotopes dissolved in liquid effluents	Same as Case 1	Reduce seepage of radioisotopes by 5	Reduce seepage of radioisotopes by 100	Same as Case 4a	Same as Case 4a	Zero liquid release	Same as Case 6a	Reduce seepage of radioisotopes by 10^3; recycle acid and water	**Same as Case 4a**
Treatment	Natural evaporation from tailings pond; seepage to ground; 10-ft-high starter dam of native material; dam raised with tailings	Same as Case 1	Natural evaporation from pond; site selected for low seepage through bottom; earth dam with clay core	Acidic effluents: lime neutralize; alkaline effluents: copperas precipitation; natural evaporation from pond sealed on bottom and sides with 5/16-in. asphalt membrane	Same as Case 4a	Same as Case 4a	Metal evaporator	Same as Case 6a	Metal evaporator and rectifier column	**Same as Case 4a**
Solid										
Objective	Eliminate windblown tailings dust after mill closes and reduce surface water leaching of tailings	Eliminate windblown tailings dust while mill is active and increase probability that the long-term tailings cover will remain intact	Reduce radon emanation from tailings by 4; eliminate penetration of tailings by vegetation or surface runoff	On-site waste disposal which permits some surface use of land; reduce radon emanation by 40	Alternate method of reducing radon emanation by 40 without deep burial; decrease leach rate of solid by 10^{10}	Fix solids in a form less leachable by underground waters; reduce radon emanation by 1000	Fix solids in a form less leachable by underground waters; reduce radon emanation by 160	Same as Case 6a	Same as Case 6a	**Reduce radon emanation by 50,000; lower leach rate of solids by 10^{10}**
Treatment										
Basic	Tailings pile; 10-ft-high starter dam of native materials; dam raised with tailings	Same as Case 1	Tailings impoundment; dam of native materials and compacted clay core; diversion ditches and dikes to bypass surface runoff; site selected for low seepage through bottom	Tailings impoundment the same as Case 3 except the bottom and sides are lined with a 5/16-in.-thick asphalt membrane	Same as Case 4a	Slurry with cement and pump to landfill or mine lined with 5/16-in. asphalt for disposal as cemented product (1 part cement to 20 parts tailings)	Sand/slime separation; incorporate slimes and evaporator concentrates in cement (1 part cement to 20 parts tailings); cemented product to landfill or mine; washed sand to landfill or mine	Sand/slime separation; incorporate slimes and evaporator concentrates in asphalt; asphalt product to landfill or mine; washed sand to landfill or mine	Substitution of nitric acid leach for conventional sulfuric acid leach; incorporate evaporator concentrates in asphalt; tailings to a Case 2 type impoundment.	**Same as Case 4a**
Cover, mill active	None	All tailings either under pond water or covered temporarily with a chemical spray or mine waste	Same as Case 2	Same as Case 2	Same as Case 2	None	Cover with final cover as milling proceeds	Same as Case 6a	Cover with final cover as milling proceeds	**Same as Case 2**
Cover, final	Six-inch earth cover topped with rock or vegetation	Two-foot earth cover topped with rock or vegetation	Eight-foot earth cover topped with rock or vegetation	Twenty-foot earth cover topped with rock or vegetation	5/16-in. asphalt membrane and 2-ft earth cover topped with rock or vegetation	Same as Case 4a	Same as Case 4a	Same as Case 4a	Twenty-ft earth cover over evaporator concentrates incorporated in asphalt; 2-ft earth cover over tailings; both topped by rock or vegetation	**1-in. asphalt membrane and 2-ft earth cover topped by rock or vegetation**

[*] All cases apply to both sulfuric acid and alkaline leach mills except where indicated.

Table 4.1. Chemical Consumption for Model Uranium Mills[a]

	lb/ton of Ore	
	Acid Leach-Solvent Extraction	Alkaline Leach
Sulfuric Acid	9.0E+1	-
Sodium Chlorate	2.7E00	-
Ammonia	2.1E00	-
Flocculant	1.2E-1	2.0E-2
Amine (long chain)	3.0E-2	-
Alcohol	7.0E-2	-
Kerosene	9.0E-1	-
Iron (rods for grinding)	5.0E-1	5.0E-1
Sodium Carbonate	-	2.6E00
Sodium Hydroxide	-	2.5E+1
Potassium Permanganate	-	7.5E00
Filter Aid	-	5.0E-2

[a] See Table 9.21 for Spring 1973 survey of chemical consumption at uranium mills.

Table 4.2. Airborne Uranium Mill Radwaste - Assumptions Used in Source Term Calculations and Design Basis for Cost Estimates

(Assumptions based on survey Sects. 9.3.2, 9.3.3, 9.4, and 9.7.2)

Ore Dusts	
Crusher, screens, conveyors, etc.	
Processing rate	125 tons/hr (Table 9.9)
Operating time	16 hr/day, 365 days/yr (Table 9.9)
Airflow: Cases 1 to 6	20,000 cfm (Table 9.9)
Case 7	3,000 cfm
Ore Bins	
Operating time	24 hr/day, 365 days/yr
Airflow: Cases 1 to 6	2,000 cfm
Case 7	500 cfm
Total dust load to the collectors:[a]	320 lb/day (calculated from estimated ore loss of a mill running a 6% moisture ore, Table 9.12)
Activity of dust	0.6 μCi of ^{238}U/lb in secular equilibrium with 13 radioactive daughters (Fig. 9.1, Table 9.2). Dust assumed to contain 2.4 times as much activity as the mill feed. (Table 9.12; supporting evidence in Tables 9.4-9.8)
Particle size of dust	
Stream to the dust collectors	Same as Stairmand's "standard industrial silica dust" (Tables 9.14-9.16)
Mill effluent	<10 μ
Uranium Concentrate Dusts	
Processing rate	7,300 lb U_3O_8/day
Operating time	24 hr/day, 365 days/yr (Table 9.10)
Airflow: Cases 1 to 7	4,500 cfm (Table 9.10)
Dust load to the collector:[a]	91 lb/day (calculated from average U_3O_8 loss of 0.02% reported by mills, plus a 25% safety factor, Table 9.13).
Activity of dust	
Acid leach mill	^{238}U: 128 μCi/lb ^{230}Th: 6.4 μCi/lb (5% of ^{238}U, Sect. 9.3.2) ^{226}Ra: 0.26 μCi/lb (0.2% of ^{238}U, Sect. 9.3.2) Other: negligible (Sect. 9.3.2)
Alkaline leach mill	^{238}U: 128 μCi/lb ^{226}Ra: 2.6 μCi/lb (2% of ^{238}U, Sect. 9.3.2) Other: negligible (Sect. 9.3.2)
Particle size of dust	
Stream to the dust collector	Same as Stairmand's "standard industrial silica dust" (Tables 9.14-9.16)
Mill effluent	<10 μ
Radon Gas	51.5 μCi/ton of ore; released from ore by crushing and grinding operations (Sect. 9.7.2)

Efficiencies of Radwaste Treatment Methods

Treatment Method	Average Pressure Drop, in. H_2O	Efficiency of Dust Collector, %	Efficiency of Radon Removal, %
Wet Scrubbers			
Orifice (baffle, self-induced spray deduster)	6.1[b]	93.6[b]	0
Wet impingement (irrigated target, perforated plate)	6.1[b]	97.9[b]	0
Venturi plus mist separator			
Low energy	12.5[b]	99.5[b]	0
Medium energy	20.0[b]	99.7[b]	0
High energy	31.5[b]	99.9[b]	0
Bag Filter: reverse jet	3.0[b]	99.9[b]	0
HEPA filter	6 to 10[c]	99.95[c]	0
Charcoal delay trap + HEPA filter		99.95[c]	99.9

[a] Dust load refers to dust treated by the scrubber or filter and does not include particulates which settle in the duct system.

[b] C. J. Stairmand, The Chemical Engineer 194, CE 322 (December 1965).

[c] C. 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.

Table 4.3. Airborne Radwaste Treatment Cases for Model Uranium Mills, Ore Dusts and Radon[a,b]
(Mill Processes Only - Tailings Area Not Included)

		Dusty Ore Containing 6% Moisture					Radon-222 Gas			
		Ore Dust Release		Maximum Adult Dose at 0.5 Mile from New Mexico Mill, 100% Food Ingestion (mrem/yr)[d]					Treatment Cost	
Case No.	Treatment	Particulates (lb/day)	^{238}U[c] (Ci/yr)	Total Body	Bone	Lung	Release (Ci/yr)	Maximum Adult Lung Dose at 0.5 Mile from New Mexico Mill[e] (mrem/yr)	Capital ($1000)	Annual ($1000)
1	Orifice or baffle	20.5	4.52E-3	18.0	192.0	19.6	37	4.4E-1	91[f]	31[f]
2	Wet impingement	6.7	1.48E-3	5.8	62.8	6.4	37	4.4E-1	109[f]	37[f]
3	Venturi: low energy	1.6	3.53E-4	1.5	15.0	1.5	37	4.4E-1	164[f]	61[f]
4	Reverse jet bag filter	0.32	7.06E-5	2.9E-1	3.0	3.1E-1	37	4.4E-1	320[f,g]	107[f,g]
5	Reverse jet bag filter	0.32	7.06E-5	2.9E-1	3.0	3.1E-1	37	4.4E-1	320[f,g]	107[f,g]
6	Reverse jet bag filter + HEPA filter	1.6E-4	3.53E-8	1.5E-4	1.5E-3	1.5E-4	37	4.4E-1	646[f,g]	214[f,g]
7	Bag filter + charcoal delay trap + HEPA filter	1.6E-4	3.53E-8	1.5E-4	1.5E-3	1.5E-4	0.37	4.4E-3	5,545[g,h]	1,381[g,h]

[a] Assumptions listed in Table 4.2.

[b] See Tables 9.9 and 9.12 for spring 1973 survey of dust control practices in the uranium milling industry.

[c] In secular equilibrium with 13 radioactive daughters (Fig. 9.1).

[d] Maximum doses at the Wyoming site are 81% of those at the New Mexico site.

[e] Maximum doses at the Wyoming site are 57% of those at the New Mexico site.

[f] 22,000-cfm airflow.

[g] Includes $10,000 capital or $3,000 annual cost for windbreaks around ore unloading yard.

[h] 3,500-cfm airflow.

Table 4.4. Effect of Moisture Content of Ore on Ore Dust Emissions from Model Uranium Mills[a,b]

		Ore Dust Release (Ci of ^{238}U/yr)[c]			Maximum Adult Dose at 0.5 Mile from New Mexico Mill, 100% Food Ingestion (mrem/yr)[d]					
					Total Body			Bone		
Case No.	Type of Dust Collector	6% Moisture	8% Moisture	9-10% Moisture	6% Moisture	8% Moisture	9-10% Moisture	6% Moisture	8% Moisture	9-10% Moisture
0	None	N.A.	N.A.	8.76E-4	N.A.	N.A.	3.5	N.A.	N.A.	37.1
1	Orifice or baffle scrubber	4.52E-3	5.95E-4	5.11E-5	18.0	2.4	2.0E-1	192.0	25.3	2.2
2	Wet impingement scrubber	1.48E-3	1.69E-4	1.75E-5	5.8	6.8E-1	7.0E-2	62.8	7.2	7.4E-1
3	Low-energy venturi scrubber	3.53E-4	4.01E-5	4.38E-6	1.5	1.6E-1	1.7E-2	15.0	1.7	1.9E-1
4	Reverse jet bag filter	7.06E-5	8.07E-6	8.76E-7	2.9E-1	3.2E-2	3.5E-3	3.0	3.4E-1	3.7E-2

[a] Calculated from ore dust losses estimated by three mill operators (Table 9.12), using model mill assumptions (Table 4.2).

[b] The long-term trend is toward wet (i.e., 9-10% moisture) ores.

[c] In secular equilibrium with 13 radioactive daughters.

[d] Maximum doses at the Wyoming site are 81% of those at the New Mexico site.

N.A. = not applicable; mills processing 6 to 8% moisture ores use dust collectors.

Table 4.5. Airborne Radwaste Treatment Cases for Model Uranium Mills, Yellow Cake Dusts[a,b,c]

				Maximum Adult Dose at 0.5 Mile from New Mexico Mill, 100% Food Ingestion (mrem/yr)[e]							
		Dust Release		Acid Leach-- Solvent Extraction Mill			Alkaline Leach Mill			Treatment Costs	
Case No.	Treatment	U_3O_8 (lb/day)	^{238}U[d] (Ci/yr)	Total Body	Bone	Lung	Total Body	Bone	Lung	Capital ($1000)	Annual ($1000)
1	Wet impingement	1.82	8.54E-2	2.2	40.4	9.3	7.3	73.5	15.2	36	12
2	Venturi: low energy	0.46	2.15E-2	5.5E-1	10.1	2.3	1.8	18.4	3.8	50	19
3	Venturi: medium energy	0.18	8.40E-3	2.2E-1	4.0	9.1E-1	7.2E-1	7.2	1.5	53	23
4	Venturi: high energy	0.09	4.38E-3	1.1E-1	2.1	4.7E-1	3.7E-1	3.7	7.8E-1	58	29
5-7	Venturi: high energy + HEPA filter	4.6E-5	2.15E-6	5.5E-5	1.0E-3	2.3E-4	1.8E-4	1.8E-3	3.8E-4	132	51

[a] Assumptions listed in Table 4.2.

[b] "Average" mill releases = ~0.80 times these maximum releases.

[c] See Tables 9.10 and 9.13 for spring 1973 survey of dust control practices in the uranium milling industry.

[d] Other radioactive materials released as impurities in the yellow cake are listed in Tables 4.6-4.9.

[e] Maximum doses at the Wyoming site are 81% of those at the New Mexico site.

Table 4.6. Airborne Source Terms for Model Acid Leach-Solvent Extraction Uranium Mill and Active Tailings Area in New Mexico Near End of 20-yr Life of Model Mill - Calculated Release of Radioactive Materials

Source	Ci/yr					
	U_{nat}	^{226}Ra	^{230}Th	^{234}Th	^{210}Pb, ^{210}Po, and ^{210}Bi, Each	^{222}Rn
Case 1						
Ore Crusher and Bins	4.5E-3	4.5E-3	4.5E-3	4.5E-3	4.5E-3	3.7E+1
Yellow Cake	8.5E-2	1.7E-4	4.7E-3	4.7E-3	-	-
Tailings Pond	-	-	-	-	-	1.7E+2
Tailings Beach						
0-10 μ	1.2E-4	1.3E-3	1.4E-3	1.2E-4	1.3E-3	3.5E+3
10-80 μ	2.8E-4	3.0E-3	3.3E-3	2.8E-4	3.0E-3	
Total	9.0E-2	9.0E-3	1.4E-2	9.6E-3	8.8E-3	3.7E+3
Case 2						
Ore Crusher and Bins	1.5E-3	1.5E-3	1.5E-3	1.5E-3	1.5E-3	3.7E+1
Yellow Cake	2.2E-2	4.3E-5	1.1E-3	1.1E-3	-	-
Tailings Pond	-	-	-	-	-	1.7E+2
Tailings Beach	-	-	-	-	-	3.5E+3
Total	2.4E-2	1.5E-3	2.6E-3	2.6E-3	1.5E-3	3.7E+3
Case 3						
Ore Crusher and Bins	3.5E-4	3.5E-4	3.5E-4	3.5E-4	3.5E-4	3.7E+1
Yellow Cake	8.4E-3	1.7E-5	4.2E-4	4.2E-4	-	-
Tailings Pond	-	-	-	-	-	2.2E+2
Tailings Beach	-	-	-	-	-	2.1E+3
Total	8.8E-3	3.7E-4	7.7E-4	7.7E-4	3.5E-4	2.4E+3
Case 4						
Ore Crusher and Bins	7.1E-5	7.1E-5	7.1E-5	7.1E-5	7.1E-5	3.7E+1
Yellow Cake	4.4E-3	8.8E-6	2.1E-4	2.1E-4	-	-
Tailings Pond	-	-	-	-	-	1.2E+2
Tailings Beach	-	-	-	-	-	2.0E+2
Total	4.5E-3	8.0E-5	2.8E-4	2.8E-4	7.1E-5	2.1E+3
Case 5						
Ore Crusher and Bins	7.1E-5	7.1E-5	7.1E-5	7.1E-5	7.1E-5	3.7E+1
Yellow Cake	2.2E-6	4.3E-9	1.1E-7	1.1E-7	-	-
Tailings Pond	-	-	-	-	-	1.2E+2
Tailings Beach	-	-	-	-	-	3.0E+2
Total	7.3E-5	7.1E-5	7.1E-5	7.1E-5	7.1E-5	4.6E+2
Case 6a and 6b						
Ore Crusher and Bins	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.7E+1
Yellow Cake	2.2E-6	4.3E-9	1.1E-7	1.1E-7	-	-
Tailings Pond	-	-	-	-	-	-
Tailings Beach	-	-	-	-	-	1.6E+2
Total	2.2E-6	3.9E-8	1.4E-7	1.4E-7	3.5E-8	2.0E+2
Case 6c						
Ore Crusher and Bins	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.7E+1
Yellow Cake	2.2E-6	4.3E-9	1.1E-7	1.1E-7	-	-
Tailings Pond	-	-	-	-	-	-
Tailings Beach	-	-	-	-	-	6.0E+1
Total	2.2E-6	3.9E-8	1.4E-7	1.4E-7	3.5E-8	9.7E+1
Case 7						
Ore Crusher and Bins	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.7E-1
Yellow Cake	2.2E-6	4.3E-9	1.1E-7	1.1E-7	-	-
Tailings Pond	-	-	-	-	-	1.2E+2
Tailings Beach	-	-	-	-	-	2.0E+3
Total	2.2E-6	3.9E-8	1.4E-7	1.4E-7	3.5E-8	2.1E+3

Table 4.7. Airborne Source Terms for Model Acid Leach-Solvent Extraction Uranium Mill and Active Tailings Area in Wyoming Near End of 20-yr Life of Model Mill - Calculated Release of Radioactive Materials

	Ci/yr					
Source	U_{nat}	^{226}Ra	^{230}Th	^{234}Th	^{210}Pb, ^{210}Po, and ^{210}Bi, Each	^{222}Rn
Case 1						
Ore Crusher and Bins	4.5E-3	4.5E-3	4.5E-3	4.5E-3	4.5E-3	3.7E+1
Yellow Cake	8.5E-2	1.7E-4	4.7E-3	4.7E-3	-	-
Tailings Pond	-	-	-	-	-	3.1E+2
Tailings Beach						
0-10 µ	3.9E-4	4.2E-3	4.5E-3	3.9E-4	4.2E-3	8.7E+2
10-80 µ	9.3E-4	1.0E-2	1.1E-2	9.3E-4	1.0E-2	
Total	9.1E-2	1.9E-2	2.4E-2	1.0E-2	1.9E-2	1.2E+3
Case 2						
Ore Crusher and Bins	1.5E-3	1.5E-3	1.5E-3	1.5E-3	1.5E-3	3.7E+1
Yellow Cake	2.2E-2	4.3E-5	1.1E-3	1.1E-3	-	-
Tailings Pond	-	-	-	-	-	3.1E+2
Tailings Beach	-	-	-	-	-	8.7E+2
Total	2.4E-2	1.5E-3	2.6E-3	2.6E-3	1.5E-3	1.2E+3
Case 3						
Ore Crusher and Bins	3.5E-4	3.5E-4	3.5E-4	3.5E-4	3.5E-4	3.7E+1
Yellow Cake	8.4E-3	1.7E-5	4.2E-4	4.2E-4	-	-
Tailings Pond	-	-	-	-	-	4.0E+2
Tailings Beach	-	-	-	-	-	1.4E+2
Total	8.8E-3	3.7E-4	7.7E-4	7.7E-4	3.5E-4	5.8E+2
Case 4						
Ore Crusher and Bins	7.1E-5	7.1E-5	7.1E-5	7.1E-5	7.1E-5	3.7E+1
Yellow Cake	4.4E-3	8.8E-6	2.1E-4	2.1E-4	-	-
Tailings Pond	-	-	-	-	-	2.1E+2
Tailings Beach	-	-	-	-	-	1.4E+2
Total	4.5E-3	8.0E-5	2.8E-4	2.8E-4	7.1E-5	4.0E+2
Case 5						
Ore Crusher and Bins	7.1E-5	7.1E-5	7.1E-5	7.1E-5	7.1E-5	3.7E+1
Yellow Cake	2.2E-6	4.3E-9	1.1E-7	1.1E-7	-	-
Tailings Pond	-	-	-	-	-	2.1E+2
Tailings Beach	-	-	-	-	-	3.0E+2
Total	7.3E-5	7.1E-5	7.1E-5	7.1E-5	7.1E-5	5.5E+2
Case 6a and 6b						
Ore Crusher and Bins	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.7E+1
Yellow Cake	2.2E-6	4.3E-9	1.1E-7	1.1E-7	-	-
Tailings Pond	-	-	-	-	-	-
Tailings Beach	-	-	-	-	-	1.6E+2
Total	2.2E-6	3.9E-8	1.4E-7	1.4E-7	3.5E-8	2.0E+2
Case 6c						
Ore Crusher and Bins	3.5E-8	3.5E-8	3.5E-3	3.5E-8	3.5E-8	3.7E+1
Yellow Cake	2.2E-6	4.3E-9	1.1E-7	1.1E-7	-	-
Tailings Pond	-	-	-	-	-	-
Tailings Beach	-	-	-	-	-	6.0E+1
Total	2.2E-6	3.9E-8	1.4E-7	1.4E-7	3.5E-8	9.7E+1
Case 7						
Ore Crusher and Bins	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.7E-1
Yellow Cake	2.2E-6	4.3E-9	1.1E-7	1.1E-7	-	-
Tailings Pond	-	-	-	-	-	2.1E+2
Tailings Beach	-	-	-	-	-	1.4E+2
Total	2.2E-6	3.9E-8	1.4E-7	1.4E-7	3.5E-8	3.6E+2

Table 4.8. Airborne Source Terms for Model Alkaline Leach Uranium Mill and Active Tailings Area in New Mexico Near End of 20-yr Life of Model Mill - Calculated Release of Radioactive Materials

	Ci/yr					
Source	U_{nat}	^{226}Ra	^{230}Th	^{234}Th	^{210}Pb, ^{210}Po, and ^{210}Bi, Each	^{222}Rn
Case 1						
Ore Crusher and Bins	4.5E-3	4.5E-3	4.5E-3	4.5E-3	4.5E-3	3.7E+1
Yellow Cake	8.5E-2	1.7E-3	-	-	-	-
Tailings Pond	-	-	-	-	-	6.5E+1
Tailings Beach						
0-10 μ	1.7E-4	2.3E-3	2.4E-3	1.7E-4	2.4E-3	5.9E+3
10-80 μ	1.2E-4	1.8E-3	1.8E-3	1.3E-4	1.8E-3	
Total	9.0E-2	1.0E-2	8.7E-3	4.8E-3	8.7E-3	5.8E+3
Case 2						
Ore Crusher and Bins	1.5E-3	1.5E-3	1.5E-3	1.5E-3	1.5E-3	3.7E+1
Yellow Cake	2.2E-2	4.3E-4	-	-	-	-
Tailings Pond	-	-	-	-	-	6.5E+1
Tailings Beach	-	-	-	-	-	5.7E+3
Total	2.4E-2	1.9E-3	1.5E-3	1.5E-3	1.5E-3	5.8E+3
Case 3						
Ore Crusher and Bins	3.5E-4	3.5E-4	3.5E-4	3.5E-4	3.5E-4	3.7E+1
Yellow Cake	8.4E-3	1.7E-4	-	-	-	-
Tailings Pond	-	-	-	-	-	7.4E+1
Tailings Beach	-	-	-	-	-	4.4E+3
Total	8.8E-3	5.2E-4	3.5E-4	3.5E-4	3.5E-4	4.5E+3
Case 4						
Ore Crusher and Bins	7.1E-5	7.1E-5	7.1E-5	7.1E-5	7.1E-5	3.7E+1
Yellow Cake	4.4E-3	8.8E-5	-	-	-	-
Tailings Pond	-	-	-	-	-	6.8E+1
Tailings Beach	-	-	-	-	-	4.3E+3
Total	4.5E-3	1.6E-4	7.1E-5	7.1E-5	7.1E-5	4.4E+3
Case 5						
Ore Crusher and Bins	7.1E-5	7.1E-5	7.1E-5	7.1E-5	7.1E-5	3.7E+1
Yellow Cake	2.2E-6	4.3E-8	-	-	-	-
Tailings Pond	-	-	-	-	-	6.8E+1
Tailings Beach	-	-	-	-	-	3.0E+2
Total	7.3E-5	7.1E-5	7.1E-5	7.1E-5	7.1E-5	4.1E+2
Case 6a and 6b						
Ore Crusher and Bins	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.7E+1
Yellow Cake	2.2E-6	4.3E-8	-	-	-	-
Tailings Pond	-	-	-	-	-	-
Tailings Beach	-	-	-	-	-	1.0E+2
Total	2.2E-6	7.8E-8	3.5E-8	3.5E-8	3.5E-8	1.4E+2
Case 7						
Ore Crusher and Bins	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.7E-1
Yellow Cake	2.2E-6	4.3E-8	-	-	-	-
Tailings Pond	-	-	-	-	-	6.8E+1
Tailings Beach	-	-	-	-	-	4.3E+3
Total	2.2E-6	7.8E-8	3.5E-8	3.5E-8	3.5E-8	4.4E+3

Table 4.9. Airborne Source Terms for Model Alkaline Leach Uranium Mill and Active Tailings Area in Wyoming Near End of 20-yr Life of Model Mill - Calculated Release of Radioactive Materials

	Ci/yr					
Source	U_{nat}	^{226}Ra	^{230}Th	^{234}Th	^{210}Pb, ^{210}Po, and ^{210}Bi, Each	^{222}Rn
Case 1						
Ore Crusher and Bins	4.5E-3	4.5E-3	4.5E-3	4.5E-3	4.5E-3	3.7E+1
Yellow Cake	8.5E-2	1.7E-3	-	-	-	-
Tailings Pond	-	-	-	-	-	1.2E+2
Tailings Beach						
0-10 u	1.1E-3	1.5E-3	1.5E-2	1.1E-3	1.5E-2	2.7E+3
10-80 u	9.4E-4	1.1E-3	1.1E-2	8.4E-4	1.1E-2	
Total	9.1E-2	3.2E-2	3.0E-2	6.4E-3	3.0E-2	2.8E+3
Case 2						
Ore Crusher and Bins	1.5E-3	1.5E-3	1.5E-3	1.5E-3	1.5E-3	3.7E+1
Yellow Cake	2.2E-2	4.3E-4	-	-	-	-
Tailings Pond	-	-	-	-	-	1.2E+2
Tailings Beach	-	-	-	-	-	2.7E+3
Total	2.4E-2	1.9E-3	1.5E-3	1.5E-3	1.5E-3	2.8E+3
Case 3						
Ore Crusher and Bins	3.5E-4	3.5E-4	3.5E-4	3.5E-4	3.5E-4	3.7E+1
Yellow Cake	8.4E-3	1.7E-4	-	-	-	-
Tailings Pond	-	-	-	-	-	1.3E+2
Tailings Beach	-	-	-	-	-	1.2E+3
Total	8.8E-3	5.2E-4	3.5E-4	3.5E-4	3.5E-4	1.4E+3
Case 4						
Ore Crusher and Bins	7.1E-5	7.1E-5	7.1E-5	7.1E-5	7.1E-5	3.7E+1
Yellow Cake	4.4E-3	8.8E-5	-	-	-	-
Tailings Pond	-	-	-	-	-	1.2E+2
Tailings Beach	-	-	-	-	-	1.1E+3
Total	4.5E-3	1.6E-4	7.1E-5	7.1E-5	7.1E-5	1.2E+3
Case 5						
Ore Crusher and Bins	7.1E-5	7.1E-5	7.1E-5	7.1E-5	7.1E-5	3.7E+1
Yellow Cake	2.2E-6	4.3E-8	-	-	-	-
Tailings Pond	-	-	-	-	-	1.2E+2
Tailings Beach	-	-	-	-	-	3.0E+2
Total	7.3E-5	7.1E-5	7.1E-5	7.1E-5	7.1E-5	4.6E+2
Case 6a and 6b						
Ore Crusher and Bins	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.7E+1
Yellow Cake	2.2E-6	4.3E-8	-	-	-	-
Tailings Pond	-	-	-	-	-	-
Tailings Beach	-	-	-	-	-	1.0E+2
Total	2.2E-6	7.8E-8	3.5E-8	3.5E-8	3.5E-8	1.4E+2
Case 7						
Ore Crusher and Bins	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.5E-8	3.7E-1
Yellow Cake	2.2E-6	4.3E-8	-	-	-	-
Tailings Pond	-	-	-	-	-	1.2E+2
Tailings Beach	-	-	-	-	-	1.1E+3
Total	2.2E-6	7.8E-8	3.5E-8	3.5E-8	3.5E-8	1.2E+3

Table 4.10. Concentrations of Airborne Radionuclides in Vent or Stack Gases from Model Uranium Mills[a,b]

Case No.	µCi/ml							
	U_{nat}	^{226}Ra	^{230}Th	^{234}Th	^{210}Pb	^{210}Po	^{210}Bi	^{222}Rn
Maximum Permissible Conc., 10 CFR 20, Table II[c] (General population)	2E-12[d]	2E-12	3E-14	1E-09	4E-12	7E-12	2E-10	3E-9
			Ore Crusher and Bin Vent - Dusty Ore Containing 6% Moisture					
1	2.0E-11	2.0E-11	2.0E-11	2.0E-11	2.0E-11	2.0E-11	2.0E-11	1.6E-7
2	6.5E-12	6.5E-12	6.5E-12	6.5E-12	6.5E-12	6.5E-12	6.5E-12	1.6E-7
3	1.5E-12	1.5E-12	1.5E-12	1.5E-12	1.5E-12	1.5E-12	1.5E-12	1.6E-7
4	3.1E-13	3.1E-13	3.1E-13	3.1E-13	3.1E-13	3.1E-13	3.1E-13	1.6E-7
5	3.1E-13	3.1E-13	3.1E-13	3.1E-13	3.1E-13	3.1E-13	3.1E-13	1.6E-7
6	1.6E-16	1.6E-16	1.6E-16	1.6E-16	1.6E-16	1.6E-16	1.6E-16	1.6E-7
7	9.6E-16[e]	9.6E-16[e]	9.6E-16[e]	9.6E-16[e]	9.6E-16[e]	9.6E-16[e]	9.6E-16[e]	1.0E-8[e]
			Yellow Cake Dryer and Packaging Vent - Acid Leach					
1	1.3E-09	2.6E-12	6.5E-11	6.5E-11	-	-	-	-
2	3.2E-10	6.4E-13	1.6E-11	1.6E-11	-	-	-	-
3	1.2E-10	2.4E-13	6.0E-12	6.0E-12	-	-	-	-
4	6.5E-11	1.3E-13	3.2E-12	3.2E-12	-	-	-	-
5	3.0E-14	6.0E-17	1.5E-15	1.5E-15	-	-	-	-
6	3.0E-14	6.0E-17	1.5E-15	1.5E-15	-	-	-	-
7	3.0E-14	6.0E-17	1.5E-15	1.5E-15	-	-	-	-
			Yellow Cake Dryer and Packaging Vent - Alkaline Leach					
1	1.3E-09	2.6E-11	-	-	-	-	-	-
2	3.2E-10	6.4E-12	-	-	-	-	-	-
3	1.2E-12	2.4E-12	-	-	-	-	-	-
4	6.5E-11	1.3E-12	-	-	-	-	-	-
5	3.0E-14	6.0E-16	-	-	-	-	-	-
6	3.0E-14	6.0E-16	-	-	-	-	-	-
7	3.0E-14	6.0E-16	-	-	-	-	-	-

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[a] Assumptions are listed in Table 4.2; source terms are given in Tables 4.6-4.9.

[b] See Table 9.11 for analysis of stack effluents during period January 1961–April 1966.

[c] The 1/3 factor has not been applied.

[d] For ore dusts, may analyze only for U_{nat}; MPC = 8×10^{-15} µCi U_{nat}/ml.

[e] Crusher airflow reduced from 20,000 to 3,000 cfm, and ore bin airflow from 2,000 to 500 cfm.

Table 4.11. Composition of Liquid Waste from Model Uranium Mills[a]

	Acid Leach-Solvent Extraction	Alkaline Leach
pH	2.0E00	1.0E+1
	Concentration, g/liter	
Calcium	5.0E-1	-
Iron	1.0E00	5.0E-4
Aluminum	2.0E00	1.0E00
Ammonia	5.0E-1	-
Sodium	2.0E-1	3.0E00
Arsenic	2.0E-4	2.0E-4
Fluoride	5.0E-3	2.0E-3
Vanadium	1.0E-4	1.0E-4
Sulfate	3.0E+1	2.0E00
Chloride	3.0E-1	1.0E00
Carbonate	-	6.0E00
Total Dissolved Solids	3.5E+1	1.2E+1
	Concentration, pCi/liter or 10^{-9} μCi/ml	
Radionuclides		
U_{nat}	6.7E+3	1.0E+4
^{226}Ra	5.0E+2	1.0E+2
^{230}Th	1.9E+5	2.0E+1
^{210}Pb	5.0E+2	8.0E+1
^{210}Po	5.0E+2	2.0E+1
^{210}Bi	5.0E+2	2.0E+1

[a] See Table 9.18 for Spring 1973 survey of liquid effluents from uranium mills, and Tables 9.19 and 9.20 for liquid effluents during periods 1959-1962.

Table 4.12. Concentrations of Radionuclides in Solid Waste (Tailings) from Model Uranium Mills[a]

	Sand, >200 mesh (pCi/g)		Slime,[b] <200 mesh (pCi/g)		
Radionuclide	Cases 1 to 6b, Case 7	Case 6c	Cases 1 to 6b, Case 7	Case 6c	Case 6c Evaporator Concentrate
		Acid Leach-Solvent Extraction			
U_{nat}	10	2.4	150	13	30
^{226}Ra	120	2.4	1,610	13	3.0E+4
^{230}Th	60	2.4	1,750	13	3.0E+4
^{234}Th[c]	10	2.4	150	13	30
^{210}Pb	120	2.4	1,610	13	3.0E+4
^{210}Po	120	2.4	1,610	13	3.0E+4
^{210}Bi	120	2.4	1,610	13	3.0E+4
		Alkaline Leach			
U_{nat}	10	Not applicable	70	Not applicable	
^{226}Ra	170		950		
^{230}Th	170		960		
^{234}Th[c]	10		70		
^{210}Pb	170		960		
^{210}Po	170		960		
^{210}Bi	170		960		

[a] Assumptions:

Acid leach-solvent extraction, all cases except Case 6c:

Slimes fraction is 30% by weight of the tailings and contains 85% of the insoluble radioactive materials (Tables 9.4 and 9.6-9.8). 91% of the uranium in the mill feed is recovered; 1.4% remains in the sands and 7.6% in the slimes. 50% of the thorium dissolves during milling and ultimately crystallizes in the slimes fraction; 50% is insoluble in the tailings (Sect. 9.3.2). Other radionuclides are insoluble (Sect. 9.3.2).

Alkaline leach, all cases:

Slimes fraction is 50% by weight of the tailings and contains 85% of the insoluble radioactive materials (Tables 9.4 and 9.7). 93% of the uranium in the mill feed is recovered; 1.0% remains in the sands and 6.0% in the slimes. 2% of the radium dissolves during milling and is precipitated with the yellow cake; 98% is insoluble in the tailings (Sect. 9.3.2). Other radionuclides are insoluble (Sect. 9.3.2).

Nitric acid leach-solvent extraction, Case 6c:

99% of all radioactive materials are leached from the ore and leave the mill as either evaporator concentrates or yellow cake.

[b] Includes radionuclides in residues from liquid.

[c] Assuming most of the ^{234}Th has decayed so that ^{234}Th activity is the same as the ^{238}U activity.

Table 4.13. Characteristics of Model Tailings Impoundment Basin Used in Estimation of Source Terms and Costs - Model is a Wedge-Shaped Natural Basin with a Square Surface

Mill Process	Site	Assumed Seepage Loss (%)	Average Area of Evaporation Pond and Wet Beach[a] (acres, Used in Source Term Calculation)	Required Area for Evaporation Pond and Wet Beach, Allowing 20% Contingency for Abnormal Weather (acres, Used in Designing Tailings Impoundment Basin)	Total Height of Dam - Earth plus Tailings[b,c] (ft)	Height of Earth Dam (ft)	Length of Dam[b] (ft)	Volume of Earth Fill in Dam[d] (yd^3)	Volume of 10-ft-thick Clay Core in Dam (yd^3)	Total Area of Impoundment Basin[e] (acres, Used in Estimating Cost of Final Stabilization and Asphalt Lining	Average Area Covered by Tailings After Mill Has Closed and Pile Has Been Stabilized[e] (acres, Used in Source Term Calculations)	Average Area of Dry Beach Near End of 20-yr Life of Mill (acres, Used in Source Term Calculations and Estimating Cost of Temporary Cover)	Area of Tailings on the Face of the Dam at Its Maximum Height (acres, Used in Source Term Calculations and Estimating Cost of Temporary and Permanent Cover)
Case 1 or Case 2													
Acid Leach-SX	New Mexico	10	80	96	100	10	2,248	25,000	None	116	116	36	12
Acid Leach-SX	Wyoming	10	145	174	69	10	2,743	30,600	None	174	147	2	10
Alkaline Leach	New Mexico	10	50	60	100	10	2,248	25,000	None	116	116	66	12
Alkaline Leach	Wyoming	10	91	109	100	10	2,248	25,000	None	116	116	25	12
Case 3													
Acid Leach-SX	New Mexico	2	87	105	100	100	2,248	1,748,400	83,300	116	116	29	None
Acid Leach-SX	Wyoming	2	158	189	65	65	2,872	968,000	69,100	189	160	2	None
Alkaline Leach	New Mexico	2	55	66	100	100	2,248	1,748,400	83,300	116	116	61	None
Alkaline Leach	Wyoming	2	99	119	99	99	2,275	1,735,100	83,400	119	116	17	None
Case 4 or Case 7													
Acid Leach-SX	New Mexico	0.1	89	107	100	100	2,248	1,748,400	83,300	116	116	27	None
Acid Leach-SX	Wyoming	0.1	161	193	63	63	2,900	920,300	67,700	193	163	2	None
Alkaline Leach	New Mexico	0.1	56	67	100	100	2,248	1,748,400	83,300	116	116	60	None
Alkaline Leach	Wyoming	0.1	101	121	97	97	2,298	1,684,200	82,600	121	116	15	None
Case 5 (Liquids Only - Solids to Landfill)													
Acid Leach-SX	New Mexico	0.1	89	107	15	15	2,160	48,000	12,000	107	N.A.[f]	N.A.	N.A.
Acid Leach-SX	Wyoming	0.1	161	193	15	15	2,900	64,400	16,100	193	N.A.	N.A.	N.A.
Alkaline Leach	New Mexico	0.1	56	67	15	15	1,708	38,000	9,500	67	N.A.	N.A.	N.A.
Alkaline Leach	Wyoming	0.1	101	121	15	15	2,296	51,000	12,800	121	N.A.	N.A.	N.A.
Case 6 (Liquids Recycled to Mill and Solids to Landfill - No Conventional Tailings Impoundment Area)													

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[a] Assumptions:
Weight of liquid effluent
Acid leach-solvent extraction: 1.5 tons per ton of ore
Alkaline leach: 1.05 tons per ton of ore
Weight of liquid sorbed on solid tailings: 0.3 ton per ton of tailings
Net average annual evaporation rate
New Mexico: 7.25 ft/yr
Wyoming: 4.0 ft/yr

[b] Density of tailings, 120 lb/ft^3; volume of tailings at mill shutdown, 9,000,000 yd^3.

[c] Dam height includes 5 ft freeboard.

[d] Dam has 10 ft crest and a 2:1 slope.

[e] Total area (including 20% contingency) is used in estimating stabilization and lining costs; average area (excluding 20% contingency) is used in source term calculations since essentially all of the tailings are deposited in this area (see Sect. 4.4.2.1).

[f] N.A. = not applicable.

Table 4.14. Airborne Source Terms for Inactive Tailings Area – Calculated Release of Radioactive Materials After Model Uranium Mill Has Closed[a]

Radwaste Treatment Case	Interim Releases, Ci/yr (While Pond Is Evaporating and Before Final Stabilization of Tailings)					Long-Term Releases (After Tailings Have Been Stabilized and Radon Diffusion Barrier Applied)	
	U_{nat}, ^{234}Th, Each	^{226}Ra	^{230}Th	^{210}Pb, ^{210}Po, ^{210}Bi, Each	^{222}Rn[b]	Windblown Particulates	^{222}Rn (Ci/yr)
			New Mexico Acid Leach-Solvent Extraction Mill				
1	1.1E-3	1.2E-2	1.2E-2	1.2E-2	9.3E+3	0	8.4E+3
2	8.4E-5	9.0E-4	9.8E-4	9.0E-4	9.3E+3	0	6.4E+3
3	8.4E-5	9.0E-4	9.8E-4	9.0E-4	8.4E+3	0	1.8E+3
4	8.4E-5	9.0E-4	9.8E-4	9.0E-4	8.4E+3	0	2.0E+2
5			No Interim Period			0	6.6E00
6			No Interim Period			0	3.0E+1[c]
7	8.4E-5	9.0E-4	9.8E-4	9.0E-4	8.4E+3	0	1.4E-1
			Wyoming Acid Leach-Solvent Extraction Mill				
1	2.8E-3	3.0E-2	3.2E-1	3.0E-2	11.3E+3	0	1.0E+4
2	1.1E-3	1.2E-2	1.3E-2	1.2E-2	11.3E+3	0	7.8E+3
3	1.1E-3	1.2E-2	1.3E-2	1.2E-2	11.6E+3	0	2.5E+3
4	1.1E-3	1.2E-2	1.3E-2	1.2E-2	11.8E+3	0	2.7E+2
5			No Interim Period			0	6.6E00
6			No Interim Period			0	3.0E+1[c]
7	1.1E-3	1.2E-2	1.3E-2	1.2E-2	11.8E+3	0	2.0E-1
			New Mexico Alkaline Leach Mill				
1	5.0E-4	6.8E-3	6.9E-3	6.9E-3	9.3E+3	0	8.4E+3
2	3.9E-5	5.3E-4	5.4E-4	5.4E-4	9.3E+3	0	6.4E+3
3	3.9E-5	5.3E-4	5.4E-4	5.4E-4	8.4E+3	0	1.9E+3
4	3.9E-5	5.3E-4	5.4E-4	5.4E-4	8.4E+3	0	2.0E+2
5			No Interim Period			0	6.6E+0
6			No Interim Period			0	1.8E+1
7	3.9E-5	5.3E-4	5.4E-4	5.4E-4	8.4E+3	0	1.4E-1
			Wyoming Alkaline Leach Mill				
1	1.3E-3	1.7E-2	1.8E-2	1.7E-2	9.3E+3	0	8.4E+3
2	5.1E-4	7.0E-3	7.0E-3	7.0E-3	9.3E+3	0	6.4E+3
3	5.1E-4	7.0E-3	7.0E-3	7.0E-3	8.4E+3	0	1.9E+3
4	5.1E-4	7.0E-3	7.0E-3	7.0E-3	8.4E+3	0	2.0E+2
5			No Interim Period			0	6.6E+0
6			No Interim Period			0	1.8E+1
7	5.1E-4	7.0E-3	7.0E-3	7.0E-3	8.4E+3	0	1.4E-1

[a] Assume 29% of airborne acid leached dust or 56% of alkaline leached dust is in the particle size range of 0-10 μ. Remaining resuspended tailings dust is assumed to be in the 10-80 μ size range.

[b] Maximum release near end of interim period, assuming all tailings are dry.

[c] Case 6c is 5.6E+1.

Table 4.15. Liquid Radwaste Treatment Cases to Reduce the Seepage of Radioactive Materials from Active Tailings Area - Model Uranium Mill Operating

Case No.	Treatment			Assumed % of the Radionuclides in Untreated Liquid Waste Lost by Seepage from Tailings Pond	Seep Rate (liters/yr)	Concentration Factor for Pond Near End of 20-yr Mill Life[a]	Calculated Source Terms in Ci/yr, for Seepage from Active Tailings Area[b]						New Mexico		Wyoming	
	Pond	Dam	Other				U_{nat}	^{226}Ra	^{230}Th	^{210}Pb	^{210}Po	^{210}Bi	Capital ($1,000)	Annual ($1,000)	Capital ($1,000)	Annual ($1,000)
					Model Acid Leach—Solvent Extraction Mill											
1	Yes	Tailings	None	10	3.0E+7	3.3	6.6E-1	5.1E-2	1.8E+1	5.1E-2	5.1E-2	5.1E-2	236	92	243	93
2	Yes	Tailings	None	10	3.0E+7	3.3	6.6E-1	5.1E-2	1.8E+1	5.1E-2	5.1E-2	5.1E-2	236	92	243	93
3	Carefully sited	Earth with clay core	None	2	4.4E+6	4.5	1.3E-1	1.0E-2	3.7E00	1.0E-2	1.0E-2	1.0E-2	2,568	651	1,538	404
4a & 4b	Asphalt lined	Earth with clay core	Lime neutralize	0.1	2.2E+6	0.5	6.6E-3	5.1E-4	1.8E-1	5.1E-4	5.1E-4	5.1E-4	4,817	1,510	3,915	1,294
5	Asphalt lined	Earth with clay core	Lime neutralize	0.1	2.2E+6	0.5	6.6E-3	5.1E-4	1.8E-1	5.1E-4	5.1E-4	5.1E-4	2,940	1,060	3,545	1,205
6a	None	None	Evaporator	-	-	-	-	-	-	-	-	-	5,824[c]	2,600[c]	5,824[c]	2,600[c]
6b	None	None	Evaporator	-	-	-	-	-	-	-	-	-	5,015	2,406	5,015	2,406
6c	None	None	Evaporator	0.002[d]	3.0E+7	-	3.4E-3	3.4E-3	3.4E-3	3.4E-3	3.4E-3	3.4E-3	e	e	e	e
7	Asphalt lined	Earth with clay core	Lime neutralize	0.1	2.2E+6	4.5	6.6E-3	5.1E-4	1.8E-1	5.1E-4	5.1E-4	5.1E-4	4,817	1,510	3,915	1,294
					Model Alkaline Leach Mill											
1	Yes	Tailings	None	10	2.6E+7	2.6	6.9E-1	6.9E-3	1.4E-3	5.5E-3	1.4E-3	6.9E-3	230	90	230	90
2	Yes	Tailings	None	10	2.6E+7	2.6	6.9E-1	6.9E-3	1.4E-3	5.5E-3	1.4E-3	6.9E-3	230	90	230	90
3	Carefully sited	Earth with clay core	None	2	4.0E+6	3.3	1.4E-1	1.4E-3	2.8E-4	1.1E-3	2.8E-4	1.4E-3	2,563	650	2,546	646
4a & 4b	Asphalt lined	Earth with clay core	Copperas	0.1	2.2E+6	0.9	6.9E-3	6.9E-5	1.4E-5	5.5E-5	1.4E-5	6.9E-5	4,185	1,042	4,003	999
5	Asphalt lined	Earth with clay core	Copperas	0.1	2.2E+6	0.9	6.9E-3	6.9E-5	1.4E-5	5.5E-5	1.4E-5	6.9E-5	1,469	391	1,984	490
6a	None	None	Evaporator	-	-	-	-	-	-	-	-	-	3,859[c]	2,106[c]	3,859[c]	2,106[c]
6b	None	None	Evaporator	-	-	-	-	-	-	-	-	-	3,050	1,912	3,050	1,912
7	Asphalt lined	Earth with clay core	Copperas	0.1	2.2E+6	3.3	6.9E-3	6.9E-5	1.4E-5	5.5E-5	1.4E-5	6.9E-5	4,185	1,042	4,003	999

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[a] The concentration of a radionuclide in the tailings pond water is equal to the concentration factor times the concentration in the mill effluent given in Table 4.11. Natural evaporation increases the concentration of dissolved radionuclides while lime neutralization or copperas treatment lowers the concentration.

[b] Near end of 20-yr life of model mill when concentrations of dissolved radionuclides have reached maximum value, and assuming a constant seep rate over the life of the mill. (In practice, tailings tend to seal the bottom and the seep rate will decrease over the mill life.

[c] Costs for Case 6a include an asphalt lining for the landfill where the concrete fixed solid wastes are buried.

[d] Percent of radionuclides dissolved during leaching which seep from the tailings impoundment.

[e] Costs for solid and liquid treatment are not separable.

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Table 4.16. Solid Radwaste Treatment Cases to Reduce the Potential Long-Term Leaching of Uranium Mill Tailings by Natural Waters

	Treatment		Calculated Leach Rate Assuming Total Immersion in Water (Ci/yr)[a]			Treatment Cost[b]	
Case	5/16-in. Asphalt Membrane	Fixation	U_{nat}, ^{234}Th Each	^{230}Th	^{226}Ra, ^{210}Pb, ^{210}Po, ^{210}Bi, Each	Capital ($1,000)	Annual ($1,000)
			Acid Leach-Solvent Extraction				
1	None	None	2.3E+1	2.6E+2	2.6E+2	0	0
2	None	None	2.3E+1	2.6E+2	2.6E+2	0	0
3	None	None	2.3E+1	2.6E+2	2.6E+2	0	0
4a	Bottom and sides	None	1.1E+1	1.3E+2	1.3E+2	976[c]	234[c]
4b	Completely encased	None	2.8E-9	3.1E-8	3.1E-8	976[c]	254[c]
5	Bottom and sides	All solids-concrete	2.0E-1[d]	2.1E00[d]	2.1E00[d]	1,405	1,919
6a	None	Slimes-concrete	3.5E00[e]	2.3E+1[e]	4.3E+1[e]	1,597	1,885
6b	None	Slimes-asphalt	3.2E00[e]	1.9E+1[e]	3.9E+1[e]	4,420	6,338
6c	None	Concentrate-asphalt	1.2E-5	1.2E-2	1.2E-2	29,180	7,863
7	Completely encased	None	2.8E-9	3.1E-8	3.1E-8	976[f]	254[f]
			Alkaline Leach				
1	None	None	2.0E+1	2.6E+2	2.6E+2	0	0
2	None	None	2.0E+1	2.6E+2	2.6E+2	0	0
3	None	None	2.0E+1	2.6E+2	2.6E+2	0	0
4a	Bottom and sides	None	9.8E00	1.3E+2	1.3E+2	976	234
4b	Completely encased	None	2.4E-9	3.2E-8	3.2E-8	976	254
5	Bottom and sides	All solids-concrete	1.6E-1[d]	2.1E00[d]	2.1E00[d]	1,405	1,919
6a	None	Slimes-concrete	2.4E00[e]	4.2E+1[e]	4.2E+1[e]	2,451	2,135
6b	None	Slimes-asphalt	2.2E00[e]	3.8E+1[e]	3.8E+1[e]	6,735	8,864
7	Completely encased	None	2.4E-9	3.2E-8	3.2E-8	976[f]	254[f]

[a] H. W. Godbee and D. S. Joy, Assessment of the Loss of Radioactive Isotopes from Radioactive Waste Solids in the Environment, Part I: Background and Theory, ORNL-TM-4333 (February 1974); Part II: Application and Projections (in preparation).

[b] Costs are arbitrarily allocated in some cases between liquid and solid treatments.

[c] Costs shown are for New Mexico. Costs will be about 50% higher in Wyoming because of the larger evaporation pond which must be asphalt lined. See Sect. 4.4.2.1.

[d] Estimated from leach rate of soluble ^{90}Sr salt in concrete. Values are probably high. [J. G. Moore, Oak Ridge National Laboratory, The Leaching of Strontium from Cement - Uranium Ore Specimens with Tap Water, unpublished memorandum (Dec. 17, 1973)].

[e] Sands are not treated and are the major source.

[f] Case 7 includes a 1-in. asphalt membrane on top to lower the radon emanation. Since this has little effect on the leach rate, only the cost of a 5/16-in. asphalt top is charged to leaching treatment.

Table 4.17. Solid Radwaste Treatment Cases to Eliminate Windblown Particulates from the Tailings Area

			Calculated Particulate Resuspension from Tailings Beach[a,b]						Maximum Adult Dose at 0.5 Mile, 100% Food Ingestion (mrem/yr)[c]			
				Source Term (Ci/yr)							
Mill Process	Site	Area of Dry Tailings Exposed to Wind Erosion (acres)	Mass (g/sec)	U_{nat}, ^{234}Th, Each	^{226}Ra	^{230}Th	^{210}Pb, ^{210}Po, ^{210}Bi, ^{222}Rn Each	Total Body	Bone	Lung	Annual Treatment Cost ($1000)
Case 1											
Mill Active, No Treatment of Tailings Beach (Near End of 20-yr Life of Model Mill When Beach Has Reached Maximum Size)											
Acid Leach-SX[d]	New Mexico	48[e]	8.5E-2	4.02E-4	4.31E-3	4.68E-3	4.31E-3	16.6	168.0	16.9	0
Acid Leach-SX	Wyoming	12[e]	2.8E-1	1.32E-3	1.42E-2	1.54E-2	1.42E-2	44.4	447.9	44.1	0
Alkaline Leach	New Mexico	78[e]	1.4E-1	3.04E-4	4.13E-3	4.18E-3	4.18E-3	16.1	166.3	16.7	0
Alkaline Leach	Wyoming	37[e]	8.6E-1	1.90E-3	2.58E-2	2.61E-2	2.61E-2	81.6	841.5	84.5	0
Mill Closed, Interim Period, No Treatment of Tailings Beach (After Pond Has Evaporated)											
Acid Leach-SX	New Mexico	128[f]	2.3E-1	1.07E-3	1.15E-2	1.25E-2	1.15E-2	44.3	448.0	45.1	0
Alkaline Leach	New Mexico	128[f]	2.3E-1	4.99E-4	6.78E-3	6.86E-3	6.86E-3	26.4	272.9	27.4	0
Mill Closed, Interim Period, Chemical Spray of Tailings Beach, 25 Acres Maximum of Untreated Tailings Beach Permitted											
Acid Leach-SX	Wyoming	25	5.8E-1	2.75E-3	2.96E-2	3.21E-2	2.96E-2	92.4	933.1	91.9	2[g]
Alkaline Leach	Wyoming	25	5.8E-1	1.28E-3	1.74E-2	1.76E-2	1.74E-2	55.1	568.6	57.1	2[g]
Mill Closed and Tailings Stabilized, 6-in. Earth Cover Topped by 6-in. Rock Cover											
Acid Leach-SX	New Mexico	0	-	-	-	-	-	-	-	-	4[h]
Acid Leach-SX	Wyoming	0	-	-	-	-	-	-	-	-	6[h]
Alkaline Leach	New Mexico	0	-	-	-	-	-	-	-	-	4[h]
Alkaline Leach	Wyoming	0	-	-	-	-	-	-	-	-	4[h]
Case 2											
Mill Active, Chemical Spray of Dry Tailings Beach											
Acid Leach-SX	New Mexico	0	-	-	-	-	-	-	-	-	7[i]
Acid Leach-SX	Wyoming	0	-	-	-	-	-	-	-	-	5[i]
Alkaline Leach	New Mexico	0	-	-	-	-	-	-	-	-	9[i]
Alkaline Leach	Wyoming	0	-	-	-	-	-	-	-	-	6[i]
Mill Closed, Interim Period, Chemical Spray of Tailings Beach, 10 Acres Maximum of Untreated Tailings Permitted											
Acid Leach-SX	New Mexico	10	1.7E-2	8.37E-5	8.98E-4	9.76E-4	8.98E-4	3.5	35.0	3.5	1[j]
Acid Leach-SX	Wyoming	10	2.3E-1	1.10E-3	1.18E-2	1.28E-2	1.18E-2	37.0	373.3	36.8	1[j]
Alkaline Leach	New Mexico	10	1.7E-2	3.90E-5	5.30E-4	5.36E-4	5.36E-4	2.1	21.3	2.1	1[j]
Alkaline Leach	Wyoming	10	2.3E-1	5.14E-4	6.97E-3	7.05E-3	7.05E-3	22.0	227.4	22.8	1[j]
Mill Closed and Tailings Stabilized, 2-ft Earth Cover Topped by 6-in. Rock Cover											
Acid Leach-SX	New Mexico	0	-	-	-	-	-	-	-	-	6[h]
Acid Leach-SX	Wyoming	0	-	-	-	-	-	-	-	-	9[h]
Alkaline Leach	New Mexico	0	-	-	-	-	-	-	-	-	6[h]
Alkaline Leach	Wyoming	0	-	-	-	-	-	-	-	-	6[h]

[a] Calculated resuspension of slimes fraction (which contains most of the radioisotopes) by a 7-mph wind in New Mexico and a 10-mph wind in Wyoming. Does not include dust storms. Does not include sand fraction which may form migrating sand dunes but is not readily airborne (Sect. 7.2).

[b] Composition of slimes fraction is given in Table 4.11.

[c] Assumes that 29% of the airborne acid-leached dust or 56% of the airborne alkaline-leached dust is in the particle size range 0 to 10 μ and is respirable. Remaining resuspended tailings dust is assumed to be in the 10- to 80-μ size range.

[d] SX = solvent extraction.

[e] Average area of dry beach and exposed tailings on the face of the dam near end of 20-yr life of model mill when beach and dam have reached maximum size, assuming 10% seepage loss of pond water and a net annual evaporation rate of 7.25 ft in New Mexico or 4.0 ft in Wyoming. Parameter for model tailings impoundment basins are given in Table 4.12.

[f] Area of dry tailings at the end of the interim period when the pond has completely evaporated. Includes area of tailings on the face of the dam.

[g] Annual cost of 20-yr annuity to accumulate capital required to purchase tank, pump, and sprayer, and to cover operating costs for interim treatment when mill closes.

[h] Annual cost of 20-yr annuity to accumulate capital required for final stabilization and cover when mill closes.

[i] Cost of biannually covering beach averaged over 20 yr.

[j] Annual cost of 20-yr annuity to accumulate capital required for operating costs of interim treatment when mill closes. Equipment bought for temporary treatment while the mill is active is used without charge.

Table 4.18. Solid Radwaste Treatment Cases to Reduce the Long-Term Radon Emanation from the Inactive Tailings Area - Model Uranium Mill Closed

	Treatment			Area of Tailings Deposit (acres)^c						Calculated ^{222}Rn Source Term (Ci/yr)			Maximum ^{222}Rn Dose to Adult Lung at 0.5 Mile (mrem/yr)				Treatment Costs			
				Acid Leach--Solvent Extraction						Acid Leach--Solvent Extraction			Acid Leach--Solvent Extraction		Alkaline Leach		Acid Leach--Solvent Extraction		Alkaline Leach	
Case No.	Earth Cover^a (ft)	Asphalt Membrane (in.)	Fixation^b	New Mexico		Wyoming		Alkaline Leach		New Mexico	Wyoming	Alkaline Leach	New Mexico	Wyoming	New Mexico	Wyoming	Capital ($1000)	Annual^d ($1000)	Capital ($1000)	Annual^d ($1000)
1	0.5	None	None	128^e		157^e		128^e		8.43E+3	1.03E+4	8.43E+3	100.5	58.9	100.5	48.2	0	4^f	0	4
2	2	None	None	128^e		157^e		128^e		6.39E+3	7.84E+3	6.39E+3	76.1	44.5	76.1	36.5	0	6^f	0	6
3	8	None	None	116		160		116		1.85E+3	2.54E+3	1.85E+3	22.0	14.5	22.0	10.6	0	13^f	0	13
4a	20	None	None	116		163		116		2.0E+2	2.7E+2	2.0E+2	2.4	1.5	2.4	1.1	0	27^f	0	27
4b	2	$5/16^g$	None	116		163		116		2.0E+2	2.7E+2	2.0E+2	2.4	1.5	2.4	1.1	0	26^f	0	26
5	20	None	All solids-concrete^h	116		116		116		6.6E00	6.6E00	6.6E00	0.1	0.04	0.1	0.04	570	1,747	570	1,747
				Sands	Fixed Slimes	Sands	Fixed Slimes	Sands	Fixed Slimes											
6a	20	None	Slimes-concrete^i	78	35	78	35	56	59	3.3E+1	3.3E+1	2.0E+1	0.4	0.2	0.2	0.1	1,131	851	1,629	1,407
6b	20	None	Slimes-asphalt^i	78	68	78	68	56	112	2.7E+1	2.7E+1	1.5E+1	0.3	0.1	0.2	0.1	4,098	5,347	6,735	7,725
6c	2^j+20^j	None	Concentrate-asphalt^k	113	5.4	113	5.4	N.A.		5.6E+1	5.6E+1	N.A.	0.7	0.3	N.A.	N.A.	341^l	450^l	N.A.	N.A.
7	2	1	None	116		163		116		1.4E-1	2.0E-1	1.4E-1	2E-3	1E-3	2E-3	1E-3	0	70	0	70

N.A. = not applicable.

[a] Earth covers assumed to have the radon attenuation properties of coarse sand containing 4% moisture as shown in Fig. 4.16 and Table 9.31.

[b] Calculated radon emanation from dry, untreated tailings pile is 72.4 Ci yr^{-1} acre^{-1}.

[c] Parameters for model tailings impoundment basins are given in Table 4.13 for Cases 1-4 and Case 7.

[d] Annual charges include cost of annuity to accumulate capital required for final stabilization and covering of tailings when mill closes after 20 yr.

[e] Includes area of tailings on the face of the dam.

[f] Costs shown are for New Mexico. Costs will be about 50% higher in Wyoming because of the larger area which must be covered. See Sect. 4.4.2.1.

[g] Calculated radon attenuation factor for 5/16-in. asphalt plus 2 ft of earth is 0.0247.

[h] Calculated radon emanation from tailings fixed in 1:20 concrete is 2.59 Ci yr^{-1} acre^{-1}; from tailings incorporated in concrete and buried under 20 ft of earth, 5.70E-2 Ci yr^{-1} acre^{-1}.

[i] Calculated radon emanation from sulfuric acid– leached sands is 15.7 Ci acre^{-1} yr^{-1}; from alkaline-leached sands, 12.1 Ci acre^{-1} yr^{-1}; from acid-leached slimes fixed in 1:20 concrete, 7.32 Ci yr^{-1} acre^{-1}; from acid-leached slimes fixed in asphalt, 0.210 Ci yr^{-1} acre^{-1}; from alkaline-leached slimes fixed in concrete, 4.20 Ci yr^{-1} acre^{-1}; and from alkaline-leached slimes fixed in asphalt, 0.122 Ci yr^{-1} acre^{-1}. Values do not include factor of 0.022 for attenuation by 20 ft earth cover.

[j] Two-foot cover over tailings and 20-ft cover over asphalt-fixed concentrate.

[k] Calculated radon emanation from nitric acid-leached tailings is 0.717 Ci yr^{-1} acre^{-1}; from asphalt-fixed evaporator concentrates, 3.07 Ci yr^{-1} acre^{-1}. Values do not include attentuation by earth cover.

[l] Costs shown are only for incorporating concentrates in asphalt and burial; the cost of the nitric acid leach is not included.

Table 4.19. Radon Concentration in Air due to Radon Release from a Stabilized 116-acre Tailings Pile at the New Mexico Site[a,b]

Distance from Tailings (miles)		^{222}Rn Concentration (pCi/liter or 10^{-9} μCi/ml of air)			
		Case 1,[c] 6-in. Earth Cover	Case 2,[c] 2-ft Earth Cover	Case 3,[d] 8-ft Earth Cover	Case 4,[d] 20-ft Earth Cover
0.5	Maximum	2.3	1.8	0.5	0.05
	Average	1.0	0.8	0.2	0.02
1.0	Maximum	0.7	0.6	0.15	0.016
	Average	0.3	0.2	0.07	0.007
5.0	Maximum	0.07	0.04	0.013	0.0015
	Average	0.03	0.02	0.006	0.0006

[a] For comparison, the average of the background measured at Salt Lake City, Utah; Monticello, Utah; and Durango, Colorado, is 0.41 pCi/liter; the probable background at Grand Junction, Colorado, is 0.79 pCi/liter [S. D. Shearer, Jr., and C. W. Sill, Health Physics 17, 77-88 (1969) and Evaluation of Radon-222 Near Uranium Tailings Piles, DER 69-1, Public Health Service, Bureau of Radiological Health, Rockville, Maryland (March 1969)].

[b] Calculated from source terms in Table 4.18 and meteorologic dilution factors from Fig. 7.2.

[c] Calculated for a 116-acre tailings deposit in a natural basin with 12 acres of tailings on the face of the dam.

[d] Calculated for a 116-acre tailings deposit in a natural basin; no tailings in the dam.

Table 4.20. Effect of Radwaste Treatment Cases on Radon Emanation from the Active Tailings Area Near End of 20-yr Life of Model Uranium Mill - Mill Operating[a]

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		Radon Emanation from the Tailings Pond[a] and Wet Beach						Radon Emanation from Dry Tailing Beach or Fixed Solids							
Case No.	Liquid Treatment	^{226}Ra Concentration in Pond (pCi/ml)	^{222}Rn from Decay of Radium Dissolved in Pond Water (pCi day^{-1} cm^{-2})	^{222}Rn Diffusing from Tailings Under Pond (pCi day^{-1} cm^{-2})	Total ^{222}Rn from Pond (pCi day^{-1} cm^{-2})	Pond Area (acres)	^{222}Rn Source (Ci/yr)	Fixation of Solids	Earth Cover Over Tailings Beach or Fixed Solids (ft)	Radon Diffusion from Exposed Tailings (Ci yr^{-1} acre^{-1})	Area of Exposed Tailings[b] (acres)	Area of Tailings Buried Under 20 ft of Earth (acres)	^{222}Rn Source (Ci/yr)	Total ^{222}Rn Emanation from Active Tailings Area - Pond plus Beach or Fixed Solids (Ci/yr)	Maximum ^{222}Rn Dose to Adult Lung at 0.5 Mile (mrem/yr)
New Mexico Solvent Extraction Mill															
1	Pond	1.7	67	78	145	80	1.7E+2	None	None	72.4	48[c]	0	3.48E+3	3.65E+3	43.5
2	Pond	1.7	67	78	145	80	1.7E+2	None	6 in.	65.9	48[c]	0	3.48E+3	3.65E+3	43.5
3	Pond	2.3	91	78	169	87	2.2E+2	None	6 in.	65.9	29	0	2.10E+3	2.32E+3	27.6
4	Precipitation, lined pond	0.25	10	78	88	89	1.2E+2	None	6 in.	65.9	27	0	1.95E+3	2.07E+3	24.6
5	Precipitation, lined pond	0.25	10	78	88	89	1.2E+2	All solids-concrete	None	2.59	116	0	3.0E+2	4.2E+2	5.0
6a	Metal evaporator	——No evaporation pond——						Slimes-concrete	20 ft	23.6	11	102	1.8E+2	1.8E+2	2.1
6b	Metal evaporator	——No evaporation pond——						Slimes-asphalt	20 ft	16.9	15	131	1.5E+2	1.5E+2	1.8
6c	Metal evaporator	——No evaporation pond——						Concentrate-asphalt	2 ft + 20 ft	0.83	d	d	6.0E+1	6.0E+1	0.7
7	Precipitation, lined pond	0.25	10		88	89	1.2E+2	None	6 in.	65.9	27	0	1.95E+3	2.07E+3	24.6
Wyoming Solvent Extraction Mill															
1	Pond	1.7	67	78	145	145	3.1E+2	None	None	72.4	12[c]	0	8.69E+2	1.18E+3	6.7
2	Pond	1.7	67	78	145	145	3.1E+2	None	6 in.	65.9	12[c]	0	8.69E+2	1.18E+3	6.7
3	Pond	2.3	91	78	169	158	4.0E+2	None	6 in.	65.9	2	0	1.45E+2	5.45E+2	3.1
4	Precipitation, lined pond	0.25	10	78	88	161	2.1E+2	None	6 in.	65.9	2	0	1.45E+2	3.55E+2	2.0
5	Precipitation, lined pond	0.25	10	78	88	161	2.1E+2	All solids-concrete	None	2.59	116	0	3.0E+2	5.1E+2	2.9
6a	Metal evaporator	——No evaporation pond——						Slimes-concrete	20 ft	23.6	11	102	1.8E+2	1.8E+2	1.0
6b	Metal evaporator	——No evaporation pond——						Slimes-asphalt	20 ft	16.9	15	131	1.5E+2	1.5E+2	0.9
6c	Metal evaporator	——No evaporation pond——						Concentrate-asphalt	2 ft + 20 ft	0.83	d	d	6.0E+1	6.0E+1	0.3
7	Precipitation, lined pond	0.25	10	78	88	161	2.1E+2	None	6 in.	65.9	2	0	1.45E+2	3.55E+2	2.0
New Mexico Alkaline-Leach Mill															
1	Pond	0.26	10	78	88	50	6.5E+1	None	None	72.4	78[c]	0	5.65E+3	5.72E+3	68.2
2	Pond	0.26	10	78	88	50	6.5E+1	None	6 in.	65.9	78[c]	0	5.65E+3	5.72E+3	68.2
3	Pond	0.33	13	78	91	55	7.4E+1	None	6 in.	65.9	61	0	4.42E+3	4.49E+3	53.6
4	Precipitation, lined pond	0.088	3.5	78	82	56	6.8E+1	None	6 in.	65.9	60	0	4.34E+3	4.41E+3	52.5
5	Precipitation, lined pond	0.088	3.5	78	82	56	6.8E+1	All solids-concrete	None	2.59	116	0	3.0E+2	3.7E+2	4.4
6a	Metal evaporator	——No evaporation pond——						Slimes-concrete	20 ft	17.3	12	103	1.1E+2	1.1E+2	1.3
6b	Metal evaporator	——No evaporation pond——						Slimes-asphalt	20 ft	10.6	17	151	8.3E+1	8.3E+1	1.0
7	Precipitation, lined pond	0.088	3.5	78	82	56	6.8E+1	None	6 in.	65.9	60	0	4.34E+3	4.41E+3	52.5
Wyoming Alkaline-Leach Mill															
1	Pond	0.26	10	78	88	91	1.2E+2	None	None	72.4	37[c]	0	2.68E+3	2.80E+3	16.0
2	Pond	0.26	10	78	88	91	1.2E+2	None	6 in.	65.9	37[c]	0	2.68E+3	2.80E+3	16.0
3	Pond	0.33	13	78	91	99	1.3E+2	None	6 in.	65.9	17	0	1.23E+3	1.36E+3	7.8
4	Precipitation, lined pond	0.088	3.5	78	82	101	1.2E+2	None	6 in.	65.9	15	0	1.09E+3	1.21E+3	6.9
5	Precipitation, lined pond	0.088	3.5	78	82	101	1.2E+2	All solids-concrete	None	2.59	116	0	3.0E+2	4.2E+2	2.4
6a	Metal evaporator	——No evaporation pond——						Slimes-concrete	20 ft	17.3	12	103	1.1E+2	1.1E+2	0.6
6b	Metal evaporator	——No evaporation pond——						Slimes-asphalt	20 ft	10.6	17	151	8.3E+1	8.3E+1	0.5
7	Precipitation, lined pond	0.088	3.5	78	82	101	1.2E+2	None	6 in.	65.9	15	0	1.09E+3	1.21E+3	6.9

[a] Assumptions:

(1) Near end of 20-yr life of model mill when tailings and pond cover maximum area and concentrations of dissolved radionuclides in pond water have reached maximum value.

(2) Tailings are kept wet as much as possible except for a minimum 2-acre dry beach to protect the dam. Parameters for tailings impoundment basin for Cases 1 to 4 and Case 7 are given in Table 4.13.

(3) Stirred pond model, i.e., all radon from decay of radium is dissolved in the pond water and all radon which diffuses to the solid-liquid interface is released to the atmosphere.

(4) Radon diffusion from wet tailings calculated using:

$$J_o = D_e C_v \sqrt{\lambda / D_e / v} \ ,$$

where:

$D_e = 1.13 \times 10^{-5} \times 0.37\ \mathrm{cm^2/sec}$

$\bar{v} = 0.37$

$\lambda = 2.1 \times 10^{-6}\ \mathrm{sec}$

$C_v = EC_t/v$

$E = 0.2$

C_t = g solids/cm^3 of bulk medium x μCi of ^{226}Ra/g solids or $2.6 \times 0.63 \times \frac{515}{2000 \times 454}$ μCi of ^{226}Ra/cm^3 of tailings deposit.

For more details, see Sect. 9.7.1.

(5) Radon diffusion from dry tailings beach or fixed solids calculated using assumptions listed in footnotes of Table 4.18. However, the area of dry tailings and depth of earth cover are usually different for the active tailings area from the stabilized pile.

(6) Tailings uniformly contain 568 pCi/g of radium (in practice, dry beach is mostly sands and will contain <568 pCi/g while wet beach and tailings under pond are rich in slimes and contain >68 pCi/g).

[b] Exposed meaning little or no radon diffusion barrier is present; i.e., dry tailings or fixed solids covered with 0 to 6 in. of earth or the chemical spray.

[c] Includes area of tailings on the face of the dam.

[d] Eleven acres of nitric leached tailings and 0.5 acre of asphalt-fixed evaporator concentrates are uncovered; 101 acres of tailings are covered with 2 ft of earth and 5 acres of asphalt fixed wastes are buried under 20 ft of earth.

Table 4.21. Comparison of Radon Concentration Calculated from ORNL Model with Environmental Monitoring Data

Type of Data	Mill	Mill Processing Rate (tons/day)	^{226}Ra^a Conc. in Tailings (pCi/g)	Tailings^a Area (acres)	Radon Concentration in Air (pCi/liter)			
					Over or Near Tailings Pile		0.5 Mile from Tailings Pile	
					Avg	Range	Avg	Range
			Active Mill					
ORNL Theoretical Calculations	Model New Mexico Solvent Extraction	2,000	566	Pond: 80 Beach: 48		6-22	0.4	0.25-1.0
PHS Environmental Monitoring	Grand Junction, Colo. Solvent Extraction	500^b	900^c	?	$7.8^{d,e}$	$1.1\text{-}28.0^{d,e}$	$1.9^{d,e}$	$0.5\text{-}4.5^{d,e}$
PHS Environmental Monitoring	Salt Lake City, Utah Solvent Extraction	600^b	$1,500^c$	?	$7.2^{d,f}$	$1.6\text{-}22^{d,f}$		
			Inactive Mill - Exposed Tailings					
ORNL Theoretical Calculations	Model New Mexico Solvent Extraction or Alkaline Leach	2,000	566	128		15-56	1.1	0.7-2.5
PHS Environmental Monitoring	Durango, Colo.	750^b	900^c	?	$16^{d,g}$	$3.8\text{-}34^{d,g}$		
			Inactive Mill - 2-ft Earth Cover					
ORNL Theoretical Calculations	Model New Mexico Solvent Extraction or Alkaline Leach	2,000	566	128		11-39	0.8	0.4-1.8
PHS Environmental Monitoring	Monticello, Utah	600^b	910^c	?	$7.2^{d,h}$	$0.89\text{-}12^{d,h}$		

[a] In the ORNL model, the radon concentration is directly proportional to the radium concentration and the area of exposed tailings.

[b] R. C. Merritt, The Extractive Metallurgy of Uranium, Colorado School of Mines Research Institute (1971), pp. 379, 529, 540, and 543.

[c] From Table 9.22.

[d] S. D. Shearer, Jr., and C. W. Sill, Health Physics 17, 77-88 (1969); Evaluation of Radon-222 Near Uranium Tailings Piles, DER 69-1, Public Health Service, Bureau of Radiological Health, Rockville, Maryland (March 1969).

[e] Probable natural background 5 miles from pile: 0.79 pCi/liter.

[f] Natural background: 0.38 pCi/liter.

[g] Natural background: 0.51 pCi/liter.

[h] Natural background: 0.34 pCi/liter.

Table 4.22. Comparison of Emanation Rate of Radon from the Surface of Stabilized Tailings Piles with the Emanation Rate from Native Soils[a]

Radwaste Treatment Case	Emanation Rate of Radon from Stabilized Tailings Piles (Multiple of Probable Natural Background)
1	450
2	345
3	285
4	11
5	0.5
6	3
7	0.008

[a] Assumes that the emanation rate of radon from tailings is 500 times higher than from native soils based on the U_3O_8 content of soils around the Highland uranium mill site prior to milling activities[35] (Sect. 4.4.3.2).

Table 6.1. Total Costs for Treatment of Radwaste from Model Acid Leach-Solvent Extraction Uranium Mill

Case No.	Capital[a] Cost ($1000)	Annual Fixed Charge[b] ($1000)	Annual Operating Cost ($1000)	Total Annual Cost ($1000)	Contribution to cost of:	
					Yellow Cake ($/lb U_3O_8)	Power[c] (Mills/kWhr)
			Wyoming			
1	370	97	83	180	0.07	0.003
1[d]	370	131	83	214	.08	.004
2	447	118	88	206	.08	.004
3	1,900	479	101	580	.22	.010
4a	4,440	1,112	434	1,546	.58	.028
4b	4,440	1,110	434	1,544	.58	.028
5	4,701	1,156	1,987	3,143	1.18	.056
6a	7,597	1,850	1,833	3,683	1.39	.066
6b	8,540	2,084	5,608	7,692	2.89	.138
6c	29,959	7,197	1,067	8,264	3.11	.148
7	9,741	2,456	458	2,914	1,10	.052
			New Mexico			
1	363	91	83	174	0.07	0.003
1[d]	363	125	83	208	.08	.004
2	430	110	91	201	.07	.003
3	2,880	705	104	809	.30	.014
4a	5,290	1,297	437	1,734	.65	.031
4b	5,290	1,296	437	1,733	.65	.031
5	4,038	997	1,987	2,984	1.12	.053
6a	7,597	1,850	1,833	3,683	1.39	.066
6b	8,540	2,084	5,608	7,692	2.89	.138
6c	29,959	7,197	1,067	8,264	3.11	.148
7	10,591	2,613	461	3,074	1.15	.055

[a] Initial cost at time of mill construction including equipment for fixation of tailings in asphalt or concrete and treatment of liquid and airborne emissions.

[b] Calculated as 24% of capital plus annual charge (20-year annuity) to pay for earth cover and stabilization of surface of tailings pile at mill shutdown.

[c] Calculated on basis of 5,000 tons of U_3O_8 required during 30-year life of 1,000 MW(e) light-water reactor (irradiation level - 33,000 MWd/metric ton, load factor 80%, thermal efficiency 32.5%). One model mill (2,000 tons ore/day) supplies 8 such reactors.

[d] Stabilized by vegetation in place of rock. Annual charge ($34,000) to buy an annuity to provide perpetual care.

Table 6.2. Total Costs for Treatment of Radwaste from Model Alkaline Leach Uranium Mill

Case No.	Capital[a] Cost ($1000)	Annual Fixed Charge[b] ($1000)	Annual Operating Cost ($1000)	Total Annual Cost ($1000)	Contribution to cost of:	
					Yellow Cake ($/lb U_3O_8)	Power[c] (Mills/kWhr)
			Wyoming			
1	357	91	83	174	0.06	0.003
1[d]	357	125	83	208	.08	.004
2	424	109	90	199	.07	.003
3	2,861	701	103	804	.29	.014
4a	4,479	1,104	123	1,227	.45	.021
4b	4,479	1,103	123	1,226	.45	.021
5	2,991	745	1,631	2,376	.87	.041
6a	6,296	1,538	1,625	3,163	1.16	.053
6b	10,563	2,575	7,325	9,900	3.65	.173
7	9,780	2,421	147	2,568	0.94	.045
			New Mexico			
1	357	90	83	173	0.06	0.003
1[d]	357	124	83	207	.08	.004
2	424	108	92	200	.07	.003
3	2,875	703	105	808	.29	.014
4a	4,656	1,145	125	1,270	.46	.022
4b	4,656	1,144	125	1,269	.46	.022
5	2,537	636	1,631	2,267	.83	.040
6a	6,296	1,538	1,625	3,163	1.16	.053
6b	10,563	2,575	7,325	9,900	3.65	.173
7	9,957	2,460	149	2,609	0.95	.045

[a] Initial cost at time of mill construction including equipment for fixation of tailings in asphalt or concrete and treatment of liquid and airborne emissions.

[b] Calculated as 24% of capital plus annual charge (20-year annuity) to pay for earth cover and stabilization of surface of tailings pile at mill shutdown.

[c] Calculated on basis of 5,000 tons of U_3O_8 required during 30-year life of 1,000 MW(e) light-water reactor (irradiation level 33,000 MWd/metric ton, load factor 80%, thermal efficiency 32.5%). One model mill (2,000 T ore/day) supplies 8 such reactors.

[d] Stabilized by vegetation in place of rock. Annual charge ($34,000) to buy an annuity to provide perpetual care.

Table 6.3. Major Capital Items for Treatment of Radwaste from Model Acid Leach-Solvent Extraction Mill in New Mexico[a] (116-acre tailings pile)

Case No.	Equipment	Capital Cost[b] ($1,000)
1	Orifice type dust collector (27,000 cfm)	72
1	Wet impingement dust collector (6,000 cfm)	36
1	Tailings pump and pipeline	138
1	Earth dam	35
1	Cyclone installation	58
1	Earth cover (0.5 ft) and rock stabilization (0.5 ft)[c]	138[d]
2	Wet impingement dust collector (27,000 cfm)	88
2	Low energy venturi dust collector (6,000 cfm)	50
2	Earth cover (2.0 ft) and rock stabilization (0.5 ft)[c]	197[d]
3	Low energy venturi dust collector (27,000 cfm)	134
3	Medium energy venturi dust collector (6,000 cfm)	53
3	Tailings dam	2,411
3	Earth cover (8 ft) and rock stabilization (0.5 ft)[c]	441[d]
4	Bag filter dust collector (27,000 cfm)	248
4	High energy venturi dust collector (6,000 cfm)	58
4	Neutralization of liquid	651
4	Asphalt seal of pond	976
4a	Earth cover (20 ft) and rock stabilization (0.5 ft)[c]	926[d]
4b	Earth cover (2 ft), asphalt (5/16 in.), rock (0.5 ft)[c]	881[d]
5	HEPA filter dust collector (6,000 cfm)	74
5	Concrete fixation	570
5	Asphalt lining for waste storage	1,567
6	HEPA filter dust collector (30,000 cfm)	326
6a	Evaporator	2,273
6a	Concrete fixation	449
6b	Asphalt fixation	3,221
6c	CCD thickeners	10,040
6c	Evaporator	11,320
6c	Fractionator	5,297
6c	Solvent extractor	2,601
6c	Waste calciner	2,016
6c	Boiler	1,754
7	Charcoal delay trap (4,000 cfm)	5,388
7	Earth cover (2 ft), asphalt (1 in.), rock (0.5 ft)[c]	2,382[d]

[a] Slightly different values were used for the Wyoming site.

[b] Capital cost including all direct and indirect costs plus 20% for contingency.

[c] Earth, $350/acre-ft; rock, $2000/acre-ft; asphalt $18,800/acre-in.

[d] Total value of the matured annuity payments after 20 years.

Table 6.4. Major Capital Items for Treatment of Radwaste from Model Alkaline Leach Mill in New Mexico[a] (116-acre tailings pile)

Case No.	Equipment	Capital Cost[b] ($1,000)
1	Tailings pump and pipeline	134
1	Earth dam	33
1	Cyclone installation	58
1	Earth cover (0.5 ft) and rock stabilization (0.5 ft)[c]	138[d]
2	Earth cover (2.0 ft) and rock stabilization (0.5 ft)[c]	197[d]
3	Tailings dam	2,411
3	Earth cover (8 ft) and rock stabilization (0.5 ft)[c]	441[d]
4	Copperas treatment equipment	22
4	Asphalt seal on pond	976
4a	Earth cover (20 ft) and rock stabilization (0.5 ft)[c]	926[d]
4b	Earth cover (2 ft), asphalt (5/16 in.), rock (0.5 ft)[c]	881[d]
5	Concrete fixation	570
5	Asphalt lining for waste storage	1,297
6	Sand-slime separator	92
6	Slime dewatering	1,200
6	Evaporator	2,028
6a	Boiler	621
6a	Concrete making	337
6b	Asphalt fixation	5,210
7	Earth cover (2 ft), asphalt (1 in.), rock (0.5 ft)[c]	2,382[d]

[a] Slightly different values were used for the Wyoming site.

[b] Capital cost including all direct and indirect costs plus 20% for contingency.

[c] Earth, $350/acre-ft; rock, $2000/acre-ft; asphalt, $18,800/acre-in.

[d] Total value of the matured annuity payments after 20 years.

Table 6.5. Unit Costs of Labor, Materials and Supplies

Item	Unit Cost
Supervision	\$15,000/man-year
Operating labor	\$12,000/man-year
Lime	\$25/ton[a]
Asphalt	\$20/ton[a]
Cement	\$35/ton[a]
Power	\$0.01/KWH
Steam	\$1.00/1000 lb
Fuel	\$0.40/million BTU
Sulfuric acid	\$22/ton[a]
Ammonia	\$70/ton[a]
Sodium chlorate	\$200/ton[a]
Flocculant	\$1.00/lb
Amine	\$0.75/lb
Alcohol	\$0.26/lb
Kerosene	\$0.28/lb
Nitric acid	\$40/ton[a]
TBP	\$1200/ton[a]
Ferrous sulfate	\$37.60/ton[a]

[a] Short ton, 2000 lb/ton.

Table 7.1. Particle Size of Uranium Ore Tailings in the <80-μ Size Class[a]

Size Class (μ)	Percentage of Particles	
	Acid Circuit	Alkaline Circuit
10-80	24	23
<10	10	30

[a] The <80-μ distribution is based on an extrapolation of a log-log plot of particle size vs percent of particles that are less than the stated size using data from Table 9.7.

Table 7.2. Frequency Distribution of Wind by Velocity Classes

Velocity Class (mph)	Fraction of Time	
	Albuquerque, N. M.	Casper, Wyoming
0-3	0.23	0.06
4-6	0.35	0.21
7-10	0.24	0.28
11-16	0.12	0.26
17-21	0.04	0.13
>21	0.01	0.06
Weighted Ave. (mph)	6.9	10.7

Table 7.3. Annual Number of Wind Events of One-Hour Duration in Velocity Classes at Albuquerque, N.M.[a]

Velocity Class (mph)	Duration (hours)
0-3	1,305
3-6	4,009
6-9	2,118
9-12	1,014
12-15	643
15-18	406
18-21	282
21-24	80
24-27	44
27-30	8
30-33	7
33-36	3
36-39	1

[a] An event is registered if wind velocity is in the velocity class for >50% of the 1-hr observation period.

Table 7.4. Source Strength for Dust Particles Suspended From a 100-Acre Tailings Area for Different Wind Velocities

Wind Velocity (mph)	Source Strength [g sec^{-1} (100 acres)$^{-1}$]					
	Tailings from Acid Circuit			Tailings from Alkaline Circuit		
	5 μ[a]	35 μ	5 μ + 35 μ	5 μ	35 μ	5 μ + 35 μ
7	0.052	0.125	0.177	0.100	0.077	0.177
10	0.68	1.64	2.33	1.32	1.01	2.33
30	214	519	733	413	317	730

---

[a] Median diameters representing particle size classes; 5 μ = 0-10 μ, 35 μ = 10-80 μ. Particles >80 μ creep along the surface and would not become airborne except at very high wind velocities.

Table 7.5. Latitude-Longitude Coordinates Used to Derive Data Sets for Population Distribution

Latitude (N)	Longitude (W)
30° 25' 83"	107° 93' 05"
35° 40' 83"	107° 83' 33"
43° 06' 67"	105° 50' 00"
42° 81' 67"	107° 61' 67"
38° 32' 50"	108° 75' 00"

Table 7.6. 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	2330
NNE	0	0	0	0	146	0	0	0	0	67	259	6053
NE	0	0	0	0	0	0	0	0	0	80	194	1197
ENE	0	0	0	0	0	0	0	0	105	91	909	2232
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	5578	5226
W	0	0	0	0	0	0	97	197	0	79	69	4185
WNW	0	0	0	0	0	0	0	102	135	338	2954	4881
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 ±3271	1761 ±4828
Cumulative	0	0	191	191	337	337	2663	4147	8182	11852	24868	53053
Density (ind./mile^2)			<— 4.3 —>				9.9	<— 3.0 —>			<— 7.1 —>	

[a] Standard deviation of the mean.

Table 7.7. Maximum Annual Doses[a] to Individuals[b] and Population[c] from Airborne Effluents of a Model Uranium Mill at the New Mexico Site, Assuming that 100% of the Food Is Produced Locally

MILL PROCESSES[d]

(Tailings area not included)

Process and Radwaste Treatment Case	Maximum Total Body Dose (mrem)	Maximum Adult Organ Doses (mrem)					Population Total Body Dose (man-rem)
		Bone	Liver	Kidney	Lung	Spleen	
Solvent Extraction							
1	20.2	232.4	23.6	40.1	29.3	23.8	4.9E-1
2	6.4	72.9	7.5	12.5	9.1	7.7	1.6E-1
3	1.7	19.0	1.8	3.3	2.9	1.8	3.7E-2
4	4.0E-1	5.1	8.0E-1	9.3E-1	1.2	4.2E-1	9.7E-3
5	2.9E-1	3.0	3.4E-1	5.1E-1	7.5E-1	3.6E-1	7.0E-3
6	2.1E-4	2.5E-3	2.2E-4	4.6E-4	4.4E-1	2.0E-4	4.7E-6
7	2.1E-4	2.5E-3	2.2E-4	4.6E-4	4.8E-3	2.0E-4	4.7E-6
Alkaline Leach							
1	25.3	265.5	28.3	40.9	35.2	29.4	6.2E-1
2	7.6	81.2	8.7	12.7	10.6	9.1	1.9E-1
3	2.2	22.2	2.3	3.4	3.5	2.4	5.2E-2
4	6.6E-1	6.7	7.0E-1	9.7E-1	1.5	7.1E-1	1.6E-2
5	2.9E-1	3.0	3.4E-1	5.1E-1	7.5E-1	3.6E-1	7.0E-3
6	3.3E-4	3.3E-3	3.4E-4	4.8E-4	4.4E-1	3.4E-4	7.9E-6
7	3.3E-4	3.3E-3	3.4E-4	4.8E-4	5.0E-3	3.4E-4	7.9E-6

[a] 50-yr dose commitment from exposure to mill effluents during the final (i.e. 20th yr) of operation.

[b] Dose to individuals is at 0.5 mile and downwind of the prevailing wind direction. Average dose is 47% of the maximum.

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

[d] 6% moisture ore, which produces a relatively large amount of dust.

Table 7.7a. Maximum Annual Doses[a] to Individuals[b] and Population[c] from Airborne Effluents of a Model Uranium Mill at the New Mexico Site, Assuming that 100% of the Food Is Produced Locally

ORE DUST[d] AND RADON

(Mill processes - tailings area not included)

Process and Radwaste Treatment Case	Maximum Total Body Dose (mrem)	Maximum Adult Organ Doses (mrem)					Population Total Body Dose (man-rem)
		Bone	Liver	Kidney	Lung	Spleen	
Solvent Extraction							
1	18.0	192.0	21.2	31.8	20.0	22.6	4.4E-1
2	5.8	62.8	6.9	10.4	6.8	7.4	1.5E-1
3	1.5	15.0	1.6	2.5	2.0	1.7	3.4E-2
4	2.9E-1	3.0	3.4E-1	5.1E-1	7.5E-1	3.6E-1	7.0E-3
5	2.9E-1	3.0	3.4E-1	5.1E-1	7.5E-1	3.6E-1	7.0E-3
6	1.5E-4	1.5E-3	1.6E-4	2.5E-4	4.4E-1	1.7E-4	3.4E-6
7	1.5E-4	1.5E-3	1.6E-4	2.5E-4	4.6E-3	1.7E-4	3.4E-6
Alkaline Leach	Same as Solvent Extraction Process						

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[a] 50-yr dose commitment from exposure to mill effluents during the final (i.e. 20th yr) of operation.

[b] Dose to individuals is at 0.5 mile and downwind of the prevailing wind direction. Average dose is 47% of the maximum.

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

[d] 6% moisture ore, which produces a relatively large amount of dust.

Table 7.7b. Maximum Annual Doses[a] to Individuals[b] and Population[c] from Airborne Effluents of a Model Uranium Mill at the New Mexico Site, Assuming that 100% of the Food Is Produced Locally

YELLOW CAKE DUST

Process and Radwaste Treatment Case	Maximum Total Body Dose (mrem)	Maximum Adult Organ Doses (mrem)					Population Total Body Dose (man-rem)
		Bone	Liver	Kidney	Lung	Spleen	
Solvent Extraction							
1	2.2	40.4	2.4	8.3	9.3	1.2	5.3E-2
2	5.5E-1	10.1	6.0E-1	2.1	2.3	3.0E-1	1.3E-2
3	2.2E-1	4.0	2.4E-1	8.1E-1	9.1E-1	1.2E-1	5.2E-3
4	1.1E-1	2.1	1.2E-1	4.2E-1	4.7E-1	6.1E-2	2.7E-3
5	5.5E-5	1.0E-3	6.0E-5	2.1E-4	2.3E-4	3.0E-5	1.3E-6
6	5.5E-5	1.0E-3	6.0E-5	2.1E-4	2.3E-4	3.0E-5	1.3E-6
7	5.5E-5	1.0E-3	6.0E-5	2.1E-4	2.3E-4	3.0E-5	1.3E-6
Alkaline Leach							
1	7.3	73.5	7.1	9.1	15.2	6.8	1.8E-1
2	1.8	18.4	1.8	2.3	3.8	1.7	4.5E-2
3	7.2E-1	7.2	7.0E-1	8.9E-1	1.5	6.7E-1	1.8E-2
4	3.7E-1	3.7	3.6E-1	4.6E-1	7.8E-1	3.5E-1	9.2E-3
5	1.8E-4	1.8E-3	1.8E-4	2.3E-4	3.8E-4	1.7E-4	4.5E-6
6	1.8E-4	1.8E-3	1.8E-4	2.3E-4	3.8E-4	1.7E-4	4.5E-6
7	1.8E-4	1.8E-3	1.8E-4	2.3E-4	3.8E-4	1.7E-4	4.5E-6

[a] 50-yr dose commitment from exposure to mill effluents during the final (i.e. 20th yr) of operation.

[b] Dose to individuals is at 0.5 mile and downwind of the prevailing wind direction. Average dose is 47% of the maximum.

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

Table 7.7c. Maximum Annual Doses[a] to Individuals[b] and Population[c] from Airborne Effluents of a Model Uranium Mill at the Wyoming Site, Assuming that 100% of the Food Is Produced Locally

MILL PROCESSES[d]

(Tailings area not included)

Process and Radwaste Treatment Case	Maximum Total Body Dose (mrem)	Maximum Adult Organ Doses (mrem)					Population Total Body Dose (man-rem)
		Bone	Liver	Kidney	Lung	Spleen	
<u>Solvent Extraction</u>							
1	16.5	189.4	19.1	32.5	23.6	19.3	4.3E-1
2	5.3	59.4	6.2	10.2	7.4	6.2	1.4E-1
3	1.4	15.5	1.5	2.7	2.2	1.6	3.5E-2
4	3.3E-1	4.2	3.8E-1	7.5E-1	8.5E-1	3.4E-1	8.5E-3
5	2.4E-1	2.5	2.8E-1	4.1E-1	4.7E-1	2.9E-1	6.1E-3
6	1.7E-4	2.0E-3	1.8E-4	3.7E-4	2.1E-1	1.7E-4	4.2E-6
7	1.7E-4	2.0E-3	1.8E-4	3.7E-4	2.4E-3	1.7E-4	4.2E-6
<u>Alkaline Leach</u>							
1	20.6	215.6	23.0	33.2	28.4	23.7	5.4E-1
2	6.3	65.9	7.2	10.4	8.6	7.3	1.7E-1
3	1.8	18.0	1.9	2.7	2.7	2.0	4.6E-2
4	5.4E-1	5.5	5.8E-1	7.9E-1	1.1	5.6E-1	1.4E-2
5	2.4E-1	2.5	2.8E-1	4.1E-1	4.7E-1	2.9E-1	6.1E-3
6	2.7E-4	2.7E-3	2.8E-4	3.9E-4	2.1E-1	2.8E-4	7.0E-6
7	2.7E-4	2.7E-3	2.8E-4	3.9E-4	2.5E-3	2.8E-4	7.0E-6

[a] 50-yr dose commitment from exposure to mill effluents during the final (i.e. 20th yr) of operation.

[b] Dose to individuals is at 0.5 mile and downwind of the prevailing wind direction. Average dose is 42% of the maximum.

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

[d] 6% moisture ore, which produces a relatively large amount of dust.

Table 7.7d. Maximum Annual Doses[a] to Individuals[b] and Population[c] from Airborne Effluents of a Model Uranium Mill at the Wyoming Site, Assuming that 100% of the Food Is Produced Locally

ORE DUST[d] AND RADON

(Mill processes - tailings area not included)

Process and Radwaste Treatment Case	Maximum Total Body Dose (mrem)	Maximum Adult Organ Doses (mrem)					Population Total Body Dose (man-rem)
		Bone	Liver	Kidney	Lung	Spleen	
Solvent Extraction							
1	14.7	156.0	17.2	25.8	16.1	18.4	3.8E-1
2	4.8	51.0	5.7	8.5	5.5	6.0	1.3E-1
3	1.2	12.2	1.3	2.0	1.5	1.5	3.0E-2
4	2.4E-1	2.5	2.8E-1	4.1E-1	4.7E-1	2.9E-1	6.1E-3
5	2.4E-1	2.5	2.8E-1	4.1E-1	4.7E-1	2.9E-1	6.1E-3
6	1.2E-4	1.2E-3	1.3E-4	2.0E-4	2.1E-1	1.5E-4	3.0E-6
7	1.2E-4	1.2E-3	1.3E-4	2.0E-4	2.2E-3	1.5E-4	3.0E-6
Alkaline Leach	Same as Solvent Extraction Process						

---

[a] 50-yr dose commitment from exposure to mill effluents during the final (i.e. 20th yr) of operation.

[b] Dose to individuals is at 0.5 mile and downwind of the prevailing wind direction. Average dose is 42% of the maximum.

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

[d] 6% moisture ore, which produces a relatively large amount of dust.

Table 7.7e. Maximum Annual Doses[a] to Individuals[b] and Population[c] from Airborne Effluents of a Model Uranium Mill at the Wyoming Site, Assuming that 100% of the Food Is Produced Locally

YELLOW CAKE DUST

Process and Radwaste Treatment Case	Maximum Total Body Dose (mrem)	Maximum Adult Organ Doses (mrem)					Population Total Body Dose (man-rem)
		Bone	Liver	Kidney	Lung	Spleen	
Solvent Extraction							
1	1.8	33.4	1.9	6.7	7.5	9.4E-1	4.8E-2
2	4.5E-1	8.4	4.8E-1	1.7	1.9	2.4E-1	1.2E-2
3	1.8E-1	3.3	1.9E-1	6.6E-1	7.4E-1	9.2E-2	4.7E-3
4	9.2E-2	1.7	9.7E-2	3.4E-1	3.8E-1	4.8E-2	2.4E-3
5	4.5E-5	8.4E-4	4.8E-5	1.7E-4	1.9E-4	2.4E-5	1.2E-6
6	4.5E-5	8.4E-4	4.8E-5	1.7E-4	1.9E-4	2.4E-5	1.2E-6
7	4.5E-5	8.4E-4	4.8E-5	1.7E-4	1.9E-4	2.4E-5	1.2E-6
Alkaline Leach							
1	5.9	59.6	5.8	7.4	12.3	5.3	1.6E-1
2	1.5	14.9	1.5	1.9	3.1	1.3	4.0E-2
3	5.8E-1	5.8	5.7E-1	7.3E-1	1.2	5.2E-1	1.6E-2
4	3.0E-1	3.0	3.0E-1	3.8E-1	6.3E-1	2.7E-1	8.2E-3
5	1.5E-4	1.5E-3	1.5E-4	1.9E-4	3.1E-4	1.3E-4	4.0E-6
6	1.5E-4	1.5E-3	1.5E-4	1.9E-4	3.1E-4	1.3E-4	4.0E-6
7	1.5E-4	1.5E-3	1.5E-4	1.9E-4	3.1E-4	1.3E-4	4.0E-6

[a] 50-yr dose commitment from exposure to mill effluents during the final (i.e. 20th yr) of operation.

[b] Dose to individuals is at 0.5 mile and downwind of the prevailing wind direction. Average dose is 42% of the maximum.

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

Table 7.8. Maximum Annual Doses[a] to Individuals[b] from Airborne Effluents of a Model Uranium Mill at the New Mexico Site, Assuming that None of the Food Is Produced Locally

MILL PROCESSES[c]

(Tailings area not included)

Process and Radwaste Treatment Case	Maximum Total Body Dose (mrem)	Maximum Adult Organ Doses (mrem)			
		Bone	Liver	Kidney	Lung
Solvent Extraction					
1	1.9	47.8	2.4	10.7	10.8
2	5.4E-1	13.7	6.8E-1	3.1	3.2
3	1.8E-1	4.2	2.1E-1	9.5E-1	1.4
4	6.9E-2	1.7	8.0E-2	3.7E-1	8.9E-1
5	1.3E-2	3.6E-1	1.9E-2	8.2E-2	4.8E-1
6	3.4E-5	8.0E-4	3.9E-5	1.8E-4	4.4E-1
7	3.4E-5	8.0E-4	3.9E-5	1.8E-4	4.6E-3
Alkaline Leach					
1	1.3	26.2	1.5	5.9	11.1
2	3.9E-1	8.3	4.4E-1	1.9	3.3
3	1.1E-1	2.1	1.2E-1	4.8E-1	1.4
4	3.9E-2	5.5E-1	3.2E-2	1.2E-1	9.1E-1
5	1.3E-2	3.6E-1	1.9E-2	8.2E-2	4.8E-1
6	1.9E-5	2.6E-4	1.6E-5	6.0E-5	4.4E-1
7	1.9E-5	2.6E-4	1.6E-5	6.0E-5	4.6E-3

[a] 50-yr dose commitment from exposure to mill effluents during the final (i.e. 20th yr) of operation.

[b] Dose to individuals is at 0.5 mile and downwind of the prevailing wind direction. Average dose is 47% of the maximum.

[c] 6% moisture ore, which produces a relatively large amount of dust.

Table 7.8a. Maximum Annual Doses[a] to Individuals[b] from Airborne Effluents of a Model Uranium Mill at the New Mexico Site, Assuming that None of the Food Is Produced Locally

ORE DUST[c] AND RADON

(Mill processes - tailings area not included)

Process and Radwaste Treatment Case	Maximum Total Body Dose (mrem)	Maximum Adult Organ Doses (mrem)			
		Bone	Liver	Kidney	Lung
Solvent Extraction					
1	7.9E-1	22.5	1.2	5.1	2.7
2	2.6E-1	7.4	3.8E-1	1.7	1.2
3	6.6E-2	1.7	9.2E-2	4.0E-1	6.2E-1
4	1.3E-2	3.6E-1	1.9E-2	8.2E-2	4.8E-1
5	1.3E-2	3.6E-1	1.9E-2	8.2E-2	4.8E-1
6	6.2E-6	1.7E-4	9.3E-6	4.0E-5	4.4E-1
7	6.2E-6	1.7E-4	9.3E-6	4.0E-5	4.4E-3
Alkaline Leach	Same as Solvent Extraction Process				

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[a] 50-yr dose commitment from exposure to mill effluents during the final (i.e. 20th yr) of operation.

[b] Dose to individuals is at 0.5 mile and downwind of the prevailing wind direction. Average dose is 47% of the maximum.

[c] 6% moisture ore, which produces a relatively large amount of dust.

Table 7.8b. Maximum Annual Doses[a] to Individuals[b] from Airborne Effluents of a Model Uranium Mill at the New Mexico Site, Assuming that None of the Food Is Produced Locally

YELLOW CAKE DUST

Process and Radwaste Treatment Case	Maximum Total Body Dose (mrem)	Maximum Adult Organ Doses (mrem)			
		Bone	Liver	Kidney	Lung
<u>Solvent Extraction</u>					
1	1.1	25.3	1.2	5.6	8.1
2	2.8E-1	6.3	3.0E-1	1.4	2.0
3	1.1E-1	2.5	1.2E-1	5.5E-1	7.9E-1
4	5.6E-2	1.3	6.1E-2	2.9E-1	4.1E-1
5	2.8E-5	6.3E-4	3.0E-5	1.4E-4	2.0E-4
6	2.8E-5	6.3E-4	3.0E-5	1.4E-4	2.0E-4
7	2.8E-5	6.3E-4	3.0E-5	1.4E-4	2.0E-4
<u>Alkaline Leach</u>					
1	5.0E-1	3.7	2.6E-1	8.0E-1	8.4
2	1.3E-1	9.3E-1	6.5E-2	2.0E-1	2.1
3	4.9E-2	3.6E-1	2.5E-2	7.8E-2	8.2E-1
4	2.6E-2	1.9E-1	1.3E-2	4.1E-2	4.3E-1
5	1.3E-5	9.3E-5	6.5E-6	2.0E-5	2.1E-4
6	1.3E-5	9.3E-5	6.5E-6	2.0E-5	2.1E-4
7	1.3E-5	9.3E-5	6.5E-6	2.0E-5	2.1E-4

[a] 50-yr dose commitment from exposure to mill effluents during the final (i.e. 20th yr) of operation.

[b] Dose to individuals is at 0.5 mile and downwind of the prevailing wind direction. Average dose is 47% of the maximum.

Table 7.8c. Maximum Annual Doses[a] to Individuals[b] from Airborne Effluents of a Model Uranium Mill at the Wyoming Site, Assuming that None of the Food Is Produced Locally

MILL PROCESSES[c]

(Tailings area not included)

Process and Radwaste Treatment Case	Maximum Total Body Dose (mrem)	Maximum Adult Organ Doses (mrem)			
		Bone	Liver	Kidney	Lung
Solvent Extraction					
1	1.6	40.1	2.1	8.6	8.7
2	4.4E-1	11.5	5.9E-1	2.4	2.6
3	1.4E-1	3.6	1.8E-1	7.6E-1	1.0
4	5.7E-2	1.4	6.9E-2	3.0E-1	5.8E-1
5	1.1E-2	3.0E-1	1.7E-2	6.6E-2	2.4E-1
6	2.8E-5	6.8E-4	3.3E-5	1.4E-4	2.1E-1
7	2.8E-5	6.8E-4	3.3E-5	1.4E-4	2.3E-3
Alkaline Leach					
1	1.1	21.9	1.3	4.8	8.9
2	3.1E-1	7.0	3.9E-1	1.5	2.6
3	9.1E-2	1.8	1.0E-1	3.8E-1	1.0
4	3.1E-2	4.5E-1	2.8E-2	9.9E-2	5.9E-1
5	1.1E-2	3.0E-1	1.7E-2	6.6E-2	2.4E-1
6	1.5E-5	2.3E-4	1.4E-5	4.8E-5	2.1E-1
7	1.5E-5	2.3E-4	1.4E-5	4.8E-5	2.3E-3

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[a] 50-yr dose commitment from exposure to mill effluents during the final (i.e. 20th yr) of operation.

[b] Dose to individuals is at 0.5 mile and downwind of the prevailing wind direction. Average dose is 42% of the maximum.

[c] 6% moisture ore, which produces a relatively large amount of dust.

Table 7.8d. Maximum Annual Doses[a] to Individuals[b] from Airborne Effluents of a Model Uranium Mill at the Wyoming Site, Assuming that None of the Food Is Produced Locally

ORE DUST[c] AND RADON

(Mill processes - tailings area not included)

Process and Radwaste Treatment Case	Maximum Total Body Dose (mrem)	Maximum Adult Organ Doses (mrem)			
		Bone	Liver	Kidney	Lung
<u>Solvent Extraction</u>					
1	6.6E-1	18.9	1.1	4.1	2.1
2	2.1E-1	6.2	3.4E-1	1.3	9.0E-1
3	5.2E-2	1.5	8.2E-2	3.2E-1	3.7E-1
4	1.1E-2	3.0E-1	1.7E-2	6.6E-2	2.4E-1
5	1.1E-2	3.0E-1	1.7E-2	6.6E-2	2.4E-1
6	5.2E-6	1.5E-4	8.2E-6	3.2E-5	2.1E-1
7	5.2E-6	1.5E-4	8.2E-6	3.2E-5	2.1E-3
<u>Alkaline Leach</u>	Same as Solvent Extraction Process				

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[a] 50-yr dose commitment from exposure to mill effluents during the final (i.e. 20th yr of operation).

[b] Dose to individuals is at 0.5 mile and downwind of the prevailing wind direction. Average dose is 42% of the maximum.

[c] 6% moisture ore, which produces a relatively large amount of dust.

Table 7.8e. Maximum Annual Doses[a] to Individuals[b] from Airborne Effluents of a Model Uranium Mill at the Wyoming Site, Assuming that None of the Food Is Produced Locally

YELLOW CAKE DUST

Process and Radwaste Treatment Case	Maximum Total Body Dose (mrem)	Maximum Adult Organ Doses (mrem)			
		Bone	Liver	Kidney	Lung
<u>Solvent Extraction</u>					
1	9.0E-1	21.2	9.8E-1	4.5	6.6
2	2.3E-1	5.3	2.5E-1	1.1	1.7
3	8.8E-2	2.1	9.6E-2	4.4E-1	6.5E-1
4	4.6E-2	1.1	5.0E-2	2.3E-1	3.4E-1
5	2.3E-5	5.3E-4	2.5E-5	1.1E-4	1.7E-4
6	2.3E-5	5.3E-4	2.5E-5	1.1E-4	1.7E-4
7	2.3E-5	5.3E-4	2.5E-5	1.1E-4	1.7E-4
<u>Alkaline Leach</u>					
1	4.0E-1	3.0	2.1E-1	6.5E-1	6.8
2	1.0E-1	7.5E-1	5.3E-2	1.6E-1	1.7
3	3.9E-2	2.9E-1	2.1E-2	6.4E-2	6.7E-1
4	2.0E-2	1.5E-1	1.1E-2	3.3E-2	3.5E-1
5	1.0E-5	7.5E-5	5.3E-6	1.6E-5	1.7E-4
6	1.0E-5	7.5E-5	5.3E-6	1.6E-5	1.7E-4
7	1.0E-5	7.5E-5	5.3E-6	1.6E-5	1.7E-4

[a] 50-yr dose commitment from exposure to mill effluents during the final (i.e. 20th yr) of operation.

[b] Dose to individuals is at 0.5 mile and downwind of the prevailing wind direction. Average dose is 42% of the maximum.

Table 7.9. Major Radionuclides Contributing to Total Body Dose from Airborne Effluents at 0.5 Mile from a Model Solvent Extraction Mill,[a] Assuming that 100% of the Food Is Produced Locally

(Mill processes - tailings area not included)

Radionuclide[b]	Percent of Total Body Dose			
	Submersion in Air[c]	Contaminated Ground[c]	Inhalation[d]	Ingestion[e]
U_{nat}[f]	<0.1	1.6	1.3	3.4
^{226}Ra	<0.1	<0.1	0.9	84.4
^{230}Th	<0.1	<0.1	6.6	0.1
^{210}Pb	<0.1	0.1	<0.1	0.7
^{210}Po	<0.1	<0.1	<0.1	1.0
^{210}Bi	<0.1	<0.1	<0.1	<0.1

[a] Case 1.

[b] Radionuclides contributing <0.02% of dose are not listed.

[c] Exposure is for 100% of the time; no shielding.

[d] Inhalation rate of 20 m^3 of air per day; inhaled particles are less than 10 μ in diameter.

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

[f] U_{nat} includes ^{238}U, ^{235}U, ^{234}U (see 10 CFR 20).

Table 7.10. Major Radionuclides Contributing to Individual Organ Doses from Airborne Effluents at 0.5 Mile from a Model Solvent Extraction Mill,[a] Assuming that 100% of the Food Is Produced Locally

(Mill processes - tailings area not included)

	Percent of Organ Dose							
	Bone		Liver		Kidney		Lung	
Radionuclide[b]	Inhaled	Ingested	Inhaled	Ingested	Inhaled	Ingested	Inhaled	Ingested
U_{nat}[c]	1.8	4.7	1.1	2.9	2.4	6.3	33.3	2.2
^{226}Ra	0.7	69.6	0.7	72.5	0.4	41.3	4.6	54.6
^{230}Th	20.6	0.5	9.4	0.3	25.7	0.7	1.6	0.1
^{210}Pb	0.1	1.7	0.2	4.9	0.5	8.1	0.3	0.5
^{210}Po	<0.1	0.4	<0.1	7.8	0.1	14.5	0.4	0.7
^{222}Rn	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.6	<0.1

[a] Case 1.

[b] Radionuclides contributing <0.02% of dose are not listed.

[c] U_{nat} includes ^{238}U, ^{235}U, ^{234}U (see 10 CFR 20).

Table 7.11. Cumulative Population and Dose (man-rem) from Airborne Effluents as a Function of Distance from a Model Solvent Extraction Uranium Mill at the New Mexico Site, Case 1[a]

(Mill processes - tailings area not included)

Distance (miles)	Population	Dose
0-2	1.91E+02	1.3E-1
0-3	1.01E+02	1.3E-1
0-4	3.37E+02	1.5E-1
0-5	3.37E+02	1.5E-1
0-10	2.66E+03	3.1E-1
0-15	4.15E+03	3.3E-1
0-25	8.23E+03	4.0E-1
0-35	1.19E+04	4.2E-1
0-45	2.49E+04	4.4E-1
0-55	5.31E+04	4.9E-1

[a] Population doses at the Wyoming site are 87% of those at the New Mexico site.

Table 7.12. Maximum Annual ^{222}Rn Doses to Lungs of Individuals at 0.5 Mile[a] from Model Uranium Tailings Areas[b]

Process and Treatment Case	Radiation Dose (mrem/year): Mill Operating (Near End of 20-Year Life of Mill When Tailings Cover Maximum Area): New Mexico	Mill Operating: Wyoming	Mill Closed and Final Cover Placed Over Tailings: New Mexico	Mill Closed and Final Cover Placed Over Tailings: Wyoming
Solvent Extraction				
1	43.5	6.7	100.5	58.9
2	43.5	6.7	76.1	44.5
3	27.6	3.1	22.0	14.5
4	24.6	2.0	2.4	1.5
5	5.0	2.9	0.10	0.04
6a	2.1	1.0	0.39	0.17
6b	1.8	0.90	0.32	0.14
6c	0.70	0.30	0.70	0.30
7	24.6	2.0	0.002	0.001
Alkaline Leach				
1	68.2	16.0	100.5	48.2
2	68.2	16.0	76.1	36.5
3	53.6	7.8	22.0	10.6
4	52.5	6.9	2.4	1.1
5	4.4	2.4	0.10	0.04
6a	1.3	0.60	0.24	0.10
6b	1.0	0.50	0.18	0.07
7	52.5	6.9	0.002	0.001

[a] Doses at 1 mile are 5.5 times lower for the New Mexico site and 3.5 times lower for the Wyoming site.

[b] The areas of wet and dry tailings for the different cases are listed in Tables 4.18 and 4.20.

Table 7.13. Maximum Annual Doses[a] to Individuals[b] and Population[c] from Airborne Effluents of Model Uranium Tailings Areas During the Twentieth Year of Operation of the Model Mill, Assuming that 100% of the Food Is Produced Locally

TAILINGS DUST, CASE 1[d]

Site and Process	Dry Tailings Area (acres)	Maximum Total Body Dose (mrem)	Maximum Adult Organ Doses (mrem)					Population Total Body Dose (man-rem)
			Bone	Liver	Kidney	Lung	Spleen	
New Mexico,[e] Solvent Extraction	48	16.6	168.0	19.4	27.0	16.9	21.6	4.0E-1
New Mexico,[e] Alkaline Leach	78	16.1	166.3	18.9	27.1	16.7	20.8	3.9E-1
Wyoming,[f] Solvent Extraction	12	44.4	447.9	51.7	71.9	44.1	57.7	1.2
Wyoming,[f] Alkaline Leach	37	81.6	841.5	95.6	137.3	84.5	105.2	2.2

[a] 50-yr dose commitment based on average annual wind speeds of 7 mph for the New Mexico site and 10 mph for the Wyoming site.

[b] Dose to individuals is at 0.5 mile and downwind of the prevailing wind direction.

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

[d] In Cases 2 through 7 tailings are treated to minimize airborne movement of tailings dust during mill operations (Sects. 4.4.1.4 and 4.4.3.1).

[e] Average doses at 0.5 mile are 47% of the maximum doses.

[f] Average doses at 0.5 mile are 42% of the maximum doses.

Table 7.13a. Maximum Annual Doses[a] to Individuals from Airborne Effluents of Model Uranium Tailings Areas During the Twentieth Year of Operation of the Model Mill, Assuming that None of the Food Is Produced Locally

TAILINGS DUST, CASE 1[b]

Site and Process	Dry Tailings Area (acres)	Dose (mrem)				
		Total Body	Bone	Liver	Kidney	Lung
New Mexico,[c] Solvent Extraction	48	2.5E-1	7.0	3.6E-1	1.5	5.5E-1
New Mexico,[c] Alkaline Leach	78	4.2E-1	12.1	6.3E-1	2.6	1.0
Wyoming,[d] Solvent Extraction	12	6.7E-1	18.6	9.6E-1	4.1	4.0E-1
Wyoming,[d] Alkaline Leach	37	2.1	61.5	3.2	13.4	5.1

[a] 50-yr dose commitment to individual at 0.5 mile and downwind of the prevailing wind direction based on average annual wind speeds of 7 mph for the New Mexico site and 10 mph for the Wyoming site.

[b] In Cases 2 through 7 tailings are treated to minimize airborne movement of tailings dust during mill operations (Sects. 4.4.1.1 and 4.4.3.1).

[c] Average doses at 0.5 mile are 47% of the maximum doses.

[d] Average doses at 0.5 mile are 42% of the maximum doses.

Table 7.14. Percentage of Total Body Dose from Airborne Tailings or Mill Process as a Function of Exposure Mode,[a] Assuming that 100% of the Food Is Produced Locally

	Submersion in Air[b]	Contaminated Ground[b]	Inhalation[c]	Ingestion[d]
Airborne Tailings				
Solvent Extraction Process	<0.1	0.1	1.4	98.5
Alkaline Leach Process	<0.1	0.1	2.5	97.4
Mill Operations				
Solvent Extraction Process	<0.1	1.4	7.8	91.0
Alkaline Leach Process	<0.1	1.1	4.1	95.0

[a] Dose at 0.5 mile from the New Mexico mill in the prevailing wind direction.

[b] Exposure is for 100% of the time; no shielding.

[c] Inhalation rate of 20 m^3 of air per day; inhaled particles are less than 10 μ in diameter.

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

Table 7.15. Total Maximum Annual Radiation Dose to Individuals at 0.5 Mile from a Operating Model Uranium Mill and Tailings Area in New Mexico, Case 1,[a,b] Assuming that 100% of the Food Is Produced Locally

MILL PROCESSES AND TAILINGS COMBINED

	Solvent Extraction Process (mrem)			Alkaline Leach Process (mrem)		
	Mill	Tailings	Total	Mill	Tailings	Total
Total body	20.2	16.6	36.8	25.3	16.1	41.4
Bone	232.4	168.0	400.4	265.5	166.3	431.8
Liver	23.6	19.4	43.0	28.3	18.9	47.2
Kidney	40.1	27.0	67.1	40.9	27.1	68.0
Spleen	23.5	21.6	45.1	29.4	20.8	50.2
Lung	29.3	60.4	89.7	35.2	84.9	120.1

[a] Twentieth year of operation when tailings cover maximum area.

[b] The doses are the sum of the doses from airborne particulates and ^{222}Rn gas from the operating mill and the active tailings area as listed in Tables 7.7, 7.12, and 7.13.

Table 7.16. Total Maximum Annual Radiation Dose to Individuals at 0.5 Mile from a Model Operating Uranium Mill and Tailings Area in Wyoming, Case 1,[a,b] Assuming that 100% of the Food Is Produced Locally

MILL PROCESSES AND TAILINGS COMBINED

	Solvent Extraction Process (mrem)			Alkaline Leach Process (mrem)		
	Mill	Tailings	Total	Mill	Tailings	Total
Total body	16.5	44.4	60.9	20.6	81.6	102.2
Bone	189.4	447.9	637.3	215.6	841.5	1057.1
Liver	19.1	51.7	70.8	23.0	95.6	118.6
Kidney	32.5	71.9	104.4	33.2	137.3	170.5
Spleen	19.3	57.7	77.0	23.7	105.2	128.9
Lung	23.6	50.8	74.4	28.4	100.5	128.9

[a] Twentieth year of operation when tailings cover maximum area.

[b] The doses are the sum of the doses from airborne particulates and ^{222}Rn gas from the operating mill and active tailings area as listed in Tables 7.7c, 7.12, and 7.13.

Table 7.17. Total Maximum Annual Radiation Dose to Lungs of Individuals at 0.5 Mile from Operating Model Uranium Mills and Tailings Areas in New Mexico and Wyoming,[a,b] Assuming that 100% of the Food Is Produced Locally

MILL PROCESSES AND TAILINGS COMBINED

	New Mexico (mrem)			Wyoming (mrem)		
Process	Mill	Tailings[a]	Total	Mill	Tailings[a]	Total
Solvent Extraction						
1	29.3	60.4	89.7	23.6	50.8	74.4
2	9.1	43.5	52.6	7.3	6.7	14.0
3	2.9	27.6	30.5	2.2	3.1	5.3
4	1.2	24.6	25.8	8.4E-1	2.0	2.8
5	7.5E-1	5.0	5.8	4.6E-1	2.9	3.4
6a	4.4E-1	2.1	2.5	2.1E-1	1.0	1.2
6b	4.4E-1	1.8	2.2	2.1E-1	9.0E-1	1.1
6c	4.4E-1	7.0E-1	1.1	2.1E-1	3.0E-1	5.1E-1
7	4.8E-3	24.6	24.6	2.4E-3	2.0	2.0
Alkaline Leach						
1	35.2	84.9	120.1	28.4	100.5	128.9
2	10.6	68.2	78.8	8.5	16.0	24.5
3	3.5	53.6	57.1	2.7	7.8	10.5
4	1.5	52.5	54.0	1.1	6.9	8.0
5	7.5E-1	4.4	5.2	4.6E-1	2.4	2.9
6a	4.4E-1	1.3	1.7	2.1E-1	6.0E-1	8.1E-1
6b	4.4E-1	1.0	1.4	2.1E-1	5.0E-1	7.1E-1
7	5.0E-3	52.5	52.5	2.5E-3	6.9	6.9

[a] Twentieth year of operation when tailings cover maximum area.

[b] The doses are the sum of the lung doses from airborne particulates and ^{222}Rn gas from the operating mill and the active tailings area as listed in Tables 7.7, 7.7c, 7.12, and 7.13. The tailings area are treated in Cases 2 to 7 to prevent tailings dust from blowing during operation of the mill.

Table 7.18. Annual Cumulative Population Dose[a] from Operating Model Uranium Mills and Tailings Areas to Total Body and Individual Organs

	Dose from Mill Operations (man-rem)			Dose from Tailings Pile (man-rem)		
	Total Body	Bone	Lung	Total Body	Bone	Lung
New Mexico						
Solvent Extraction Process	4.9E-1	5.6	6.9E-1	4.0E-1	4.0	4.1E-1
Alkaline Leach Process	6.2E-1	6.4	8.4E-1	3.9E-1	4.0	4.0E-1
Wyoming						
Solvent Extraction Process	4.3E-1	5.1	6.2E-1	1.2	12.0	1.2
Alkaline Leach Process	5.4E-1	5.8	7.5E-1	2.2	22.5	2.3

[a] Annual cumulative dose to population living within a 55-mile radius of the model mill and tailings area, Case 1.

Table 7.19. Curies of Long-Lived Radionuclides Released During the Twenty-Year Life of the Facility[a]

Radionuclide	Mill Process Dusts	Tailings Pile[b]	Total	Ci/m^2 [c]
^{234}U	1.79E00	2.38E-2	1.81E00	8.90E-11
^{238}U	1.79E00	2.38E-2	1.81E00	8.90E-11
^{226}Ra	1.24E-1	3.13E-1	4.37E-1	2.15E-11
^{230}Th	9.01E-2	3.18E-1	4.08E-1	2.00E-11
^{222}Rn	-	8.43E+3[d]	8.43E+3	-

[a] The worst case, a Wyoming mill using the alkaline leach process.

[b] Tailings dust resuspended from an average of 20 acres of dry beach over the 20-year life of the mill and from 25 acres of untreated tailings for 2 years following mill closures and before the final earth cover is placed.

[c] 2.033×10^{10} m^2 in an area of 50-mile radius.

[d] Continuous annual release of ^{222}Rn from a 128-acre tailings pile with a 6-inch earth cover after mill has closed.

Table 7.20. Major Radionuclides and Exposure Modes Contributing to the Annual Total Body Dose[a] to the Average Individual After the Mill Is Closed Until Significant Decay of Radionuclides Occurs

Radionuclide	Exposure Mode Submersion in Air (mrem)	Contaminated Ground (mrem)	Inhalation (mrem)	Ingestion (mrem)	Total (mrem)
^{234}U	1.2E-12	2.3E-4	8.6E-7	6.9E-6	2.4E-4
^{238}U	7.1E-12	3.8E-4	7.6E-7	6.1E-6	3.9E-4
^{226}Ra	1.3E-12	2.5E-5	6.5E-6	6.6E-4	6.9E-4
^{230}Th	2.6E-13	4.4E-5	2.1E-5	2.3E-6	6.7E-5
Total	9.9E-13	6.8E-4	2.9E-5	6.7E-4	1.4E-3

[a] Dose after the mill closes from radon and the radioactive materials which were dispersed during 20 years operation of the Wyoming alkaline-leach mill and 2 years wind erosion of the tailings pile before the final cover was placed assuming Case 1 releases and a uniform distribution of the radioactive dusts within a 50-mile radius of the mill.

Table 7.21. Annual Dose[a] to the Average Individual After the Mill Is Closed Until Significant Decay of Radionuclides Occurs

Radionuclide	Total Body Dose (mrem)	Organ Dose (mrem) per Exposure Mode			
		Bone		Lung	
		Inhalation	Ingestion	Inhalation	Ingestion
^{234}U	2.4E-4	1.4E-5	1.1E-4	3.5E-5	6.9E-6
^{238}U	3.9E-4	1.3E-5	1.0E-4	3.1E-5	6.1E-6
^{226}Ra	6.9E-4	6.3E-5	6.4E-3	5.5E-5	6.6E-4
^{230}Th	6.7E-5	7.6E-4	8.3E-5	7.7E-6	2.3E-6
^{222}Rn	-	-	-	3.4E-1	-
Total	1.4E-3	8.5E-4	6.7E-3	3.4E-1	6.7E-4

[a] Dose after mill closes from radon and the radioactive materials which were dispersed during 20 years operation of the Wyoming alkaline-leach mill and 2 years of wind erosion of the tailings pile before the final cover was laid assuming Case 1 releases and a uniform distribution of the radioactive dusts within a 50-mile radius of the mill.

Table 7.22. Annual Dose to the Population[a] After the Mill Is Closed Until Significant Decay of Radionuclides Occurs

	Dose (man-rem per 5.3×10^4 persons)[b]		
Radionuclide	Total Body	Bone	Lung
^{234}U	1.3E-2	6.7E-3	2.2E-3
^{238}U	2.1E-2	6.1E-3	1.9E-3
^{226}Ra	3.6E-2	3.4E-1	3.8E-2
^{230}Th	3.6E-3	4.5E-2	5.3E-4
^{222}Rn	-	-	1.8E+1
Total	7.4E-2	4.0E-1	1.8E+1

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

[b] Actual population within the 55-mile radius of the Wyoming model mill.

Table 8.1. Total Annual Cost[a] for Reduction of the Maximum Annual Dose from Model Uranium Mills and Tailings Piles in New Mexico

		Maximum Annual Individual Dose at 0.5 Mile												
		Mill Operating											Mill Closed, Tailings Pile Stabilized	
		100% of Food Produced Locally						None (0%) of Food Produced Locally						
Case No.	Total Annual Cost[a] ($1000)	Total Body (mrem)	Bone (mrem)	Lung (mrem)	Liver (mrem)	Kidney (mrem)	Spleen (mrem)	Total Body (mrem)	Bone (mrem)	Lung (mrem)	Liver (mrem)	Kidney (mrem)	Lung (mrem)	Population Total Body[b] Dose, Mill Operating (man-rem)
						Acid Leach—Solvent Extraction Mill								
1	174	3.7E+1	4.0E+2	9.0E+1	4.3E+1	6.7E+1	4.5E+1	2.2E00	5.5E+1	5.4E+1	2.8E00	1.2E+1	1.0E+2	8.9E-1
2	201	6.4E00	7.3E+1	5.3E+1	7.5E00	1.3E+1	7.7E00	5.4E-1	1.4E+1	4.7E+1	6.8E-1	3.0E00	7.6E+1	1.6E-1
3	809	1.7E00	1.9E+1	3.1E+1	1.8E00	3.3E00	1.8E00	1.8E-1	4.2E00	2.9E+1	2.1E-1	9.5E-1	2.2E+1	3.7E-2
4a	1,734	4.0E-1	5.1E00	2.6E+1	8.0E-1	9.3E-1	4.2E-1	6.9E-2	1.7E00	2.5E+1	8.0E-2	3.7E-1	2.4E00	9.7E-3
4b	1,733	4.0E-1	5.1E00	2.6E+1	8.0E-1	9.3E-1	4.2E-1	6.9E-2	1.7E00	2.5E+1	8.0E-2	3.7E-1	2.4E00	9.7E-3
5	2,984	2.9E-1	3.0E00	5.8E00	3.4E-1	5.1E-1	3.6E-1	1.3E-2	3.6E-1	5.5E00	1.9E-2	8.2E-2	1.0E-1	7.0E-3
6a	3,683	2.1E-4	2.5E-3	2.5E00	2.2E-1	4.6E-1	2.0E-4	3.4E-5	8.0E-4	2.5E00	3.9E-5	1.8E-4	3.9E-1	4.7E-6
6b	7,692	2.1E-4	2.5E-3	2.2E00	2.2E-1	4.6E-1	2.0E-4	3.4E-5	8.0E-4	2.2E00	3.9E-5	1.8E-4	3.2E-1	4.7E-6
6c	8,264	2.1E-4	2.5E-3	1.1E00	2.2E-1	4.6E-1	2.0E-4	3.4E-5	8.0E-4	1.1E00	3.9E-5	1.8E-4	7.0E-1	4.7E-6
7	3,074	2.1E-4	2.5E-3	2.5E+1	2.2E-1	4.6E-1	2.0E-4	3.4E-5	8.0E-4	2.5E+1	3.9E-5	1.8E-4	2.0E-3	4.7E-6
							Alkaline Leach Mill							
1	173	4.1E+1	4.3E+2	1.2E+2	4.7E+1	6.8E+1	5.0E+1	1.7E00	3.8E+1	8.0E+1	2.1E00	8.5E00	1.0E+2	1.0E00
2	200	7.6E00	8.1E+1	7.9E+1	8.7E00	1.3E+1	9.1E00	3.9E-1	8.3E00	7.1E+1	4.4E-1	1.9E00	7.6E+1	1.9E-1
3	808	2.2E00	2.2E+1	5.7E+1	2.3E00	3.4E00	2.4E00	1.1E-1	2.1E00	5.5E+1	1.2E-1	4.8E-1	2.2E+1	5.2E-2
4a	1,270	6.6E-1	6.7E00	5.4E+1	7.1E-1	9.7E-1	7.1E-1	3.9E-2	5.5E-1	5.3E+1	3.2E-2	1.2E-1	2.4E00	1.6E-2
4b	1,269	6.6E-1	6.7E00	5.4E+1	7.1E-1	9.7E-1	7.1E-1	3.9E-2	5.5E-1	5.3E+1	3.2E-2	1.2E-1	2.4E00	1.6E-2
5	2,267	2.9E-4	3.0E00	5.2E00	3.4E-1	5.1E-1	3.6E-1	1.3E-2	3.6E-1	4.9E00	1.9E-2	8.2E-2	1.0E-1	7.0E-3
6a	3,163	3.3E-4	3.3E-3	1.7E00	3.4E-4	4.8E-4	3.4E-4	1.9E-5	2.6E-4	1.7E00	1.6E-5	6.0E-5	2.4E-1	7.9E-6
6b	9,900	3.3E-4	3.3E-3	1.4E00	3.4E-4	4.8E-4	3.4E-4	1.9E-5	2.6E-4	1.4E00	1.6E-5	6.0E-5	1.8E-1	7.9E-6
7	2,609	3.3E-4	3.3E-3	5.3E+1	3.4E-4	4.8E-4	3.4E-4	1.9E-5	2.6E-4	5.3E+1	1.6E-5	6.0E-5	2.0E-3	7.9E-6

[a] Total cost for reduction in release of radioactive materials in airborne and seepage effluents and improving the long-term integrity of the stored tailings.

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

Table 8.2. Total Annual Cost[a] for Reduction of the Maximum Annual Dose from Model Uranium Mills and Tailings Piles in Wyoming

		Maximum Annual Individual Dose at 0.5 Mile												
		Mill Operating											Mill Closed, Tailings Pile Stabilized	
		100% of Food Produced Locally						None (0%) of Food Produced Locally						
Case No.	Total Annual Cost[a] ($1000)	Total Body (mrem)	Bone (mrem)	Lung (mrem)	Liver (mrem)	Kidney (mrem)	Spleen (mrem)	Total Body (mrem)	Bone (mrem)	Lung (mrem)	Liver (mrem)	Kidney (mrem)	Lung (mrem)	Population Total Body[b] Dose, Mill Operating (man-rem)
						Acid Leach—Solvent Extraction Mill								
1	180	6.1E+1	6.4E+2	7.4E+1	7.1E+1	1.0E+2	7.7E+1	2.3E00	5.9E+1	1.6E+1	3.1E00	1.3E+1	5.9E+1	1.6E00
2	206	5.3E00	5.9E+1	1.4E+1	6.2E00	1.0E+1	6.2E00	4.4E-1	1.2E+1	9.3E00	5.9E-1	2.4E00	4.4E+1	1.4E-1
3	580	1.4E00	1.6E+1	5.3E00	1.5E00	2.7E00	1.6E00	1.4E-1	3.6E00	4.1E00	1.8E-1	7.6E-1	1.5E+1	3.5E-2
4a	1,546	3.3E-1	4.2E00	2.8E00	3.8E-1	7.5E-1	3.4E-1	5.7E-2	1.4E00	2.7E00	6.9E-2	3.0E-1	1.5E00	8.5E-3
4b	1,544	3.3E-1	4.2E00	2.8E00	3.8E-1	7.5E-1	3.4E-1	5.7E-2	1.4E00	2.7E00	6.9E-2	3.0E-1	1.5E00	8.5E-3
5	3,143	2.4E-1	2.5E00	3.4E00	2.8E-1	4.1E-1	2.9E-1	1.1E-2	3.0E-1	3.1E00	1.7E-2	6.6E-2	4.0E-2	6.1E-3
6a	3,683	1.7E-4	2.0E-3	1.2E00	1.8E-4	3.7E-4	1.7E-4	2.8E-5	6.8E-4	1.2E00	3.3E-5	1.4E-4	1.7E-1	4.2E-6
6b	7,692	1.7E-4	2.0E-3	1.1E00	1.8E-4	3.7E-4	1.7E-4	2.8E-5	6.8E-4	1.1E00	3.3E-5	1.4E-4	1.4E-1	4.2E-6
6c	8,264	1.7E-4	2.0E-3	5.1E-1	1.8E-4	3.7E-4	1.7E-4	2.8E-5	6.8E-4	5.1E-1	3.3E-5	1.4E-4	3.0E-1	4.2E-6
7	2,914	1.7E-4	2.0E-3	2.0E00	1.8E-4	3.7E-4	1.7E-4	2.8E-5	6.8E-4	2.0E00	3.3E-5	1.4E-4	1.0E-3	4.2E-6
						Alkaline Leach Mill								
1	174	1.0E+2	1.1E+3	1.3E+2	1.2E+2	1.7E+2	1.3E+2	3.2E00	8.3E+1	3.0E+1	4.5E00	1.8E+1	4.8E+1	2.7E00
2	199	6.3E00	6.6E+1	2.5E+1	7.2E00	1.0E+1	7.3E00	3.1E-1	7.0E00	1.9E+1	3.9E-1	1.5E00	3.7E+1	1.7E-1
3	804	1.8E00	1.8E+1	1.1E+1	1.9E00	2.7E00	2.0E00	9.1E-2	1.8E00	8.8E00	1.0E-1	3.8E-1	1.1E+1	4.6E-2
4a	1,227	5.4E-1	5.5E00	8.0E00	5.8E-1	7.9E-1	5.6E-1	3.1E-2	4.5E-1	7.5E00	2.8E-2	9.9E-2	1.1E00	1.4E-2
4b	1,226	5.4E-1	5.5E00	8.0E00	5.8E-1	7.9E-1	5.6E-1	3.1E-2	4.5E-1	7.5E00	2.8E-2	9.9E-2	1.1E00	1.4E-2
5	2,376	2.4E-1	2.5E00	2.9E00	2.8E-1	4.1E-1	2.9E-1	1.1E-2	3.0E-1	2.6E00	1.7E-2	6.6E-2	4.0E-2	6.1E-3
6a	3,163	2.7E-4	2.7E-3	8.1E-1	2.8E-4	3.9E-4	2.8E-4	1.5E-5	2.3E-4	8.1E-1	1.4E-5	4.8E-5	1.0E-1	7.0E-6
6b	9,900	2.7E-4	2.7E-3	7.1E-1	2.8E-4	3.9E-4	2.8E-4	1.5E-5	2.3E-4	7.1E-1	1.4E-5	4.8E-5	7.0E-2	7.0E-6
7	2,568	2.7E-4	2.7E-3	6.9E00	2.8E-4	3.9E-4	2.8E-4	1.5E-5	2.3E-4	6.9E00	1.4E-5	4.8E-5	1.0E-3	7.0E-6

[a] Total cost for reduction in release of radioactive materials in airborne and seepage effluents and improving the long-term integrity of the stored waste.

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

ORNL-TM-- 4903 (V.II)

Table 9.1. Uranium Mills and Processes

Company	Mill Location	Mill Startup	Processing Rate[b] (tons of ore per day)	Mine: Underground	Mine: Open Pit	Mine: Wet	Artifical Drying or Roasting	Acid Leach: 2-Stage Leaching	Acid Leach: Solid-Liquid Separation: Sand-Slime Separation	Acid Leach: Solid-Liquid Separation: Classifiers	Acid Leach: Countercurrent Decantation	Acid Leach: Solvent Extraction: Amine: Alamine 336	Acid Leach: Solvent Extraction: Amine: Adogen 364	Acid Leach: Solvent Extraction: Alcohol: Isodecanol	Acid Leach: Solvent Extraction: Alcohol: Tridecanol	Acid Leach: Solvent Extraction: Strip: NaCl	Acid Leach: Solvent Extraction: Strip: $(NH_4)_2SO_4$	Acid Leach: Solvent Extraction: Strip: NH_4Cl	Acid Leach: Ion Exchange: Continuous RIP	Acid Leach: Ion Exchange: Basket RIP	Acid Leach: Ion Exchange: Fixed Bed IX	Acid Leach: Ion Exchange: Moving Bed IX	Acid Leach: Ion Exchange: Eluant: $NaCl-H_2SO_4$	Acid Leach: Ion Exchange: Eluant: $NH_4NO_3-H_2SO_4$	Acid Leach: Ion Exchange: Eluant: $NaCl-(NH_4)_2SO_4$	Acid Leach: Ion Exchange: Eluant: $H_2SO_4-(NH_4)_2SO_4$	Acid Leach: Ion Exchange: Eluex-Amine Solvent Extraction with $(NH_4)_2SO_4$ Strip	Acid Leach: Precipitation: Ammonia	Acid Leach: Precipitation: 2-Stage (Lime-MgO)	Alkaline Leach: Staged Filtration	Alkaline Leach: Caustic Precipitation	Alkaline Leach: Dissolve Ppt. in H_2SO_4 and Reppt. NH_3	Alkaline Leach: Dissolve Ppt. in H_2SO_4 and Reppt. H_2O_2	Other: Vanadium	Other: Molybdenum	Other: H_2SO_4 Plant
Anaconda	Bluewater, N.M.	1955[a] (also had alkaline leach 1953-1959)	2,000[d] (near future 3,000[d])		d				d	d										d			d						d							
Atlas Corp.	Moab, Utah	Alkaline 1956[a] Acid 1967[a]	e e																																	
Conoco- Pioneer Nuclear	Karnes County, Texas	1972[f]	2,000[f]		f	f	f				f	f		f				f										f							f	
Cotter	Canon City, Colorado	Alkaline 1958[a] Acid 1967[g]	h																																	
Dawn	Ford, Washington	1957[i]	350		w	w		w			w										w			w				w								
Exxon	Douglas, Wyoming	1972[j]	2,000[j]		j	j					j	j	j	j			j											j								
Federal American	Gas Hills, Wyoming	1959[a]	950[c]		a	?	a		a	a									a							a	a	a								
Kerr McGee	Grants, N.M.	1958[a]	5,000[k]	k		k			k		k	k		k		k												k							v	a
Petrotomics	Shirley Basin, Wyoming	1962[a]	1,100[l] (near future 550[l])		l	l					l	l	l		l		l											l								
Rio Algom	La Sal, Utah	1972[m]	550[m] (near future 600[m])	m		m																								m	m		m			
Susquehanna Western	Ray Point, Texas	1970[n]	1,000[c]		o	o																								o	o	?	?			
Union Carbide	Uravan, Colorado	1915[a]	900[x]	x			x	a			x										x		x					x						a		a
Union Carbide	Gas Hills, Wyoming	1960[a]	1,400[x]		x	x			x	x									x							x	x	x								
United Nuclear-Homestake	Grants, New Mexico	1958[a]	1,800[p]	p		p	p																							p	p			p		
Utah International	Gas Hills, Wyoming	1958[a]	1,200[q]		q	q	q	q			q											q				q	q	q								
Utah International	Shirley Basin, Wyoming	1971[r]	1,200[c]		s	s		t			t										t				t			t								
Western Nuclear	Jeffrey City, Wyoming	1957[a]	1,100[u]	u		u	u		u	u	u								u							u	u	u								a
	TOTAL, tons of ore per day		22,550	9,350	13,200	≥19,650		3,650	10,450	5,450	14,850	10,100	3,100	9,000	1,100	5,000	3,100	2,000	3,450	2,000	2,450	1,200	2,900	350	1,200	4,650	4,650	17,200	2,000	3,350	3,350		550			
												10,100							9,100																	
								19,200																						3,350						

[a] R. C. Merritt, The Extractive Metallurgy of Uranium, Colorado School of Mines Research Institute, 1971. This reference describes industry as it was in 1967.

[b] Where available, actual operating rates in the Spring 1973 are given. Otherwise the nominal capacity from ref. c is used.

[c] Statistical Data of the Uranium Industry, GJO-100(73) (Jan. 1, 1973), p. 65.

[d] T. R. Beck (Asst. to the Manager, The Anaconda Company), response to questionnaire, Apr. 9, 1973. Also see ref. a.

[e] Expect to modify alkaline plant and rebuild solvent extraction circuit in near future; prefer not to comment on processes at this time; P. V. Bethurum, Manager Utah Operations, Atlas Minerals, letter to R. E. Blanco, March 29, 1973.

[f] Eng. Mining J., pp. 74-77 (August 1972).

[g] H. W. Harrah, Denver Equipment Co. Bull. M4-B137, Spring 1969.

[h] Currently recovering 70 lb of uranium per day by ion exchange of mine waters followed by elution and precipitation of the uranium. Most milling operations are shut down. A. Hazle, J. B. Baird, and B. Crist (Occupational and Radiological Health Division, Colorado Dept. of Health), personal communication to R. Dahlman, Apr. 13, 1973.

[i] D. Hargrove, Mining World, pp. 34-41 (February 1958).

[j] G. D. Ortloff (Environmental Advisor, Minerals Dept., Exxon Company), response to questionnaire, Apr. 12, 1973. Also see Highland Uranium Mill (Humble), DOCKET 408102-1, July 1971.

[k] B. Stevens (Manager, New Mexico Operations, Kerr-McGee Corp.), letter to R. E. Blanco, Apr. 16, 1973. Also see ref. a.

[l] J. H. Whitman (Manager, Petrotomics Company), letter to R. E. Blanco, Apr. 4, 1973. Also see ref. a.

[m] R. D. Haddenham (Metallurgist, Rio Algom Corp.), response to questionnaire, Apr. 7, 1973. Also see Uranium Concentrator (Rio Algom Corp.), DOCKET 40808-1, November 1971.

[n] The Nuclear Industry, 1970, p. 43.

[o] A. H. Ross (A. H. Ross & Associates, Toronto, Canada), personal communication, Feb. 13, 1973.

[p] Roger Madsen (Chief Mechanical Engineer, United Nuclear-Homestake Partners), personal communication, Apr. 11, 1973. Also see ref. a.

[q] D. C. Anderson (Mine Manager, Utah International Inc., Lucky Me Mine), letter to R. E. Blanco, Apr. 18, 1973. Also see ref. a.

[r] The Nuclear Industry, 1971, WASH-1174-71, p. 21.

[s] Shirley Basin Uranium Mill, Docket 406622-2, Nov. 9, 1971.

[t] M. I. Ritchie, Utah Construction and Mining Company's Unique Shirley Basin Uranium Mill, Sao Paulo Symposium on Recovery of Uranium from Its Ore and Other Sources, Aug. 17-21, 1970, Paper IAEA-SM-135/22.

[u] Response to questionnaire received Apr. 16, 1973. Also see ref. a.

[v] John R. Rookstool (Chief Metallurgist, Kerr-McGee Corp.), personal communication, Apr. 10, 1973.

[w] Response to questionnaire received June 5, 1973; also see ref. i.

[x] R. G. Beverly (Director of Environmental Control, Mining and Metals Division, Union Carbide Corp.), response to questionnaire, June 8, 1973.

Table 9.2. Secular Equilibrium of Uranium, Radium, and Thorium in Domestic Uranium Ores[a]

	Uranium ($^{238}U + ^{235}U$)			Radium ($^{226}Ra + ^{223}Ra$)			Thorium ($^{230}Th + ^{227}Th$)		
Ore	% U_3O_8	dpm/g[b]	µCi/g	dpm/g	µCi/g	% Equil.	dpm/g	µCi/g	% Equil.
Ambrosia Lake 1	0.375	2,420	10.9E-4	2,560	11.5E-4	106	2,040	9.18E-4	84
Arrowhead	0.133	717	3.23E-4	1,820[c]	8.19E-4	254	1,410[d]	6.35E-4	197
Schwartzwalder	1.2	7,750	34.9E-4	7,290	32.8E-4	94	7,650	34.5E-4	99
Ambrosia Lake 2	0.162	1,050	4.72E-4	1,110	5.00E-4	106	1,090	4.91E-4	104
Ambrosia Lake 3	0.208	1,340	6.04E-4	1,220	5.50E-4	91	1,400	6.31E-4	104
Lukachukai Blend	0.270	1,740	7.83E-4	1,940	8.73E-4	111	2,260	10.2E-4	130
Hidden Splendor	0.306	1,980	8.97E-4	7,210	32.7E-4	364	7,570	34.3E-4	382
Lukachukai	0.244	1,580	7.15E-4	1,690	7.66E-4	107	1,560	7.08E-4	99
Northgate #7	0.18	1,160	5.27E-4	792	3.59E-4	68	914	4.14E-4	79
Midnight	0.089	575	2.61E-4	607	2.75E-4	106	724	3.28E-4	126
Gas Hills #1	0.257	1,660	7.57E-4	1,680	7.57E-4	101	1,690	7.61E-4	102
Gas Hills #2	0.36	2,330	1.06E-4	2,170	9.77E-4	93	2,096	9.44E-4	90

[a] January 1960 - Summary Report, WIN-112, National Lead Company, Winchester Laboratory (Feb. 1, 1960), p. 95.

[b] Calculated using % U_3O_8 x 6460 = dpm/g ($^{238}U + ^{235}U$).

[c] May include ^{224}Ra.

[d] May include $^{232}Th + ^{228}Th$.

Table 9.3. Comparison of Maximum Permissible Concentrations of Uranium—Radium Family with ^{90}Sr and ^{239}Pu

(From 10 CFR 20, Appendix B, Table 11, Col. 2. The 1/3 factor has not been applied.)

	MPC_{air} (µCi/ml)		MPC_{water} (µCi/ml)	
	Soluble	Insoluble	Soluble	Insoluble
U_{nat}	3E-12[a]	2E-12[a]	2E-5[a]	2E-5[a]
$U_{ore\ dust}$	-	8E-13[a]	-	-
^{238}U	3E-12	5E-12	4E-5	4E-5
^{234}Th	2E-9	1E-9	2E-5	2E-5
^{234}Pa	3E-8	3E-8	-	-
^{234}U	2E-11	4E-12	3E-5	3E-5
^{230}Th	3E-14	3E-13	2E-6	3E-5
^{226}Ra	3E-12	2E-12	3E-8	3E-5
^{222}Rn	3E-9	-	-	-
^{218}Po	2E-14	2E-14	3E-8	3E-8
^{214}Pb	3E-8	3E-8	-	-
^{214}Bi	3E-8	3E-8	-	-
^{214}Po	2E-14	2E-14	3E-8	3E-8
^{210}Pb	4E-12	8E-12	1E-7	2E-4
^{210}Bi	2E-10	2E-10	4E-5	4E-5
^{210}Po	2E-11	7E-12	7E-7	3E-5
^{239}Pu	6E-14	1E-12	5E-6	3E-5
^{90}Sr	3E-11	2E-10	3E-7	4E-5

[a] µCi U_{nat}/ml.

Table 9.4. Uranium Concentration as a Function of Particle Size in the Leach Feed and Tailings[a]

	Leach Feed			Tailings		
	% of Total	U_3O_8		% of Total	U_3O_8	
Mesh Size	Weight	% Assay	% of Total	Weight	% Assay	% of Total
Mill D — Acid Circuit — Monthly Composite for February 1961						
+28	3.72	0.186	3.09	3.57	0.0170	7.42
-28 +35	9.46	0.130	5.49	9.14	0.0092	10.28
-35 +48	16.88	0.113	8.51	16.69	0.0046	9.38
-48 +65	18.37	0.098	8.03	19.27	0.0037	8.72
-65 +100	17.15	0.099	7.58	17.90	0.0048	10.51
-100 +150	8.35	0.119	4.44	8.58	0.0047	4.93
-150 +200	4.50	0.151	3.03	4.43	0.0075	4.06
-200	21.57	0.621	59.83	20.42	0.0179	44.70
Calc. Head	100.00	0.224	100.00	100.00	0.0082	100.00
Mill I — Alkaline Circuit — Monthly Composite for June 1972						
+48	10.5	0.103	8.2	3.6	0.054	16.4
-48 +65	21.0	0.084	13.4	12.5	0.012	12.6
-65 +100	16.8	0.082	10.5	16.7	0.008	11.2
-100 +150	11.2	0.090	7.6	13.8	0.007	8.1
-150 +200	8.9	0.097	6.6	11.4	0.006	5.7
-200	31.6	0.224	53.7	42.0	0.013	46.0
Calc. Head	100.0	0.132	100.0	100.0	0.012	100.0

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[a] From the files of A. H. Ross, A. H. Ross & Associates, Toronto, Canada.

Table 9.5. Activity of Uranium Mill Dust as a Function of Particle Size[a]

Fraction	Average Size[b] (μ)	% of Total Weight	Radium (dpm/g)	Uranium (dpm/g)	Thorium (dpm/g)
Dust:					
1	118.7	54.6	1145	1082	1023
2	81.9	17.4	1321	1242	1342
3	58.5	19.5	1164	1278	1580
4	41.2	6.4	1888	1574	1530
5	32.2	1.29	2007	1881	-
6	8.8	0.59	2146	1856	1946
7	5.3	0.25	3053	2917	2849
	Weighted Average		1291	1238	1300
	Gross Sample Analysis		1340	1588	1315

[a] *Quarterly Report April 1, 1960 - June 30, 1960*, WIN-117, National Lead Company, Winchester Laboratory (Aug. 26, 1960), p. 21.

[b] Nominal size.

Table 9.6. Radium Distribution in Acid-Leached Tailings

Mill	Tailings Fraction	% of Total Weight[a]	% of Total Radium[b]	Radium Concentration (pCi/g or 10^{-6} µCi/g)
Mines Development, 1957[c]	Sands	87	27	170
	Slimes	13	73	2,930
Mines Development, 1966[d]	Sands	84	33	204
	Slimes	16	67	2,130
Gunnison[e]	Sands	45	22	235
	Slimes	55	78	680
Climax[f]	Sands	82	22	140
	Slimes	18	78	2,200
Monticello, East Pond[g]	Sands	N.A.	N.A.	193
	Slimes	N.A.	N.A.	800

[a] Calculated from process stream data presented in references.

[b] Calculated from process stream data and radium concentrations presented in references.

[c] E. C. Tsivoglou, D. C. Kalda, and J. R. Dearwater, The Resin-In-Pulp Uranium Extraction Process. Mines Development Company, Edgemont, South Dakota, Technical Report W62-17, U. S. Public Health Service, R. A. Taft Sanitary Engineering Center, Cincinnati, Ohio (1962), pp. 9, 12.

[d] R. J. Velten and others, National Environmental Research Center, Cincinnati, Ohio, "Evaluation of the Radioactivity Levels in the Vicinity of the Mines Development Inc. Uranium Mill at Edgemont, South Dakota," unpublished memorandum (September 1966), pp. 5, 9, 12.

[e] S. D. Shearer, C. E. Sponagle, J. D. Jones, and E. C. Tsivoglou, The Acid Leach-Solvent Extraction Uranium Refining Process. I. Gunnison Mining Company, Gunnison, Colorado, Technical Report W62-17, op. cit., pp. 24, 27, 28.

[f] J. B. Cohen, C. E. Sponagle, R. M. Shaw, J. D. Jones, and S. D. Shearer, The Acid Leach-Solvent Extraction Uranium Refining Process. II. Climax Uranium Company, Grand Junction, Colorado, Technical Report W62-17, op. cit., pp. 43, 47, 50.

[g] Data courtesy of Region IV Office of the AEC Directorate of Regulatory Operations, Denver, Colorado, unidentified memorandum dated Feb. 27, 1964.

N.A. = Not available.

Table 9.7. Total Gamma Activity in Tailings as a Function of Particle Size, Spring 1973[a]

	Particle Size Distribution		% of Total Weight	% of Total Gamma[b]
	Mesh Size	μ		
Mill A, Acid Leach	+20	>840	0.1	0.2
	-20 +35	500-840	3.0	1.3
	-35 +60	250-500	31.3	6.4
	-60 +120	125-250	27.3	2.9
	-120 +250	61-125	10.5	2.2
	-250 +325	44-61	1.0	0.5
	-325	<44	26.6	86.5
Mill C, Acid Leach	+20	>840	1.7	0.6
	-20 +35	500-840	12.9	1.8
	-35 +60	250-500	27.5	3.8
	-60 +120	125-250	22.8	6.1
	-120 +250	61-125	9.9	3.5
	-250 +325	44-61	3.7	1.4
	-325	<44	21.5	82.8
Mill D, Acid Leach	+150		80	15[c]
	-150		20	85[c]
Mill F, Alkaline Leach	+20	>840	0.02	0.003
	-20 +35	500-840	0.03	0.03
	-35 +60	250-500	1.2	0.6
	-60 +120	125-250	11.6	3.8
	-120 +250	61-125	21.0	7.5
	-250 +325	44-61	11.4	4.9
	-325	<44	54.8	83.1

[a] F. G. Seeley (ORNL), preliminary data.

[b] Samples not in equilibrium when counted, so that an absolute radium analysis could not be made; radium is proportional to the total gamma and the % ratios give a good estimate of the radium distribution.

[c] Samples at equilibrium.

Table 9.8. Radium Activity as a Function of Particle Size of Acid-Leached Tails[a]

	Weight[b]		Radium	
Mesh Size	g	% of Total	dpm/g	% of Total
+200	28.0	50.0	845	14.5
-200 +325	8.6	15.4	1,220	6.5
-325 +400	0.824	1.5	1,610	0.8
-400	18.5	33.1	6,150	78.2

[a] January 1960 - Summary Report, WIN-112, National Lead Company, Winchester Laboratory (Feb. 1, 1960), p. 92.

[b] Ore sample was ground in the laboratory and is not necessarily representative of a typical mill grind.

Table 9.9. Dust Control in Ore Handling

Mill	Crusher[a] Operating Time (hr/day)	Crushing Rate (tons/hr)	Air Flow from Crusher, Screens, Belt Transfer Points, Ore Bins, etc. (cfm per 100 tons ore crushed per hr)	Type of Dust Collector	Efficiency[b] of Dust Collector (%)
A	10	200	20,000	Orifice[c]	93.6
B	5	70	36,000	Bag filter	99.9
C	16	125	18,000	Wet impingement[d]	97.9
D	14	357	2,800	Not used	-
E	10	110	None	-	-
F	13	42	37,000	Bag filter	99.9
G	12	75	26,000	Orifice[c]	93.6
H	10	140	None	-	-
I	8	225	7,300	Crusher: wet centrifugal Screens: wet dynamic precipitator[e]	91.0 98.5
J	6	200	4,000	n.a.	n.a.

n.a. = not available.

[a] Ore bins operate 24 hr/day.

[b] C. J. Stairmand, The Chemical Engineer 194, CE322 (December 1965).

[c] Also called baffle or self-induced spray deduster.

[d] Also called irrigated target or perforated plate.

[e] Also called disintegrator.

Table 9.10. Dust Control in Yellow Cake Handling

Mill	Operating Time (hr/day)	Air Flow (cfm per 1000 lb U_3O_8 processed per 24 hr)	Type of Dust Collector	Efficiency[a] of Dust Collector (%)
A	16	690	Dryer: wet impingement[b] Packaging: wet dynamic precipitator[c]	97.9 98.5
B	24	n.a.	n.a.	
C	24	370	Wet dynamic precipitator[c]	98.5
D	24	750	Wet dynamic precipitator[c]	98.5
E	18	220	n.a.	
F	24	750	Dryer: venturi Packaging: bag filter	99.8 99.8
G	24	1,140	Wet impingement[b]	97.9
H	24	n.a.	n.a.	
I	16	620	Dryer: orifice[d] Packaging: bag filter	93.6 99.8
J	24	n.a.	n.a.	
K	24	170	n.a.	

n.a. = not available.

[a] C. J. Stairmand, The Chemical Engineer <u>194</u>, CE322 (December 1965).

[b] Also called irrigated target or perforated plate.

[c] Also called disintegrator.

[d] Also called baffle or self-induced spray deduster.

Table 9.11. Stack Effluents from Uranium Mills,[a]
January 1961 - April 1966
(U_{nat}, 10^{-12} μCi/ml)

	Ore Dusts		Yellow Cake Dusts	
Mill	Crusher	Ore Dryer	Dryer	Other
L	1.4		230	320
M	42		676	
N	24		179	
O		415	157	1,814
P			3.4	
Q			1,300	
R			≤1,780	
S			84	
T		300	1,510,000 (22 cfm)	102,000; 3,900 (57 cfm);(19 cfm)
U		66		
V			17,180 (2500 cfm)	
W			9.6	
X			218	61
Y			5,920	1,936
Z			26,907	18

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[a] Data courtesy of Region IV Office of the AEC Directorate of Regulatory Operations, Denver, Colorado.

Table 9.12. Ore Dust Losses, Spring 1973

Mill	Ore Dust Loss (% of ore processed)	Moisture Content of Ore (%)	Type of Dust Collector	Efficiency[a] of Dust Collector (%)	Calc. Dust Load to the Dust Collector (% of ore processed)	Ratio of Uranium Content of Ore Stack Dusts to Uranium Content of Mill Feed
D	1.0E-4 (By weight)	9-10	None	-	0.0001 (By weight)	2.25
A	1.6E-4 (By Ci of U_{nat})	8	Orifice	93.6	0.002 (By Ci of U_{nat})	?
G	5.0E-4 (By weight)	6	Orifice	93.6	0.008 (By weight)	2.5

[a] C. J. Stairmand, The Chemical Engineer 194, CE322 (December 1965).

Table 9.13. Yellow Cake Dust Losses, Spring 1973

Mill	U_3O_8 Dust Loss (% of U_3O_8 produced)	Type of Dust Collector	Efficiency[a] of Dust Collector (%)	Calc. Dust Load to the Dust Collector (% of U_3O_8 produced)
A	0.018	Impingement	97.9	$0.9 < x < 1.2$
		Wet dynamic	98.5	
D	0.021	Wet dynamic	98.5	1.4
G	0.023	Impingement	97.9	1.1
F	0.0019	Venturi	99.8	
		Bag filter	99.8	1.0

[a] C. J. Stairmand, The Chemical Engineer 194, CE322 (December 1965).

Table 9.14. Average Medium Particle Size of Dust Samples Collected Inside Uranium Mills[a]

Mill[b]	Average Mass Medium Size (μ)		
	Ore Sampling Areas	Ground Ore	Concentrate
A	-	-	-
B	4.5	3.3	-
C	5.0	-	2.0
D	-	-	-
E	4.3	3.3	2.9
F	4.2	3.1	2.3
G	4.5	2.7	2.4
H	4.2	3.5	-
I	4.9	-	3.1
J	-	-	-
K	4.6	2.1	-
L	4.6	-	2.2
Average	4.5	3.0	2.5

[a] W. B. Harris, A. J. Breslin, H. Glauberman, and M. S. Weinstein, Arch. Ind. Health 20, 374 (1959).

[b] Mill code refers to different mills from those in the Spring 1973 survey.

Table 9.15. Particle Size Distribution of Uranium Mill Dust[a]

Fraction	Average Size[b] (μ)	% of Total Weight
1	118.7	54.6
2	81.9	17.4
3	58.5	19.5
4	41.2	6.4
5	32.2	1.29
6	8.8	0.59
7	5.3	0.25

[a] *Quarterly Report April 1, 1960 - June 30, 1960*, WIN-117, National Lead Company, Winchester Laboratory (Aug. 26, 1960), p. 21.

[b] Nominal size.

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Table 9.16. Particle Size Distribution of Standard Industrial Test Dust[a]

(Fine silica, density 2.7 g/cm^3)

Size of Grade (μ)	Percentage, by Weight, in Grade	Percentage, by Weight, Smaller than Top Size of Grade
104-150	3	100
75-104	7	97
60-75	10	90
40-60	15	80
30-40	10	65
20-30	10	55
15-20	7	45
10-15	8	38
7-1/2-10	4	30
5-7-1/2	6	26
2-1/2-5	8	20
<2-1/2	12	12

[a] C. J. Stairmand, The Chemical Engineer 194, CE311 (December 1965).

Table 9.17. Environmental Monitoring of Airborne Dust at the Site Boundary of Unrestricted Area, Spring 1973 Survey

Mill	U_{nat} (10^{-14} µCi/ml)
A	10
C	2
D	7
E	2.7
F	0.55
H	0.6-7.6
I	14.7
J	10
K	6.4-14.8

Table 9.18. Liquid Effluents from Uranium Mills, Spring 1973

			Radioisotopes							Chemicals (g/liter)				
		Volume of Liquid Waste (tons/ton of	(g/liter)[d]	(pCi/liter or 10^{-9} µCi/ml)										
Process	Mill	ore processed)	U	^{226}Ra	^{230}Th	^{210}Pb	^{210}Po	Gross α	pH	SO_4^{2-}	Cl^-	Na^+	Na_2CO_3	$NaHCO_3$
Solvent Extraction	1	1.4	0.02						3.0					
	2	1.6	0.009	600[a]	1,200[a]			25,000	1.5	30	3			
	3	1.4	0.015	360	87,000				2.7	18	1			
Resin-in-Pulp Ion Exchange	4	2.7	0.03	27	150,000				2.6	6.5	3.3	2.2		
	5	2.5	0.005	539	11,000				1.5					
	6	1.6[b]	0.13						1.8	15	1			
	7	1.2	0.020						1.9					
	8	2.5	0.009	0.25[c]	0.95[c]				6-7[c]	10	None			
Alkaline Circuit	9	0.8	0.030					3,220	9.4	0.9	0.8	1.5		
	10	0.3	0.015	100	20	80	20		10.5	20	-1		6.0	1.3

[a] Mill operator has little confidence in analysis.

[b] Moving-bed ion exchange.

[c] Neutralized effluent.

[d] 1 g U_{nat}/liter = 3.3 x 10^{-4} µCi U_{nat}/ml.

Table 9.19. Liquid Effluents from Uranium Mills, 1959-1962[a]
(mg/liter)

Chemical	Public Health Service Drinking Water Standards	Mill Effluent to Tailings			Tailings Pond Overflow Composition			
		Resin-in-Pulp Ion Exchange[b]	Alkaline Circuit		Amine Solvent Extraction[e]	Resin-in-Pulp Ion Exchange[e]	Alkaline Circuit[e]	
			c	d				
Cl	250	1,350	275	286	110	190		81
SO_4	250	6,450			2,910	3,860		1,760
Mg		550			72	535		<10
NO_3	45	100			-	1,270		-
Cu	1				-	1.3		-
F					3.8	-		-
B					-	0.1		-
Fe	0.3	350			220	42	<0.1	-
Mn	0.05	450			30	110	0	-
Pb	0.05				-	0.65		-
As	0.01		0.20	0.49	-	0.21		-
U_3O_8						3.4	16	9.9
Na		1,050	2,950	4,450				3,450
Ca		550			520	530		<10
HCO_3					0		1,590	1,100
CO_3					0		8,210	4,610
Dissolved Solids	500	11,000		12,200	4,370	7,360	12,300	8,270
pH			9.6	10.1	2.6	3.3	10.3	10.8

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[a] Data on salt roast and di(2-ethylhexyl)phosphoric acid solvent extraction processes intentionally omitted since their wastes are quite different from those today.

[b] S. W. West, "Disposal of Uranium Mill Effluents Near Grants, New Mexico," U. S. Geol. Survey Profess. Paper No. 421, D376-379 (1961).

[c] J. B. Cohen, H. R. Pahren, and M. W. Lammering, "The Carbonate Leach Uranium Extraction Process. I. Homestake - New Mexico Partners Company, Grants, New Mexico," Technical Report W62-17, U. S. Public Health Service, R. A. Taft Sanitary Engineering Center, Cincinnati, Ohio (1962), pp. 60, 69.

[d] H. R. Pahren, M. W. Lammering, and J. Hernandez, "The Carbonate Leach Uranium Extraction Process. II. Homestake - Sapins Partners, Grants, New Mexico," Technical Report W62-17, *op. cit.*, pp. 78, 79, 88.

[e] Raw Materials Development Laboratory, Winchester, Mass., "Nature of Wastes from the Uranium Milling Industry" in *Industrial Radioactive Waste Disposal (Hearings before the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States, 86th Congress, 1st Session, Jan. 28-30 and Feb. 2-3, 1959)*, Vol. 1, p. 63.

Table 9.20. Radium and Thorium Content in Uranium Mill Tailings or Tailings Pond Water, 1959[a]

Mill Process	pH	Radium (pCi/liter or 10^{-9} μCi/ml)	Thorium (pCi/liter or 10^{-9} μCi/ml)
Acid-RIP[b]	1.9	8,870	
Acid-RIP	1.8	5,300	58,100
Acid-RIP	2.0	2,920	
Acid-RIP	2.2	7,610	
Acid-RIP	1.6	11,300	147,000
Acid-RIP	2.5	2,630	1,150
Acid-IX Columns[c]	1.9	81,600	477,000
Acid-IX Columns	1.8	24,900	186,000
Acid-SX[d]	1.5	4,010	
Acid-SX[d]	1.8	6,490	
Acid-SX[d]	2.8	1,860	
Acid-SX[d]	1.5	4,010	
Acid-SX[d]	1.7	1,890	
Alkaline-Filtration	9.8	17	
Alkaline-Filtration	9.8	99	
Alkaline-Filtration	10.2	4,910	
Alkaline-Filtration	10.3	261	
Alkaline-RIP	10.1	113	
Acid-RIP + Alkaline-Filtration[e]	7.1	440	
Acid-RIP + Alkaline-Filtration[e]	6.8	126	
Acid-SX[d] + Alkaline-Filtration[e]	6.7	88	10
Acid-SX[d] + Alkaline[c]	6.9	447	130
Acid-RIP (plus lime)	7.7	323	

[a] January 1960 - Summary Report, WIN-112, National Lead Company, Winchester Laboratory (Feb. 1, 1960), p. 57.

[b] RIP = resin-in-pulp ion exchange.

[c] IX = ion exchange.

[d] Acid-SX process in 1959 would have been one of the di(2-ethylhexyl) phosphoric acid (EHPA) solvent extraction processes which are now obsolete.

[e] Wastes neutralized by mixing acid and alkaline wastes from 2 separate circuits at the mill.

Table 9.21. Chemical Usage in Uranium Mills, Spring 1973

		Chemical Usage (lb/ton of ore processed)															
Process	Mill	H_2SO_4	Na_2ClO_3	MnO_2	NH_3	NaOH	MgO	CaO	NaCl	NH_4NO_3	Na_2CO_3	Amine[a]	Alcohol[b]	Kerosene	Flocculent	Ion-Exchange Resin	Grinding Rods
Solvent Extraction	1	60	2.0	-	1.7	-	-	-	-	-	-	0.03	0.08	0.08	0.13	-	0.5
	3	85	2.4	-	2.8	-	-	-	-	-	-	0.04	0.04	1.19	0.19	-	Yes
Ion Exchange	4	59	-	7.8	0.75	-	1.4	4.4	38	-	-	-	-	-	-	0.32	0.5
	5	92	2.0	-	8.5	-	-	-	-	-	-	0.03	0.03	0.30	-	0.34	Yes
	6	60	5.0	-	2.5	0.2	-	-	-	-	-	0.008	0.02	0.42	-	0.34	Yes
	7	47	1.5	-	4.4	-	-	-	-	-	-	0.02	0.02	0.31	-	0.04	Yes
	8	165	-	4	2	1.2	-	12	-	8	-	-	-	-	Yes	Yes	Yes
Alkaline Circuit	9	-	-	-	-	15	-	-	-	-	12	-	-	-	-	-	Yes
	10	3.3	-	-	-	76	-	-	-	-	6	-	-	-	1.8	-	Yes

[a] Alamine 336 and Adogen 364 are used interchangeably.

[b] Isodecanol and tridecanol are used interchangeably although isodecanol is more common.

Table 9.22. Composition of Uranium Mill Tailings

Location of Pile[a]	Status as of 8/70	Tons of Material as of 8/70[b]	U (μg/g)[m]			^{226}Ra (pCi/g or 10^{-8} μCi/g)				^{230}Th (pCi/g or 10^{-8} μCi/g)			^{210}Pb (pCi/g or 10^{-8} μCi/g)		
			PHS[c]	IDO[d,e]	HASL[d,e]	AEC[f]	PHS[c]	IDO[d,e]	HASL[d,e]	PHS[c]	IDO[d,e]	HASL[d,e]	PHS[c,g]	IDO[e,h]	HASL[d,e]
Arizona															
Tuba City	Inactive	796,000				980									
Colorado															
Canon City	Active	590,000				1,400									
Durango (large pile)	Inactive	1,622,000	340	294	241	890	992	516	800	918	775	660	213	690	700
Durango (small pile)	Inactive		310				633			347			46		
Grand Junction	Inactive	2,028,000				900									
Gunnison	Inactive	545,000	70	94	62	440	407	217	240	202	133	61	61	340	400
Maybell	Inactive	2,566,000				290									
Naturita	Inactive	723,000	350	766	639	850	594	814	880	474	882	880	39	580	810
Naturita (upgrading)	Inactive		470				147			174			99		
Rifle (old mill)	Inactive	200,000	270	374	306	1,040	557	480	600	399	496	420	146	520	720
Rifle (new mill)	Active	2,060,000				910									
Slick Rock	Inactive	468,000	70	103	76	750	140	140	170	42	691	59	50	220	240
Slick Rock (n. cont.)	Inactive					730									
Uravan	Active	5,520,000				710									
New Mexico															
Ambrosia Lake, Kerr-McGee	Active	12,600,000				670									
Ambrosia Lake, old Philips pile	Inactive	2,684,000		159	106	760		555	650		568	550		840	920
Bluewater, Anaconda	Active	9,800,000				690									
Grants, old Homestakes Partners	Inactive	1,218,000		144	88	670	490[i]	524	450		441	370		1,070	560
Grants, United Nuclear, Homestake	Active	11,100,000				610	510[j]								
Shiprock	Inactive	1,549,000				710									
Utah															
Green River	Inactive	123,000	130	180	122	890	143	177	160	53	88	130	19	280	380
Hite	Inactive	20,000	240				555			199			191		
Mexican Hat	Inactive	2,000,000	150[k]			820	370[k]			1,960[k]					
Moab	Active	6,200,000				1,030									
Monticello	Inactive	903,000				910									
Monument Valley	Inactive	1,100,000	33[l]			90	59[l]			46[l]					
Salt Lake City - South	Inactive			108	92			487	1,360		238	150		1,180	700
Salt Lake City - North	Inactive			163	116			1,590	1,650		522	350		2,660	1,400
Wyoming															
Converse County, Western Nuclear	Inactive					290									
Gas Hills, Federal American	Active					540									
Gas Hills, Utah Int.	Active					900									
Gas Hills, Union Carbide	Active					450									
Jeffrey City	Active					690									
Riverton	Inactive			122	97	660		442	460		393	360		700	590
Shirley Basin, Petrotomics	Active					600									
Other															
Oregon, Lakeview - 6NW	Inactive			47	17	420		5	8		61	52		20	26
Oregon, Lakeview - Main	Inactive			96	58			269	310		136	120		400	250
South Dakota, Edgemont	Active					590									
Texas, Falls City	Active					500									
Washington, Ford	Inactive					700									

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[a] This is not a definitive list of piles, but only those which have been sampled.

[b] R. J. Augustine, "Inventory of Active Uranium Mills and Tailings Piles at Former Uranium Mills," Criteria and Standards Division, Office of Radiation Programs, August 1970, as quoted by D. L. Duncan in Overview and Suggestions for Correcting the Uranium Mill Tailings Problem, Western Environmental Research Laboratory, Environmental Protection Agency, June 1971.

[c] Federal Water Pollution Control Administration, Region VIII, Denver; U. S. Dept. of Health, Education and Welfare, "Disposition and Control of Uranium Mill Tailings Piles in the Colorado River Basin," as published in Radioactive Water Pollution in the Colorado River Basin (Hearings before the Subcommittee on Air and Water Pollution of the Committee on Public Works, United States Senate, Eighty-Ninth Congress, 2nd Session, May 6, 1966), p. 124.

[d] J. H. Harley (Health and Safety Laboratory, New York), Analyses of Tailings Pile Materials, memorandum to D. I. Walker (Director, Region IV, Division of Compliance, Denver), April 28, 1964.

[e] IDO and HASL numbers are independent analyses of "split" samples. These are difficult analyses to do, and the accuracy seems to be only ±15 or 20%.

[f] M. B. Biles (Director, Division of Operational Safety, AEC), correspondence to V. G. MacKenzie (Deputy Director, Bureau of Disease Prevention and Occupational Health, Public Health Service, HEW), March 13, 1967, as quoted by D. L. Duncan, loc. cit.

[g] PHS analyses for lead appear to be low by comparison with IDO and HASL, and are inconsistent with secular equilibrium.

[h] C. W. Sill (Health and Safety Branch, Idaho Operations Office), Analysis of Mill Tailing for Lead-210, memorandum to D. I. Walker (Director, Region IV, Division of Compliance, Denver), Sept. 18, 1964.

[i] J. B. Cohen, H. R. Pahren, and M. W. Lammering, The Carbonate Leach Uranium Extraction Process, I. Homestake-New Mexico Partners Company, Grants, New Mexico, Technical Report W-62-17, U. S. Public Health Service, R. A. Taft Sanitary Engineering Center, Cincinnati, Ohio (1962), pp. 60, 66.

[j] H. R. Pahren, M. W. Lammering, and J. Hernandez, The Carbonate Leach Uranium Extraction Process, II. Homestake-Sapins Partners, Grants, New Mexico, Technical Report W-62-17, op. cit., pp. 78, 85.

[k] R. N. Snelling, Radiol. Health Data Rept. 11, 511-17 (1970).

[l] R. N. Snelling, Radiol. Health Data Rept. 12, 17-28 (1971).

[m] 1 μg U_{nat}/g = 0.33 pCi U_{nat}/g = 0.33 x 10^{-8} μCi U_{nat}/g.

Table 9.23. Maximum Gamma Radiation Levels Three Feet Above Tailings Pile[a]

Mill[b]	Gamma Radiation Level (mR/hr)
B	1.6
C	0.5
G	1.2
H	0.7
I	0.8
K	0.5
L	1.0
Average	0.9

[a] W. B. Harris, A. J. Breslen, H. Glauberman, and M. S. Weinstein, Arch. Ind. Health 20, 374 (1959).

[b] Mill code refers to different mills from those in the Spring 1973 survey.

Table 9.24. Range of Composition of Uranium Mill Tailings

	Monument Valley[a]		Mexican Hat[b]		Tuba City[c]	
	Avg.	Range	Avg.	Range	Avg.	Range
U, μg/g[d]	33	17-49	150	27-470		
^{226}Ra, pCi/g[e]	59	48-77	370	27-860		
^{230}Th, pCi/g	46	28-56	1960	220-3,700		
Gamma radiation level, mR/hr						
Surface	0.09	0.02-0.3	0.5	0.01-3.0	0.9	0.02-6.0
At 3 ft	0.08	0.03-0.2	0.5	0.02-3.0	0.7	0.03-5.8

[a] R. N. Snelling, Radiol. Health Data Rept. 11, 511-17 (1970).

[b] R. N. Snelling, Radiol. Health Data Rept. 12, 17-28 (1971).

[c] R. N. Snelling and S. D. Shearer, Radiol. Health Data Rept. 10, 475-87 (1969).

[d] 1 μg U_{nat}/g = 0.33 pCi U_{nat}/g = 0.33 x 10^{-6} μCi U_{nat}/g.

[e] 1 pCi/g = 10^{-6} μCi/g.

Table 9.25. Airborne Radioactive Dust from Tailings Piles[a]
(Mills Inactive)

		Wind Speed (mph)				Sampling Station		Airborne Particulates[b] (10^{-14} μCi/ml of Air)												Ratio, Gross α to ^{226}Ra
								Gross α			^{226}Ra			^{230}Th			^{210}Po			
Pile	Sampling Period	Month	Avg.	Range of Daily Avg.	Max.	Code	Distance From Pile (miles)	High[c]	Low[c]	Avg.[d]	High[c]	Low[c]	Avg.[d]	High[c]	Low[c]	Avg.[d]	High[c]	Low[c]	Avg.[d]	
Grand Junction, Colorado	4/6-7/6/65	April	8.4	3.9-17.3	38	A	0.5 NW	180	59	121	3.5	0.86	1.7							71
		May	9.1	5.2-15.7	35	B	2.1 NW	118	30	62	0.69	0.23	0.6							111
		June	9.0	4.6-13.9	49	C	1.5 NW	195	40	101	0.97	0.27	0.7							154
						D	0.3 W	332	48	144	5.3	0.67	2.7							52
						E	0.6 SW	79	21	42	1.3	0.10	0.4							114
						F	0.25 S	170	24	82	2.7	0.20	0.9							93
	10/13-10/24/65					A	0.5 NW				3.8	0.57	1.5	3.20	0.35	1.20	71.0	17.9	40.3	
						D	0.3 W				2.00	0.51	0.92	1.19	0.42	0.74	26.0	7.8	12.6	
						E	0.6 SW				0.60	0.11	0.23			0.26	16.0	4.4	7.0	
Durango, Colorado	4/7-7/7/65					G	0.4 ENE	24	2.8	8.4	0.44	0.03	0.2							56
						H	0.4 NE	23	0.9	9.8	0.28	0.03	0.1							98
						I	0.3 NNE	60	2.2	15.9	0.69	0.10	0.3							52
						J	0.1 W	72	8.9	36.1	8.3	0.30	2.1							17

[a] D. Lambdin and L. J. Dymerski, Progress Report Uranium Mill Tailings Study Phase II, National Center for Radiological Health, HEW, May 1967.

[b] Precipitation during April, May, and June, 1965, was 4.63 in. total; normal precipitation for these 3 months is 1.77 in.

[c] One-week composite samples.

[d] Average over 3-month survey period.

Table 9.26. Airborne Radioactivity from Tailings Pile
(Mills Inactive)

		Tailings Composition			Sampling Station			Airborne Particulates[a]						Radon Gas[a,b]	
								10^{-14} µCi/ml of Air							
Pile	Area (acres)	^{226}Ra (pCi/g)	^{230}Th (pCi/g)	Wind	Code	Location	Sampling Period	Gross α	^{226}Ra	^{230}Th	^{218}Po	^{214}Pb	^{214}Bi	Date Sampled	(10^{-9} µCi/ml of Air or pCi/liter of air)
Tuba City,[c] Arizona	65	980[d]		Unstable atmospheric conditions with strong westerly winds, atmospheric radon minimal due to atmospheric dilution	1	~1200 ft E of pile	5/8–5/12/67	1,320	560					5/9, 5/12/67	3.2
					2	N		14	2						
					3	N		11	3					5/11/67	0.2
					4	NE		2	2						
					5	NE		15	2					5/12/67	0.5
					6	NE		36	5					5/9, 5/11, 5/12/67	1.3
					7	On pile, downwind		670	180					5/9, 5/11, 5/12/67	3.5
					8	S		14	1						
					10	On pile, upwind		40	7						
					12	On pile, center								5/9/67	1.8
Monument Valley,[e] Arizona	25	59	46	Calm first 6 days, strong winds last 4 days	1	On pile	5/29–6/7/67	10.3	2.3	4.5				5/28, 6/3, 6/6/67	0.8
					2	Downwind		7.0	0.5	0.7				5/28/67	0.1
					3	Upwind		1.6	0.1	0.6				5/28, 6/3/67	0.4
					4	Downwind		10.3	0.6	1.1				6/3/67	0.5
Mexican Hat,[f] Utah	35	370	1,960	Light wind first 7 days; last 4 days, 10-20 mph winds during daylight, light inversions at night	1	Upwind	5/27–6/6/68	<1	0.02	ND[g]				5/27/68	0.3
					2	Upwind		<1	0.02	ND				5/28/68	0.4
					3	Mill area		2.2	0.2	0.7				5/29, 6/6/68	1.6, 0.6
					4	On tailings, NW side		1.5	0.1	0.3				5/30, 6/4/68	5.7, 0.7
					5	On tailings, NE side		10	0.5	0.7				5/31/68	8.4
					6	500 ft NE of pile		19	0.7	1.4				6/1/68	7.5
					7	NE of pile		<1	0.07	ND					
					8	1 mile N of pile		<1	0.02	ND					
					9	1 mile N of pile		<1	0.03	ND					
					3	Mill area	6/5				22,000	4,000	0		
					4	On tailings, NW side	6/4				0	300	6,000		
					5	On tailings, NE side	6/4				0	12,000	16,000		
					5	On tailings, NE side	6/3				0	1,000	10,000		
					5A	NE of pile	6/3				1,000	3,000	3,000	6/3/68	14.0
					5B	NE of pile	6/3				21,000	5,000	1,000	6/2/68	13.0
					5B	NE of pile	6/2				12,000	9,000	8,000		

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[a] Presumably samples were collected 3 ft above the ground or surface of the tailings since this is the height at which the gamma survey was made.

[b] Grab samples at Tuba City and Monument Valley; 24-hr samples at Mexican Hat.

[c] R. N. Snelling and S. D. Shearer, Radiol. Health Data Rept. 10, 475-87 (1969).

[d] Estimated.

[e] R. N. Snelling, Radiol. Health Data Rept. 11, 511-17 (1970).

[f] R. N. Snelling, Radiol. Health Data Rept. 12, 17-28 (1971).

[g] ND = not detected.

Table 9.27. Atmospheric Radon in the Vicinity of Uranium Mill Tailings[a]

Pile	Status During Survey	Location of Sampling Stations	Number of Stations	Radon-222[b] (10^{-9} µCi/ml or pCi/liter of air)		Gross Gamma Radiation Level[c] (mR/hr)
				Average	Range	
Grand Junction, Colo.	Active	On pile	5	7.8	1.1-28.0	0.2-0.4
		1/2 mile from pile	4	1.9	0.50-4.5	
		Other off-pile	16	0.83[d]	0.13-4.4	0.02
Durango, Colo.	Inactive, dry	On pile	2	16.0	3.8-34.0	0.4
		1/4 mile from pile	1	1.4	0.44-2.3	
		Other off-pile	5	0.51[e]	0.09-1.3	0.01-0.02
Monticello, Utah	Stabilized with 2-ft soil cover	On-pile	4	3.5	0.89-12	0.03-0.06
		Off-pile	8	0.34[e]	0.03-1.3	0.01
Salt Lake City, Utah	Active, 9 months; inactive and wet, 3 months	On-pile	2	7.2	1.6-22	1.1
		Off-pile	10	0.38[e]	0.06-1.4	0.01

[a] S. D. Shearer, Jr., and C. W. Sill, Health Phys. <u>17</u>, 77-88 (1969); <u>Evaluation of Radon-222 Near Uranium Tailings Pile</u>, DER 69-1, Public Health Service, Bureau of Radiological Health, Rockville, Md. (March 1969).

[b] 48-hr sample collected 3 ft above surface of ground or tailings once every 3 weeks during a calendar year. Analysis of samples cross-checked at AEC Health Services Laboratory at Idaho Falls and PHS Southwestern Radiological Health Laboratory at Las Vegas.

[c] 30-day exposure of thermoluminescent dosimeter 3 ft above ground or tailings at one or two on-pile stations and two to four off-pile stations.

[d] Probable natural background 5 miles from site = 0.79 pCi/liter.

[e] Off-pile = natural background for region.

Table 9.28. Radon Concentrations in Air over Uranium Mill Tailings[a]

Mill[b]	Radon-222 (10^{-9} μCi/ml or pCi/ liter of air)
B	4.5
C	2.8
D	2.4
G	8.1
H	6.5
I	6.8
J	0.8
K	29.6
L	1.8

[a] W. B. Harris, A. J. Breslin, H. Glauberman, and M. S. Weinstein, Arch. Ind. Health 20, 374 (1959).

[b] Mill code refers to different mills from those in the Spring 1973 survey.

Table 9.29. Diffusion Coefficients for Radon in Various Media[a]

Medium	Moisture Content (%)	Effective Diffusion Coefficient / Void Fraction, D_e/V (cm^2/sec)
Air	?	1.0 to 1.2E-1
Water	100	1.13E-5
Sand		
Fine quartz	0	6.8E-2
Building sand (1.40 g/cm^3, 39% voids)	4	5.4E-2
Fine quartz	8.1	5.0E-2
Fine quartz	15.2	1.0E-2
Fine quartz	17	5.0E-3
Soils		
Granodiorite	?	4.5E-2
Yucca Flats[b] (25% voids)	?	3.6E-2
Metamorphic rock	?	1.8E-2
Granite	?	1.5E-2
Loams	?	8.0E-3
Varved clays	?	7.0E-3
Mud (1.57 g/cm^3)	37.2	5.7E-6
Mud (1.02 g/cm^3)	85.5	2.2E-6
Concrete, 5% voids[c]		3.4E-4

[a] A. B. Tanner, "Radon Migration in the Ground," in _The Natural Radiation Environment_, J. A. S. Adams and W. M. Lowder, Eds., _published for Rice University_ by University of Chicago Press, Chicago, 1964, p. 166.

[b] H. W. Kraner, G. L. Schroeder, and R. D. Evans, "Measurements of the Effects of Atmospheric Variables on Radon-222 Flux and Soil-Gas Concentrations," _The Natural Radiation Environment_, _op. cit._, p. 210

[c] M. V. J. Culot, H. G. Olson, and K. J. Schrager, _Radon Progeny Control in Buildings (Final Report on EPA Grant ROI EC00153 and AEC Contract AT(11-)-2273)_, Colorado State University, Fort Collins, Colorado (May 1973), pp. 80, 155.

Table 9.30. Physical Properties of Uranium Mill Tailings

Medium	Void Fraction	g Tailings (cm^3 of medium)
Acid leached sands, Grand Junction, Colo.[a]	0.36	1.62
Acid leached tailings, Powder River Basin, Wyoming[b]	0.37	1.67
Alkaline leached tailings, LaSal, Utah[c]	0.47	1.377

[a] M. V. J. Culot, H. G. Olson, and K. J. Schiager, Radon Progeny Control in Buildings (Final Report on EPA Grant R01 EC00153 and AEC Contract AT(11-1)-2273), Colorado State University, Fort Collins, Colorado (May 1973), p. 78.

[b] Humble Oil and Refining Co. (now the Exxon Co.), Mineral Dept., Applicant's Response Agency Comments on Draft Statement Highland Uranium Mill, DOCKET 40-8102 (Aug. 28, 1972), Exhibit III, pp. 1, 2.

[c] Rio Algom Corp., Applicant's Supplemental Environmental Report Operating License Stage for Uranium Concentrates, DOCKET 40-8084 (Nov. 1971), Appendix M.

Table 9.31. Diffusion Theory Prediction of Attenuation in Radon Emanation from Tailings Piles by Various Covers[a]

Depth of Cover		Attenuation, $\frac{C_{(x)}}{C_p} = e^{-\sqrt{\lambda v/D_e}\,x}$				
ft	cm	Building Sand, 4% Moisture, $e^{-0.00623x}$	Yucca Flats Soil, $e^{-0.00764x}$	Fine Quartz Sand, 15% Moisture, $e^{-0.0145x}$	Varved Clay, $e^{-0.0173x}$	Mud, 37% Moisture, $e^{-0.61x}$
1/2	15	0.91	0.89	0.80	0.76	1.1E-4
1	30	0.83	0.79	0.64	0.59	1.2E-8
2	61	0.69	0.63	0.41	0.35	8.5E-17
3	91	0.57	0.49	0.27	0.21	
5	152	0.39	0.31	0.11	0.07	
10	305	0.15	0.10	0.01	5.1E-3	
20	610	0.022	9.5E-3	1.5E-4	2.6E-5	
40	1,219	5.0E-4	9.0E-5	2.1E-8	6.8E-10	

[a] Diffusion constants from Table 9.29.

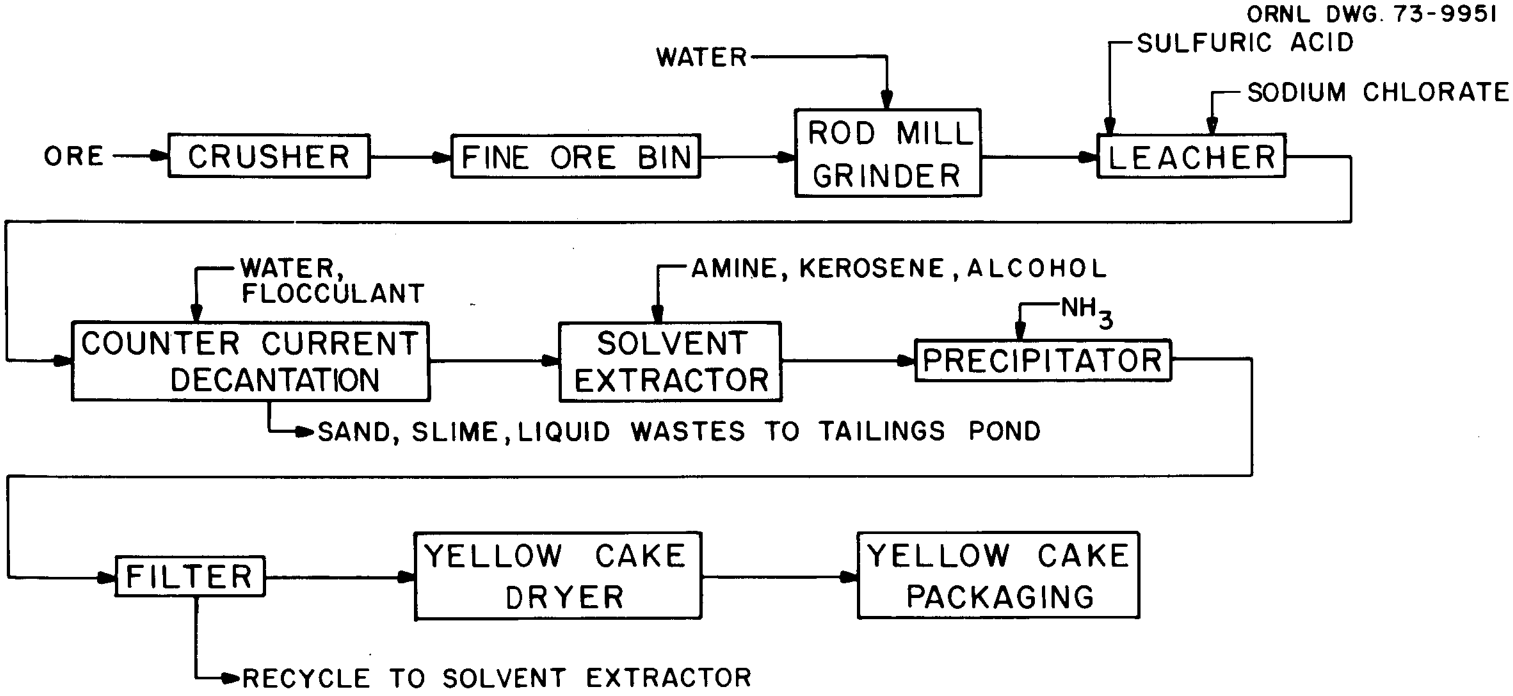


Fig. 4.1. Flowsheet for Model Acid Leach--Solvent Extraction Uranium Mill.

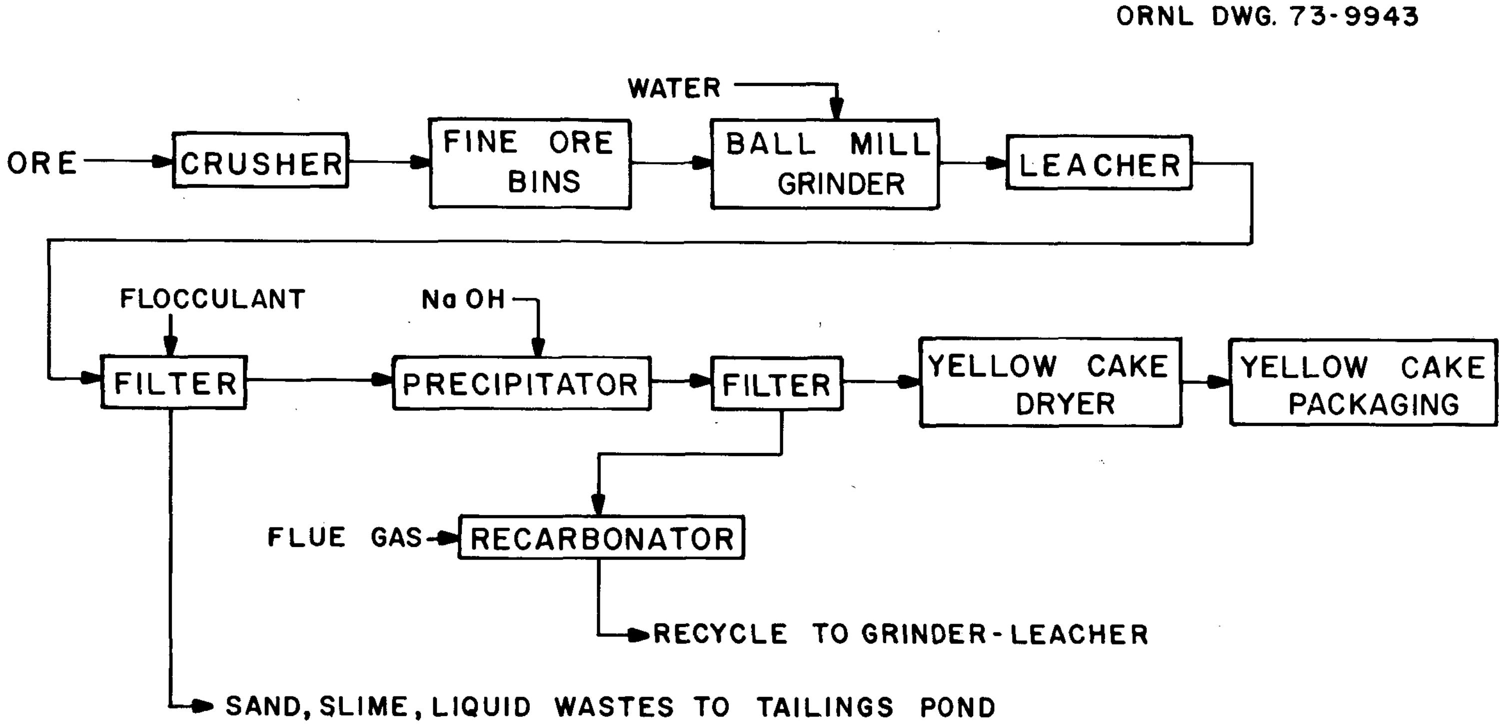
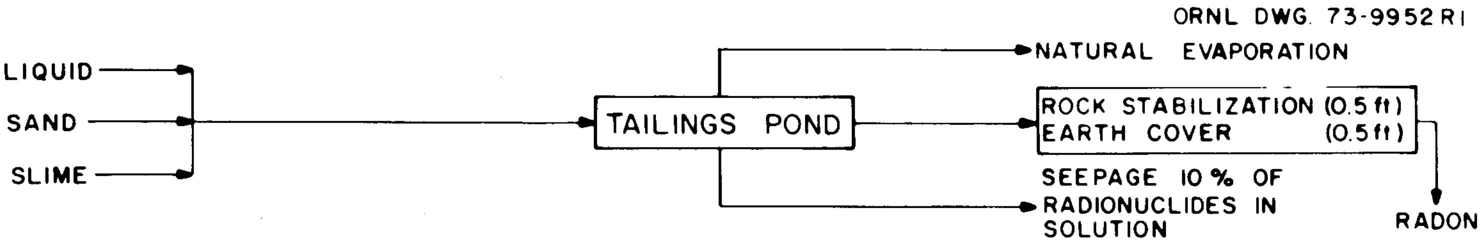
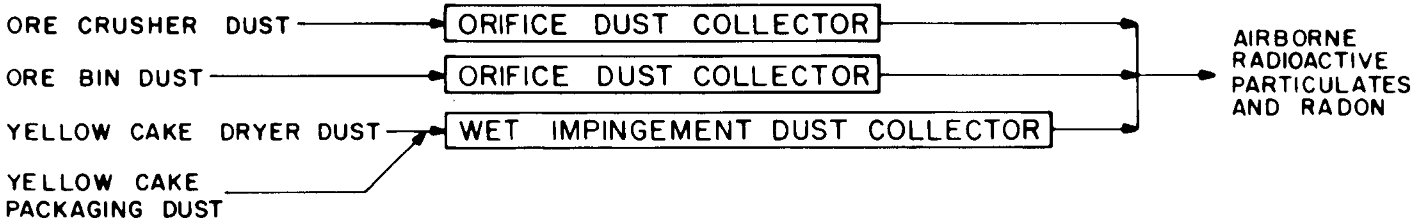


Fig. 4.2. Flowsheet for Model Alkaline-Leach Uranium Mill.



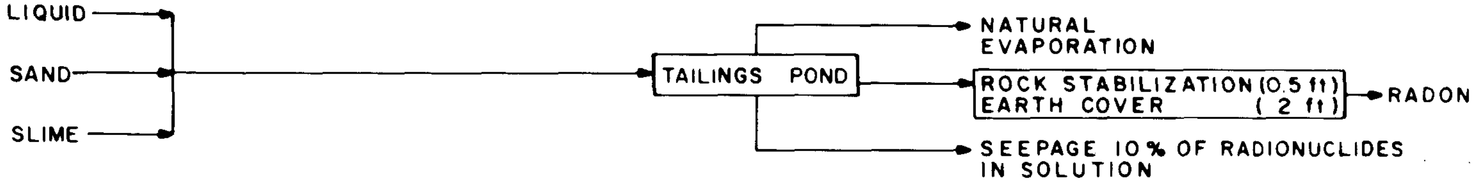
LIQUID AND SOLID RADWASTE TREATMENT



AIRBORNE MILL RADWASTE TREATMENT

Fig. 4.3. Radwaste Treatment Systems for Model Acid- and Alkaline-Leach Uranium Mill — Case 1, Base Case, Current Practice.

ORNL DWG. 73-9949R1



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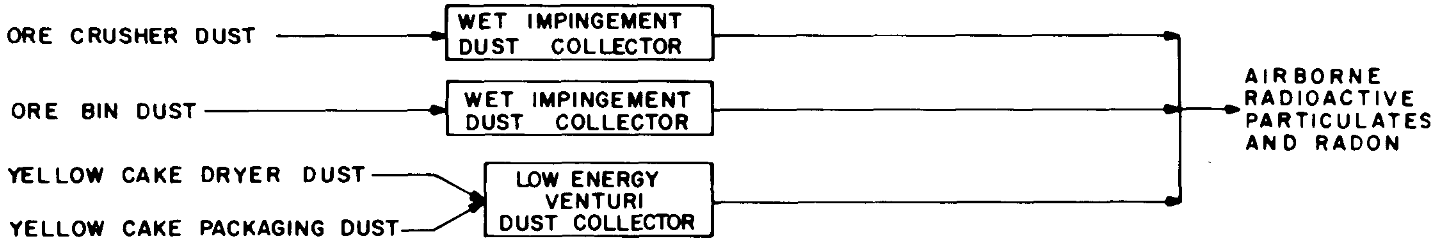
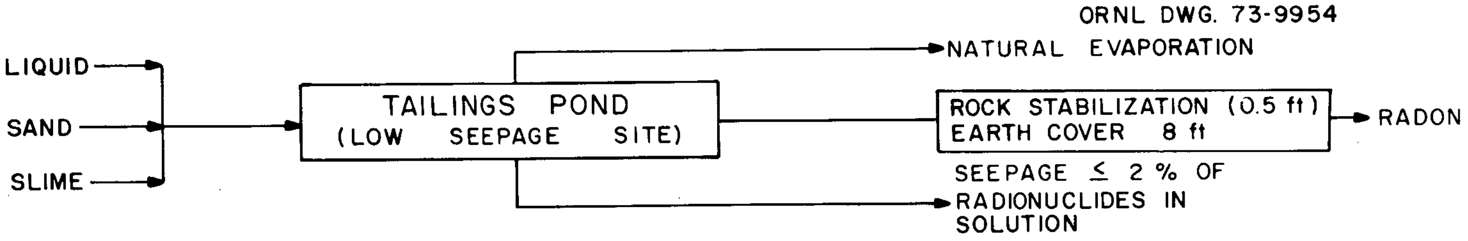


AIRBORNE MILL RADWASTE TREATMENT

Fig. 4.4. Radwaste Treatment Systems for Model Acid- and Alkaline-Leach Uranium Mill — Case 2, Used Currently on a Limited Basis.



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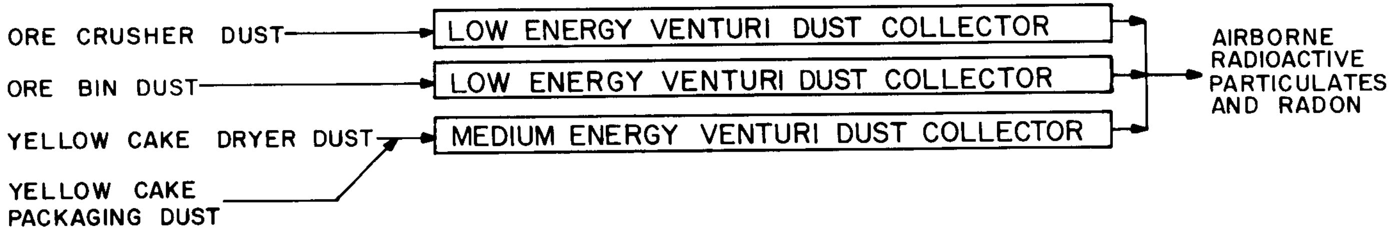
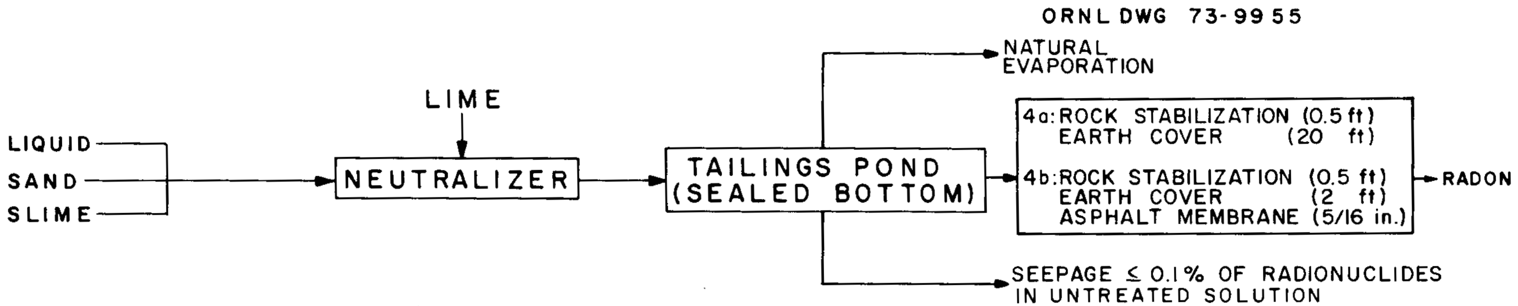


AIRBORNE MILL RADWASTE TREATMENT

Fig. 4.5. Radwaste Treatment Systems for Model Acid- and Alkaline-Leach Uranium Mill – Case 3.



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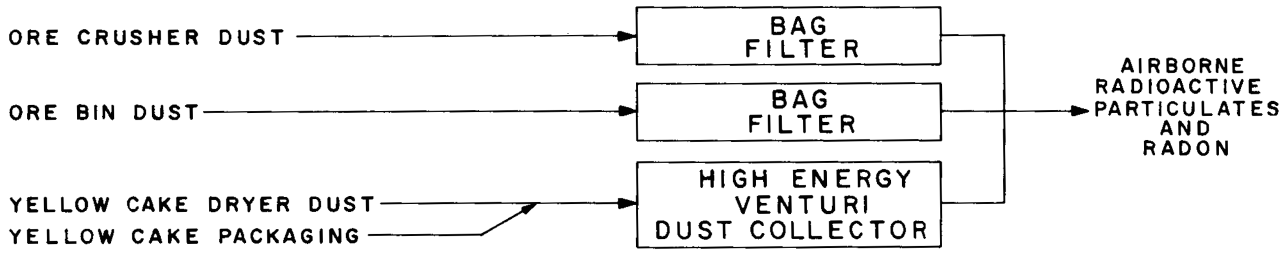
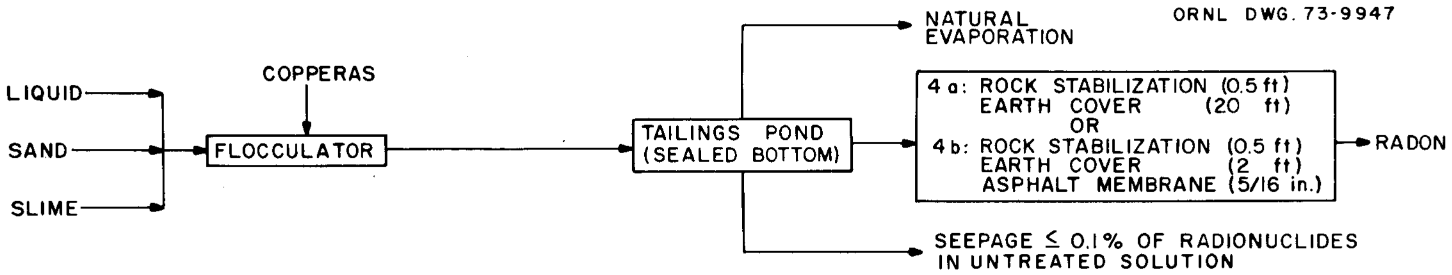


AIRBORNE MILL RADWASTE TREATMENT

Fig. 4.6. Radwaste Treatment Systems for Acid Leach--Solvent Extraction Uranium Mill — Cases 4a and 4b.



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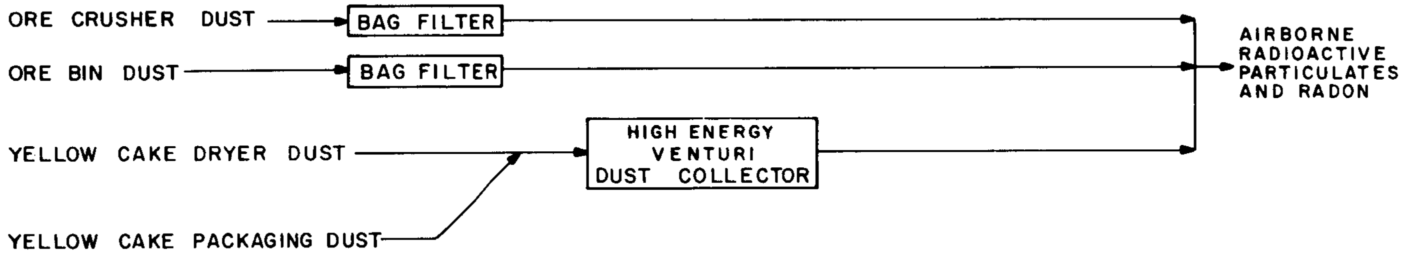
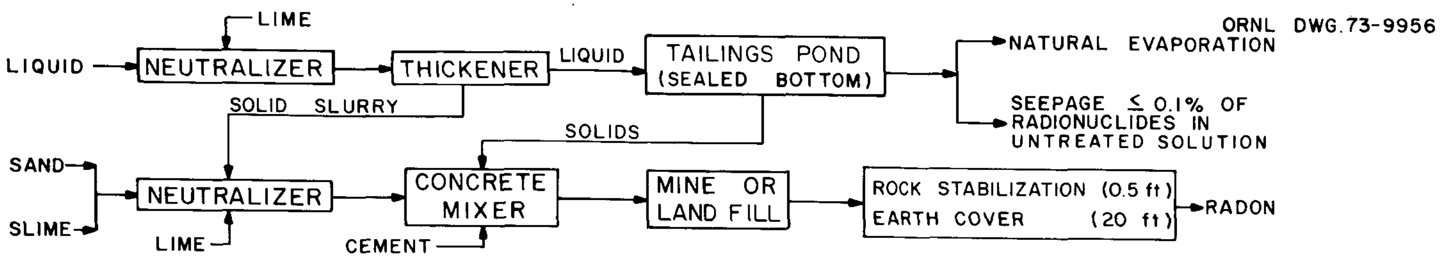


AIRBORNE MILL RADWASTE TREATMENT

Fig. 4.7. Radwaste Treatment Systems for Alkaline-Leach Uranium Mill – Cases 4a and 4b.



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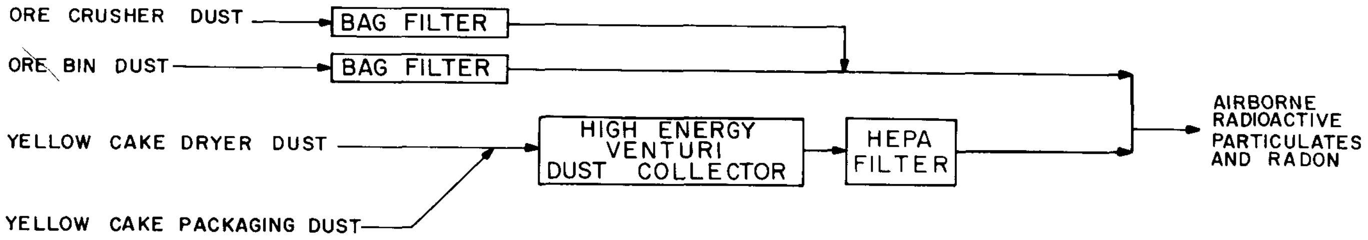


AIRBORNE MILL RADWASTE TREATMENT

Fig. 4.8. Radwaste Treatment Systems for Acid Leach--Solvent Extraction Uranium Mill – Case 5.

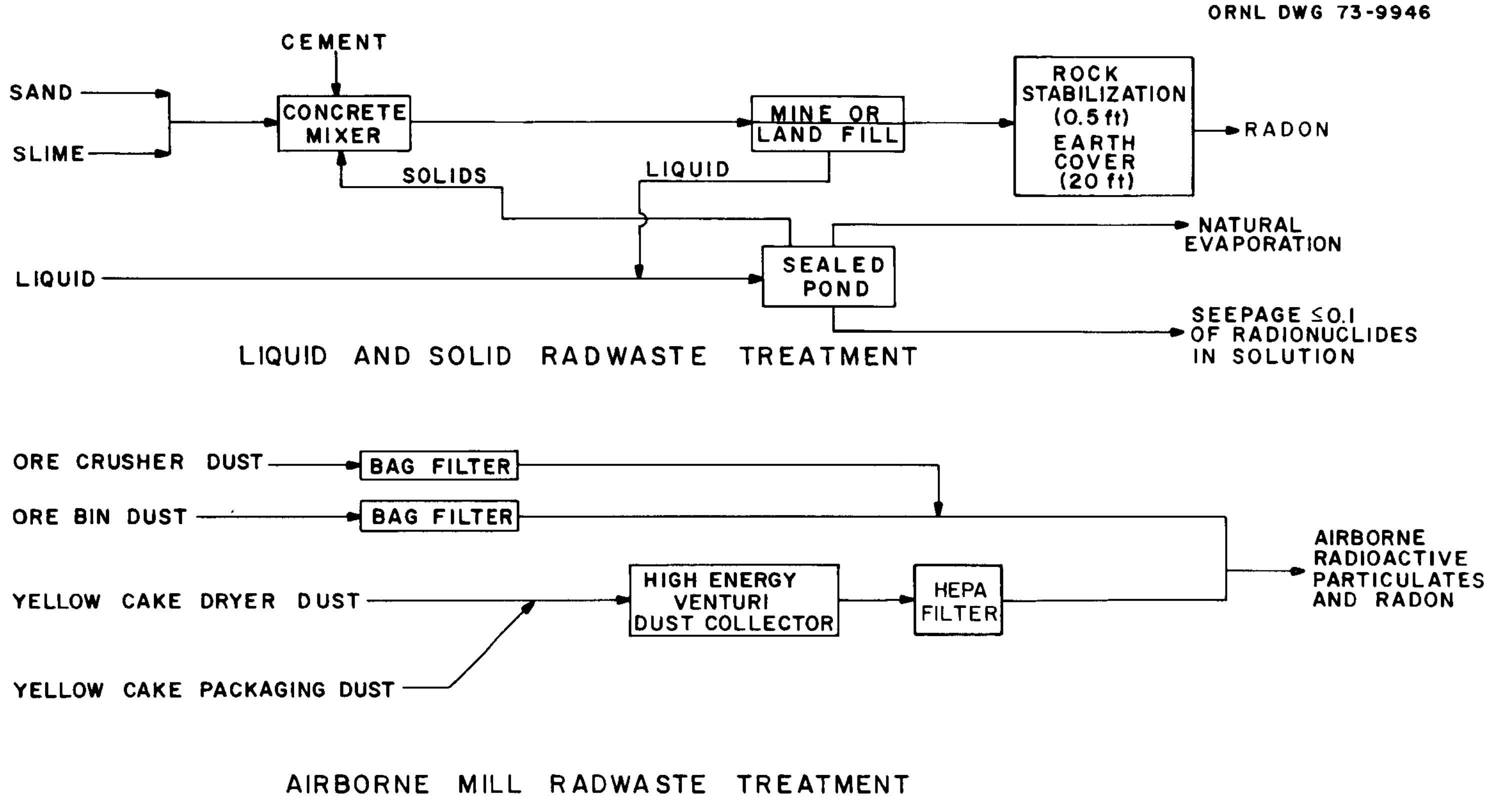
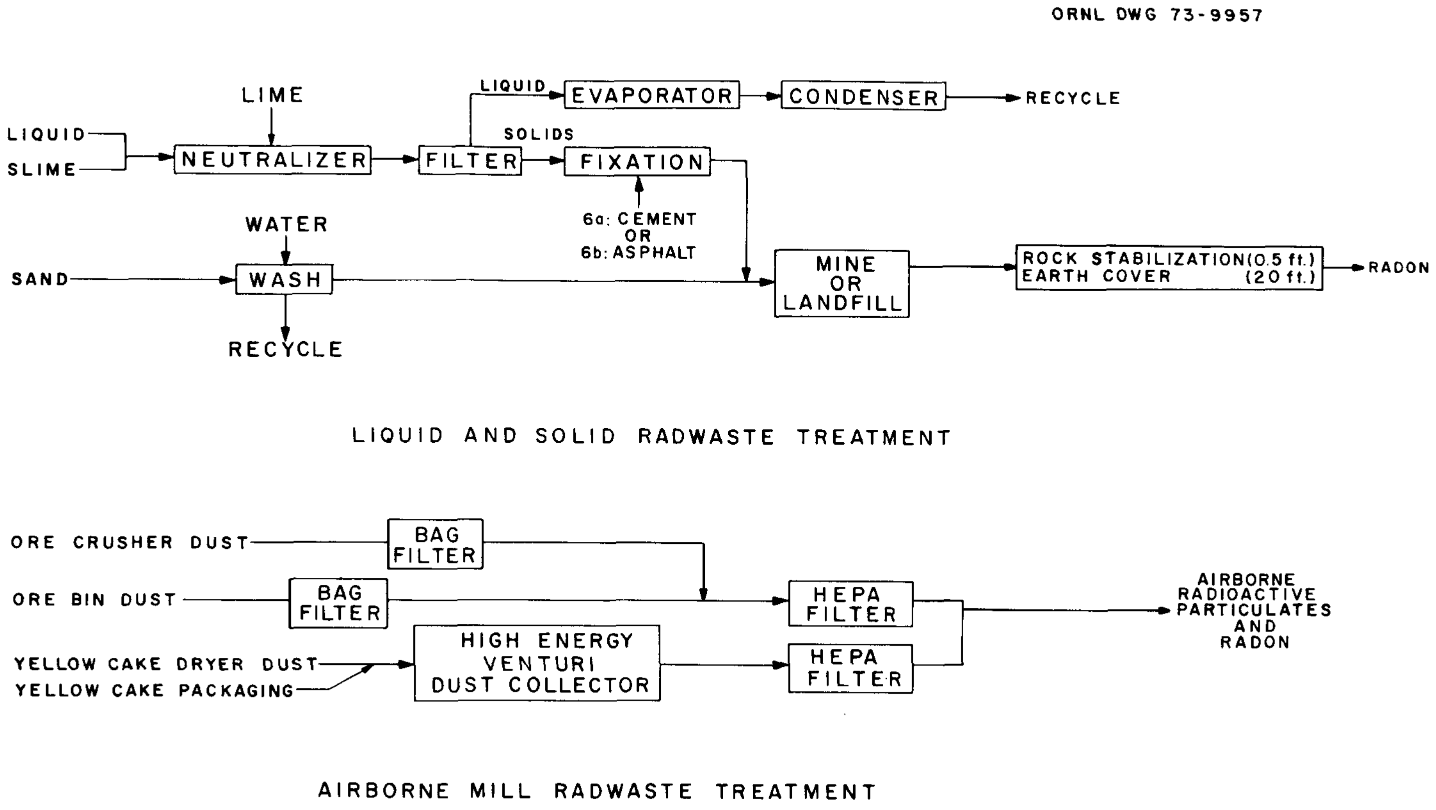


Fig. 4.9. Radwaste Treatment Systems for Alkaline-Leach Uranium Mill — Case 5.



LIQUID AND SOLID RADWASTE TREATMENT

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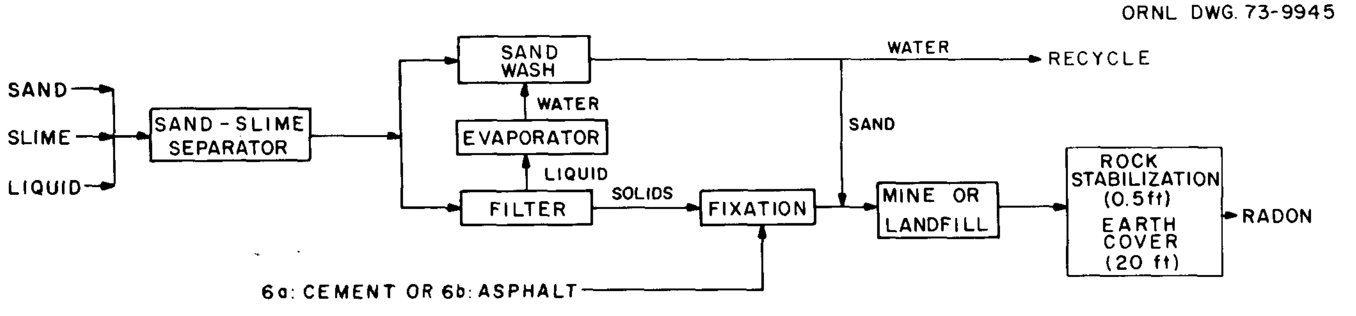
Fig. 4.10. Radwaste Treatment Systems for Acid Leach--Solvent Extraction Uranium Mill — Cases 6a and 6b.



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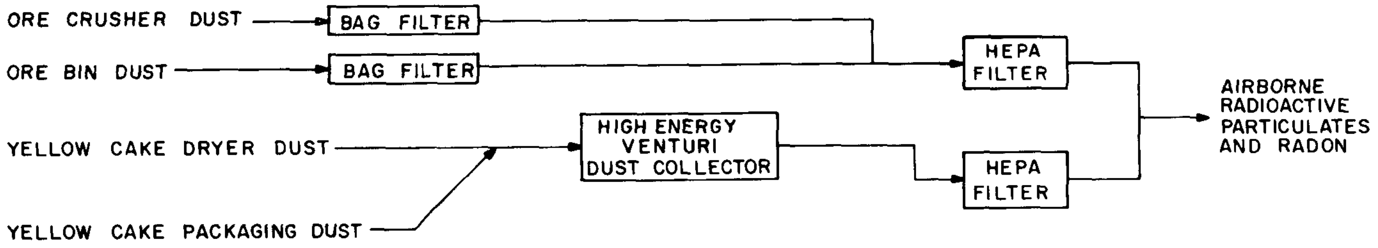

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Fig. 4.11. Radwaste Treatment Systems for Alkaline-Leach Uranium Mill — Cases 6a and 6b.

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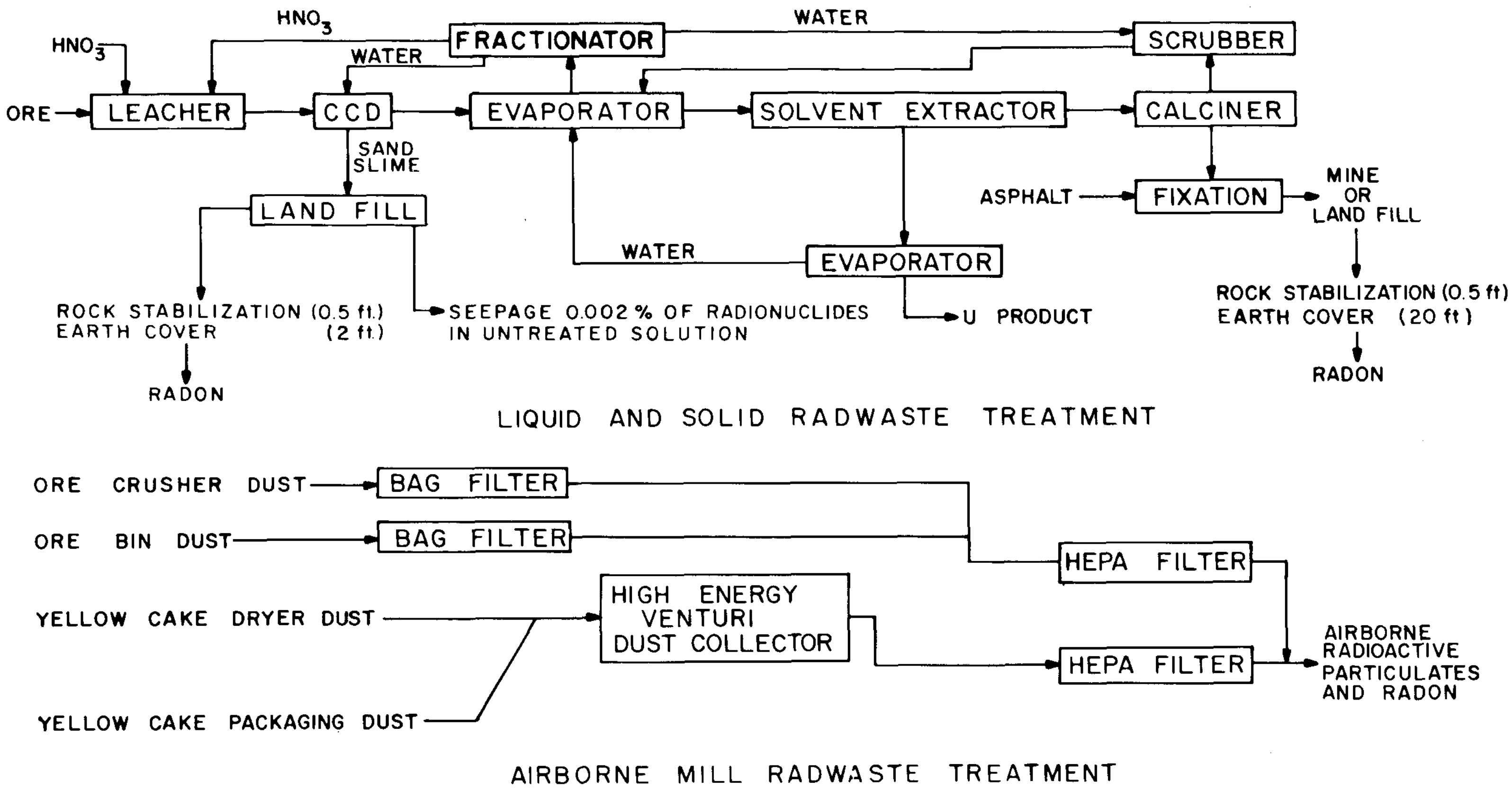

LIQUID AND SOLID RADWASTE TREATMENT

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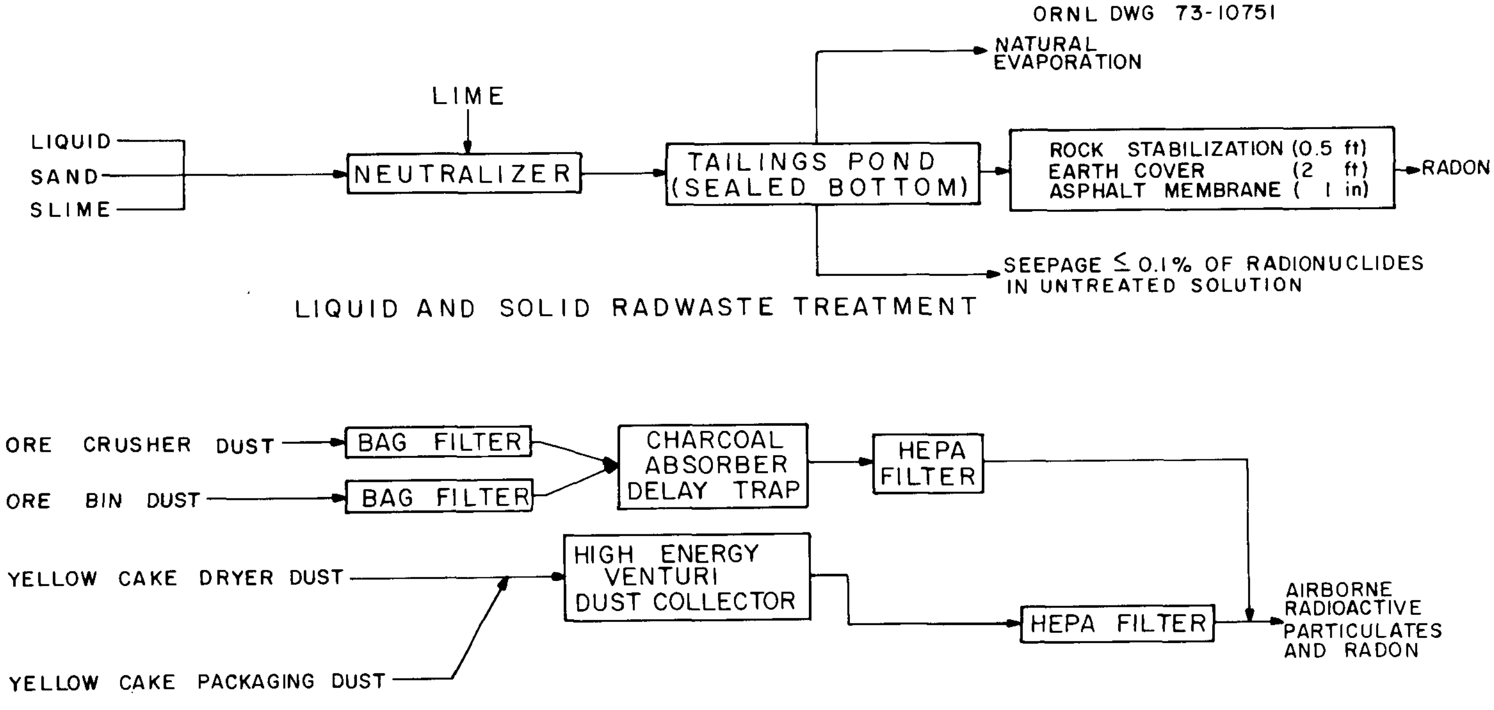
Fig. 4.12. Nitric Acid Flowsheet and Radwaste Treatment Systems for Uranium Mill – Case 6c.



LIQUID AND SOLID RADWASTE TREATMENT

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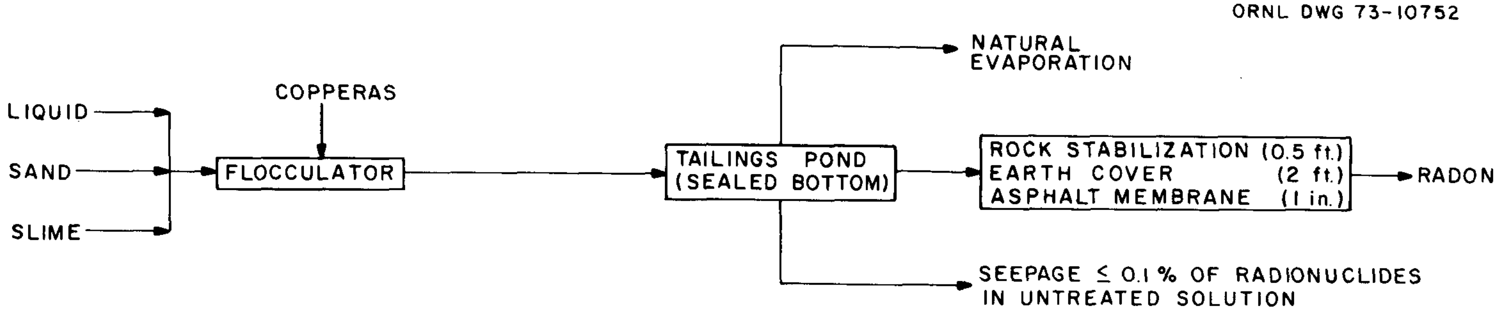
Fig. 4.13. Radwaste Treatment Systems for Acid Leach--Solvent Extraction Uranium Mill — Case 7.



LIQUID AND SOLID RADWASTE TREATMENT

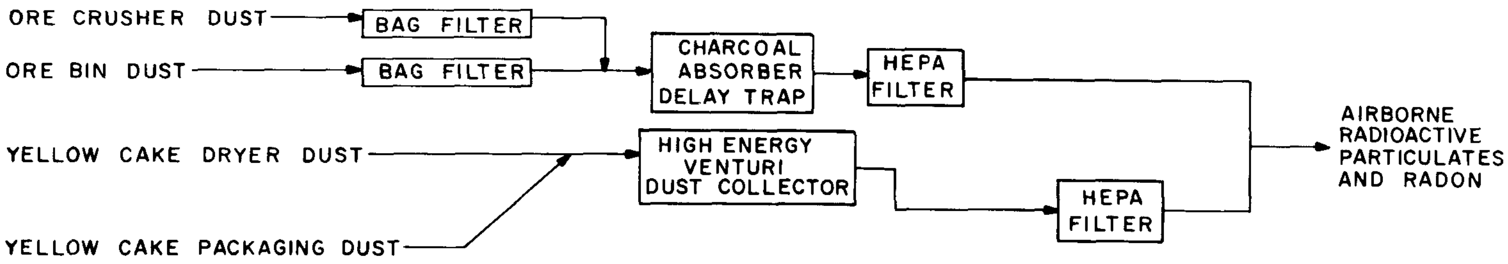


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Fig. 4.14. Radwaste Treatment Systems for Alkaline-Leach Uranium Mill – Case 7.

ORNL DWG 73-11955

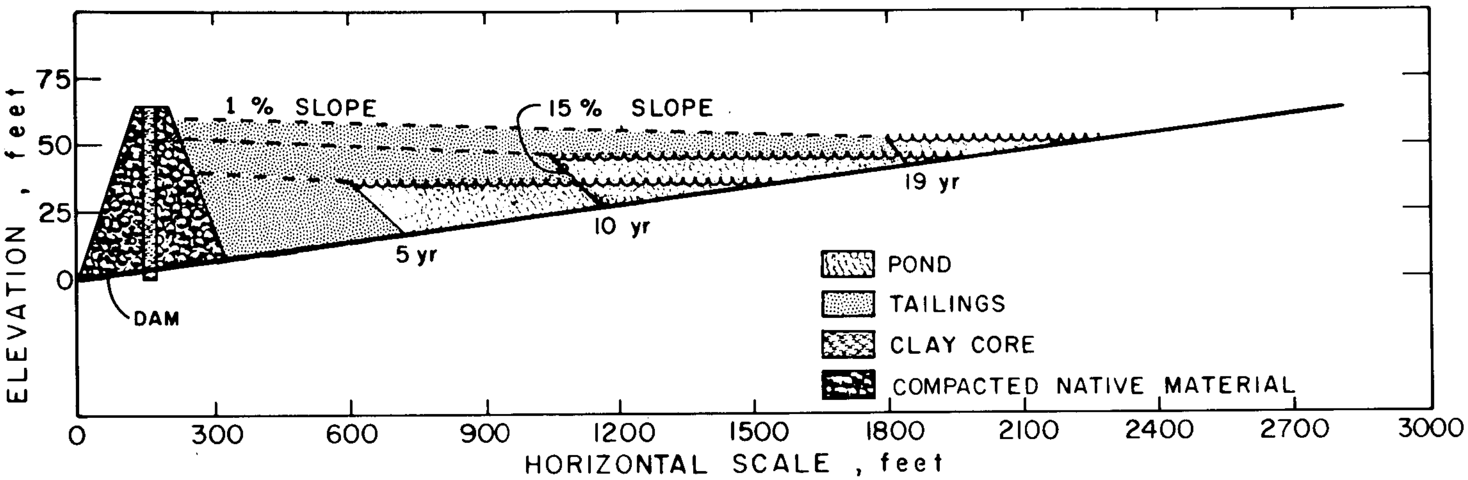

Fig. 4.15. Profile of a Model Tailings Pile.

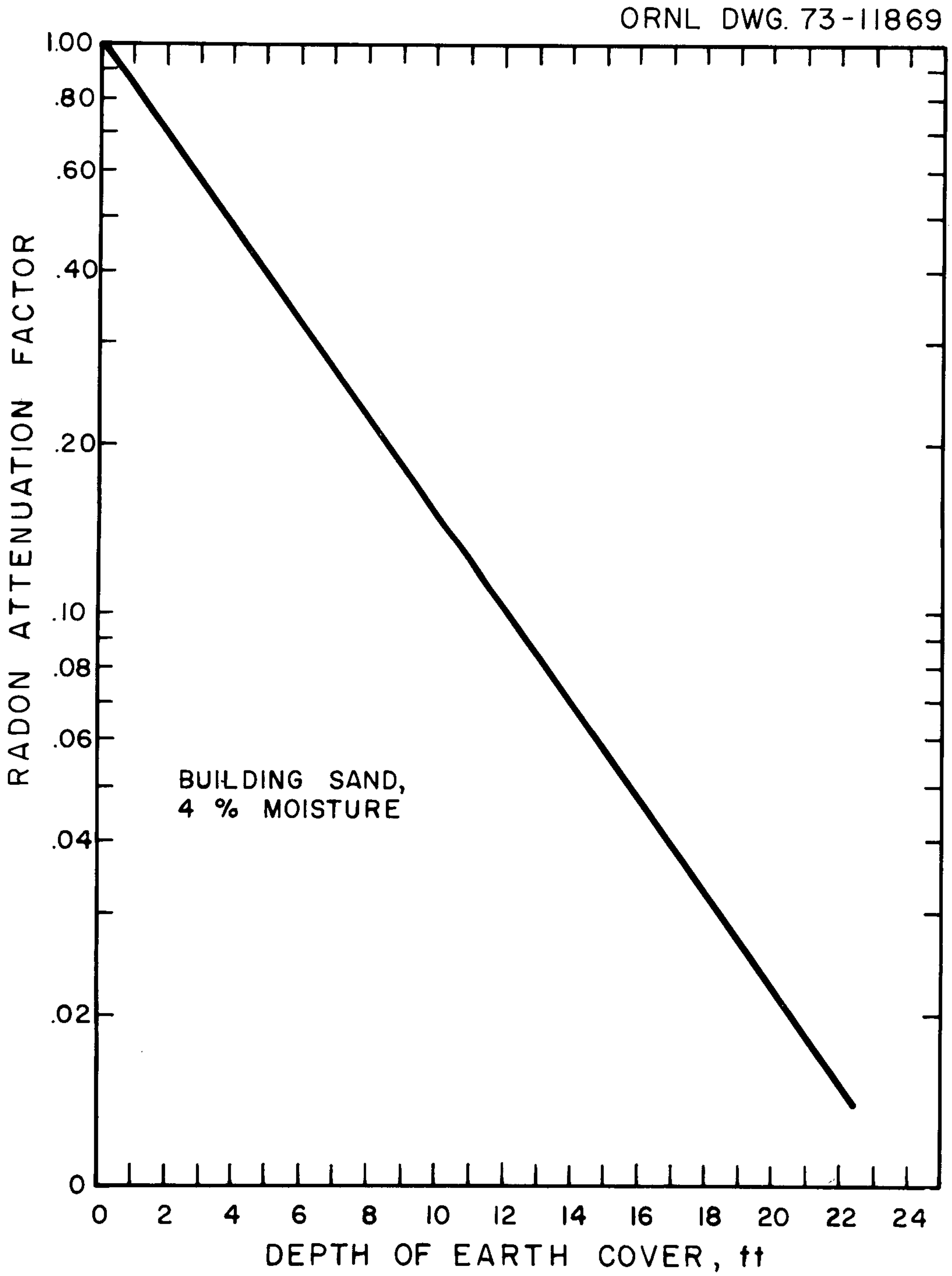

Fig. 4.16. Radon Attenuation by Earth Cover over Tailings Pile.

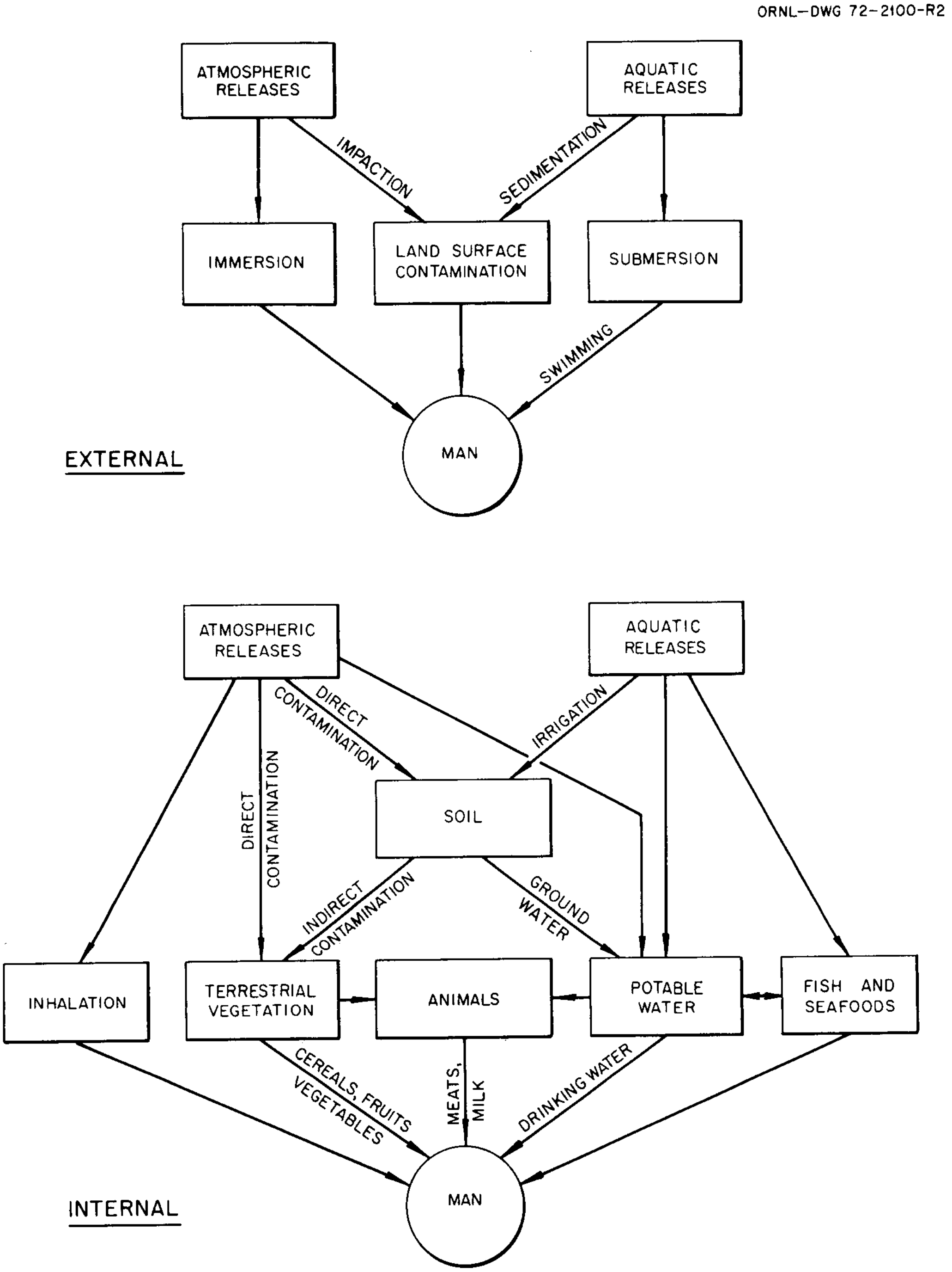

Fig. 7.1. Pathways for External and Internal Radiation Exposure of Man.

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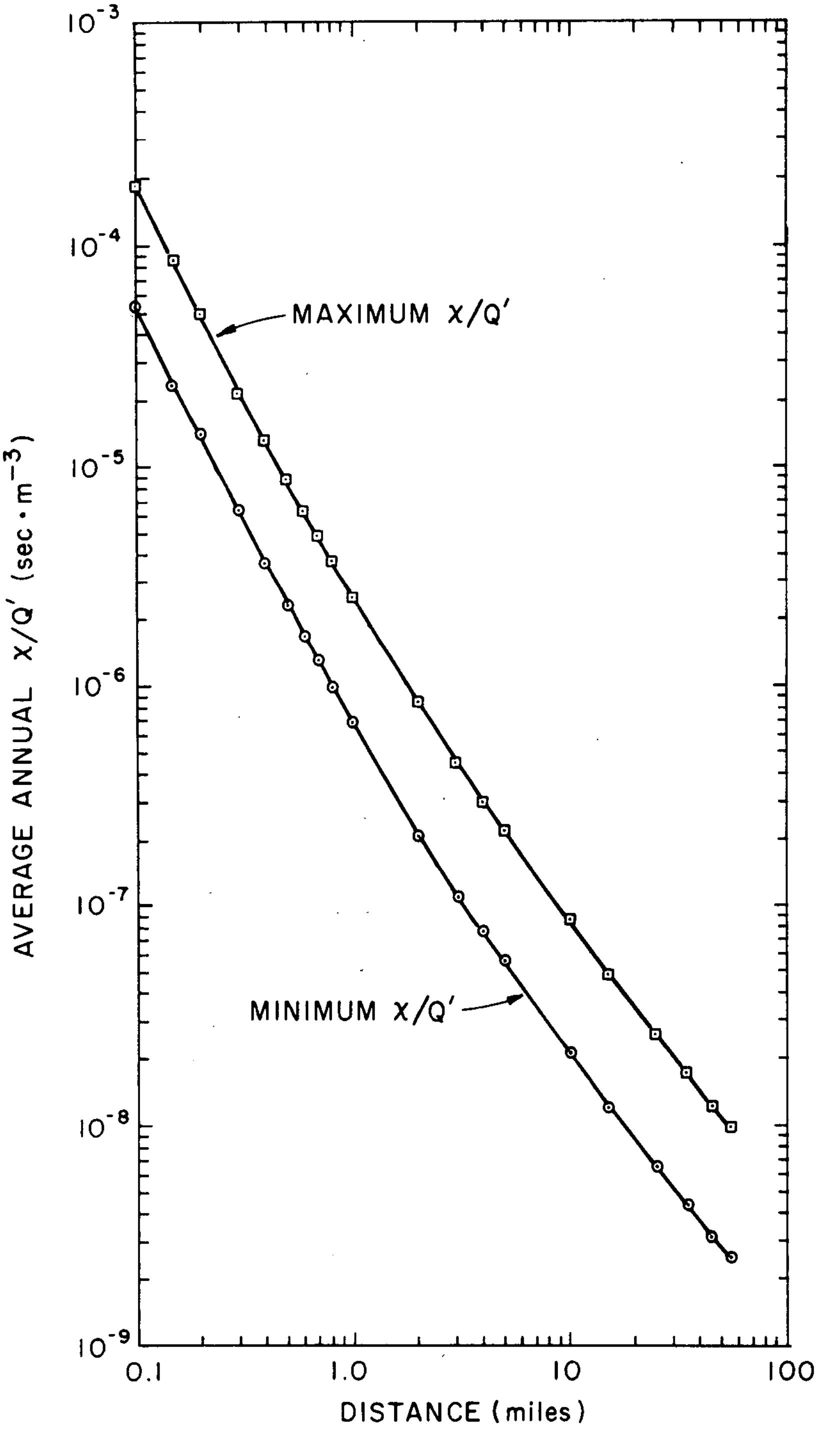

Fig. 7.2. Minimum and Maximum X/Q' Values for Ground Level Release at the New Mexico Site. All values of X/Q' for 16 sectors fall between these limits at respective distances.

ORNL DWG 73-10798R

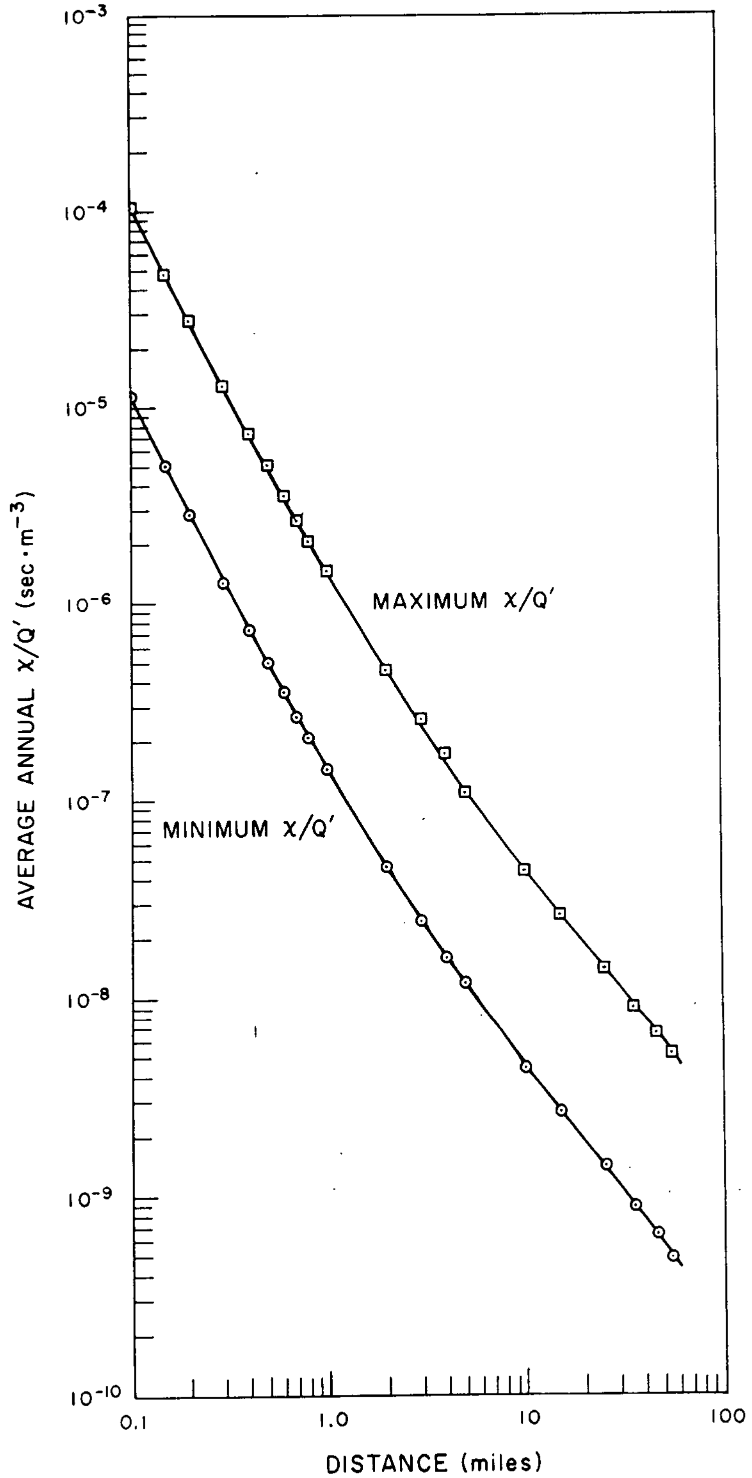

Fig. 7.3. Minimum and Maximum X/Q' Values for Ground Level Release at the Wyoming Site. All values of X/Q' for 16 sectors fall between these limits at respective distances.

ORNL DWG 74-75

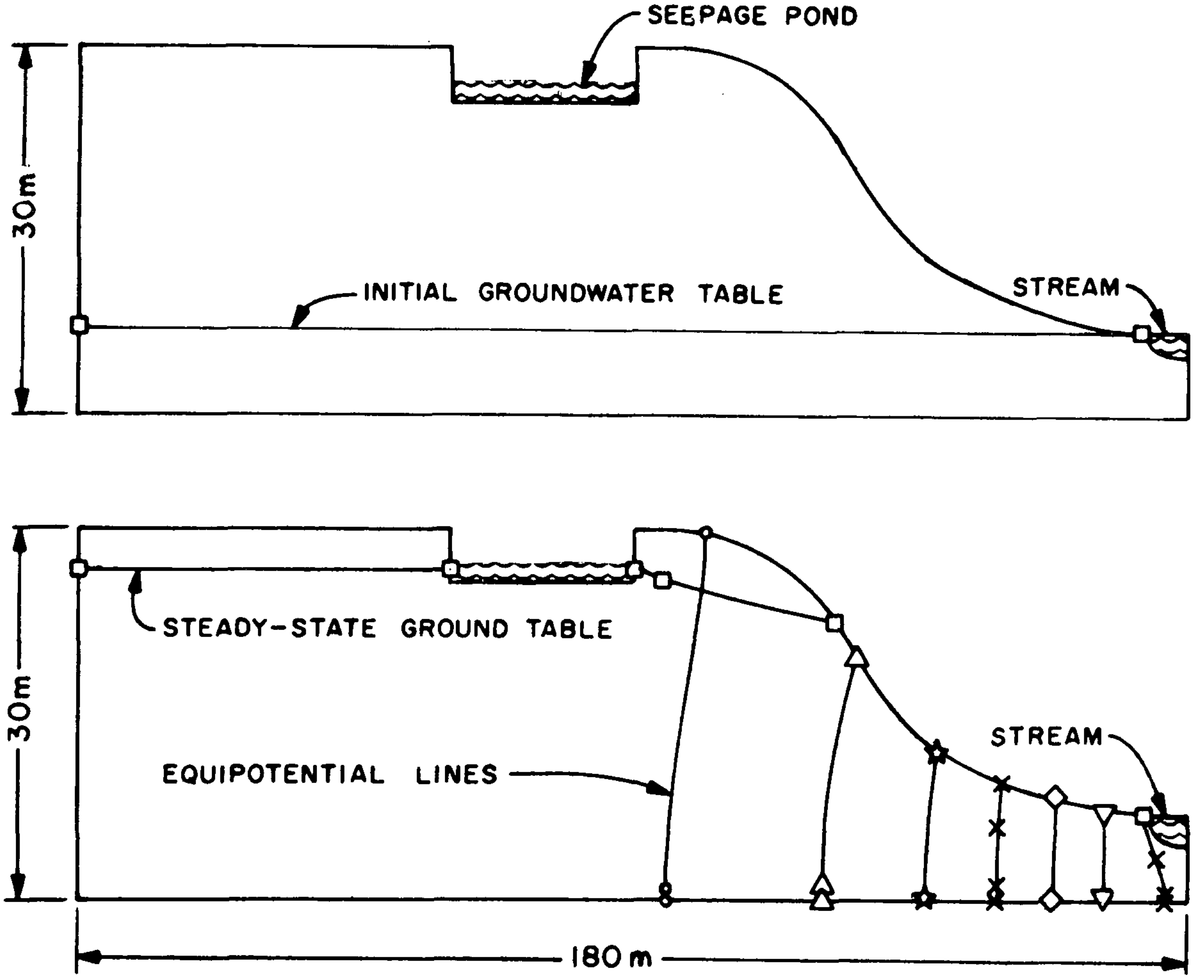

Fig. 7.4. Initial and Steady-State Conditions of Water Flow from a Seepage Pond.

ORNL DWG 73-12792

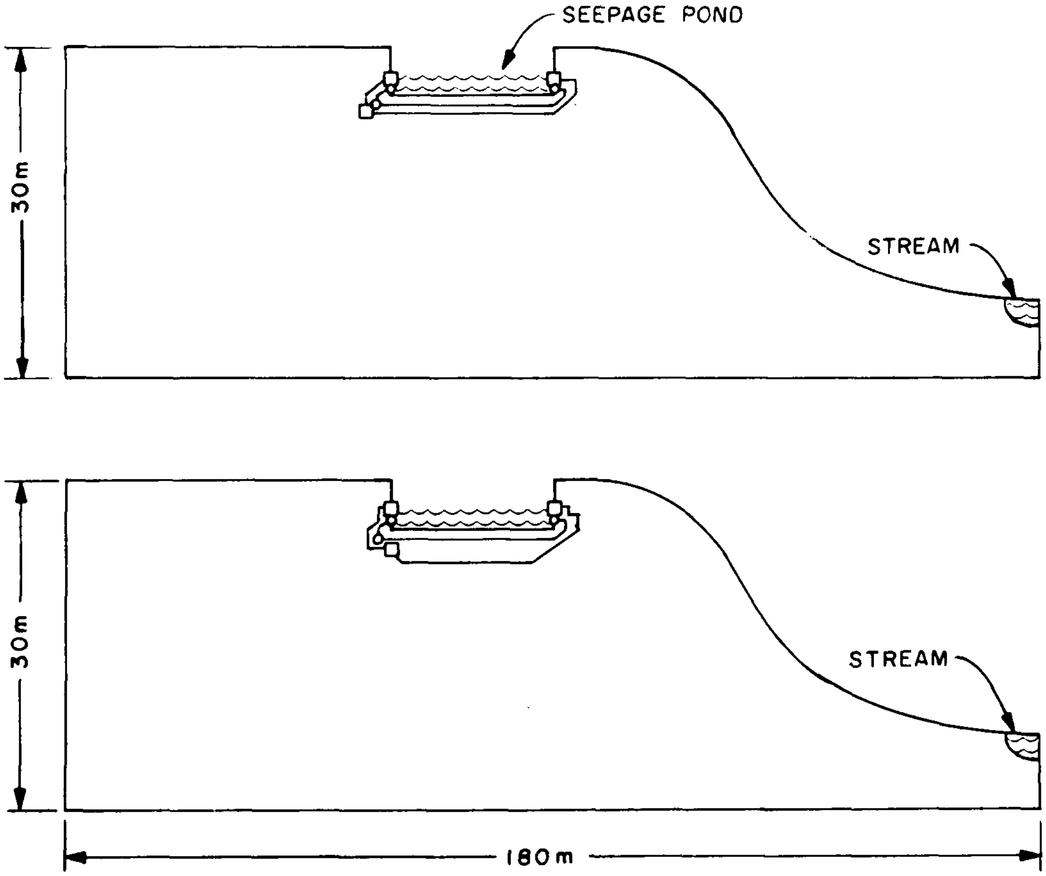

Fig. 7.5. Concentration Contours Showing Decreasing Concentration Outward from a Seepage Pond for a K_d of 100. The first contour beyond the boundary of the pit represents 50% of the concentration in the pit and the second contour represents 10% of the pit concentration. The elapsed time is 5 years (top) and 20 years (bottom).

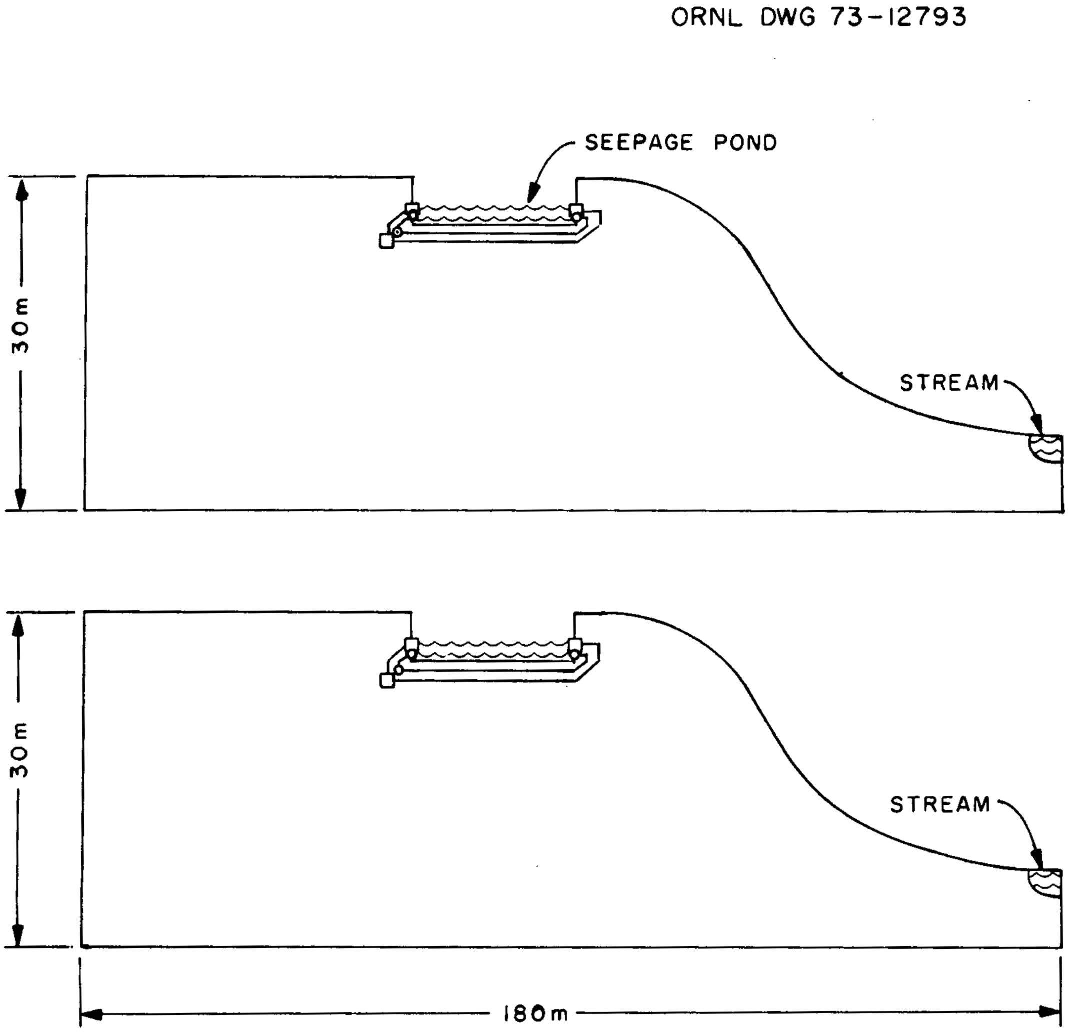

Fig. 7.6. Concentration Contours Showing Decreasing Concentration Outward from a Seepage Pond for a K_d of 1000. The first contour beyond the boundary of the pit represents 50% of the concentration in the pit and the second contour represents 10% of the pit concentration. The elapsed time is 5 years (top) and 20 years (bottom).

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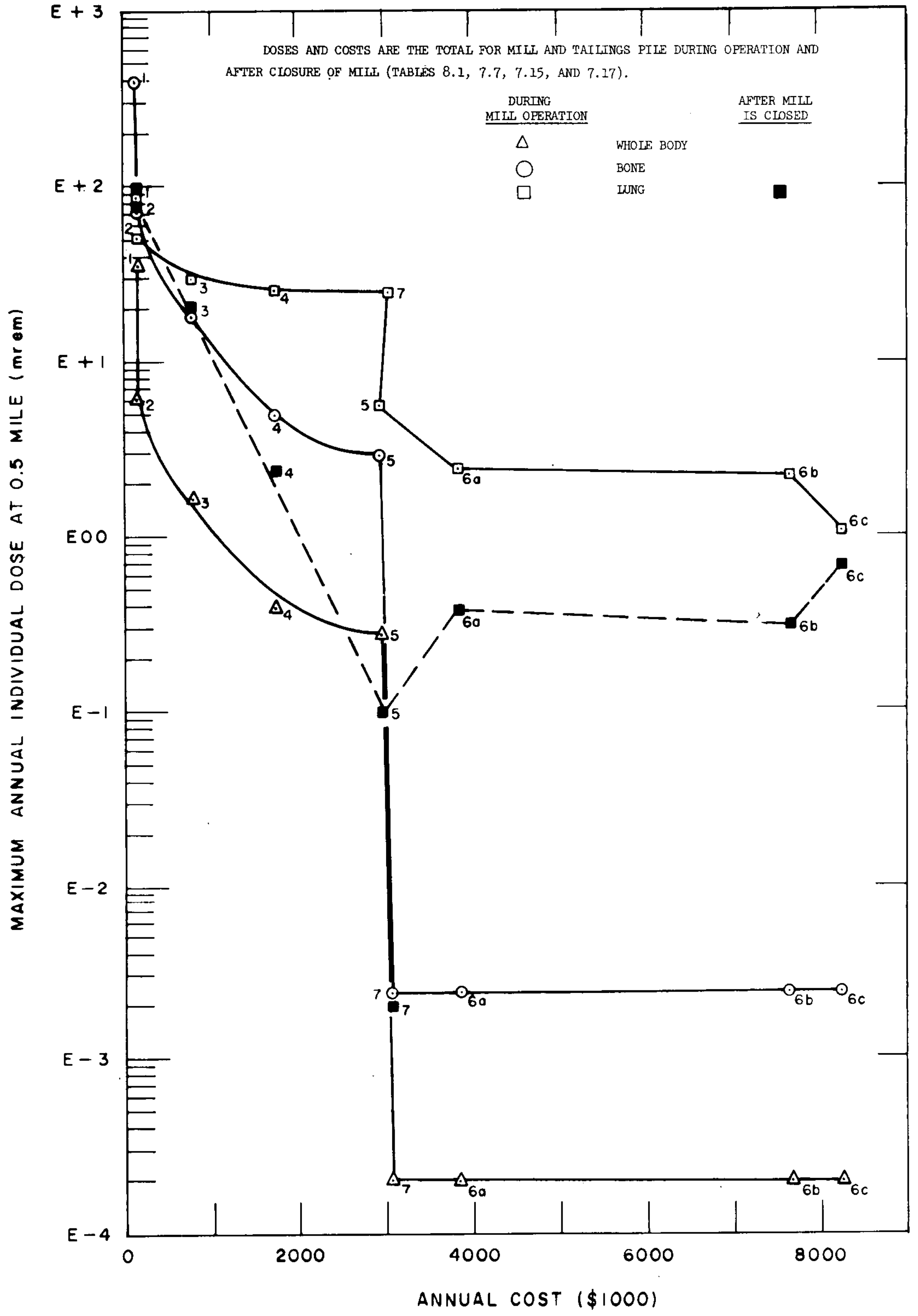


Fig. 8.1. Total Annual Cost for Reduction of Maximum Annual Dose (100% Food Ingestion) from Airborne Effluents from an Acid Leach--Solvent Extraction Mill and Tailings Pile in New Mexico.

ORNL DWG 74-648 R1

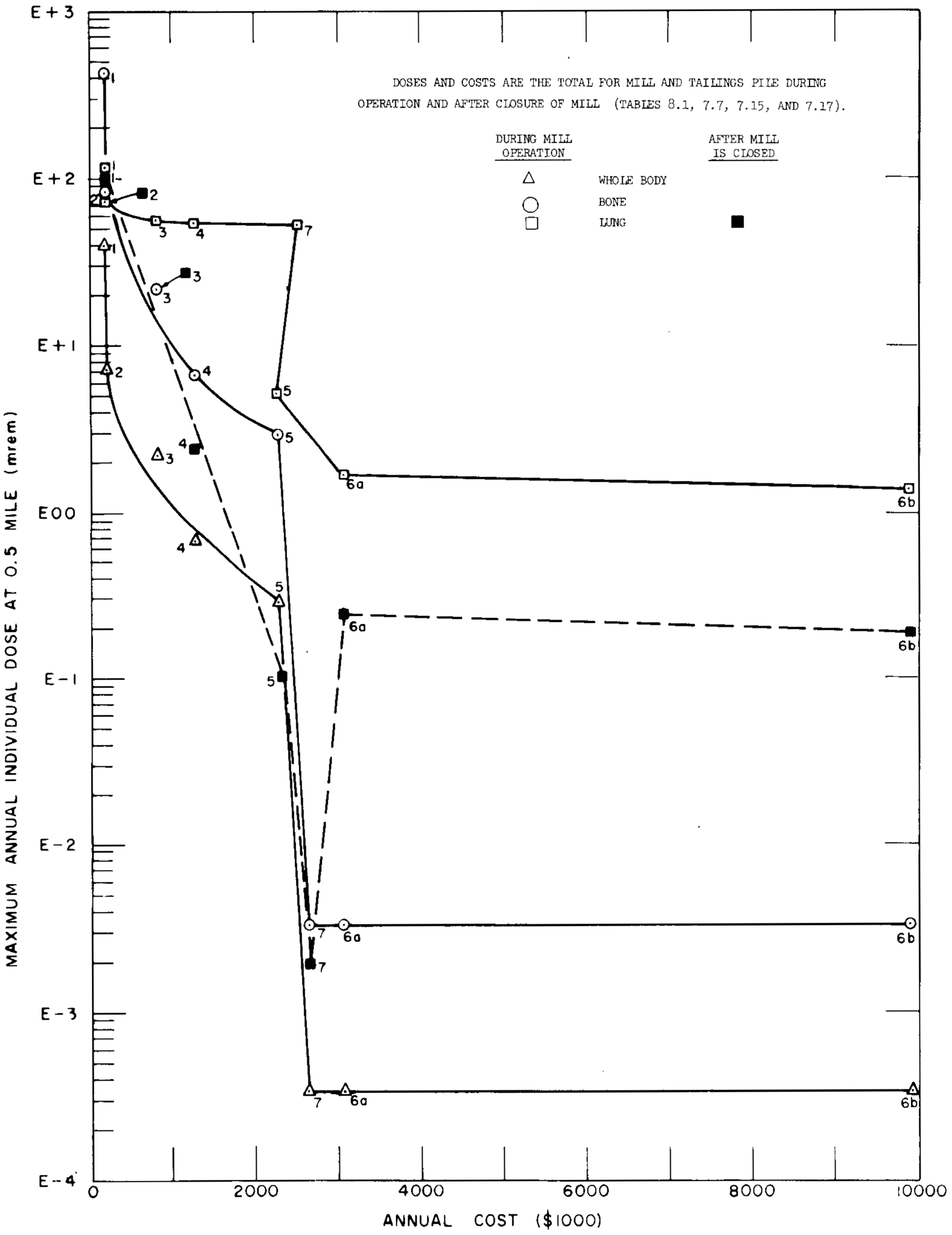


Fig. 8.2. Total Annual Cost for Reduction of Maximum Annual Dose (100% Food Ingestion) from Airborne Effluents from an Alkaline-Leach Mill and Tailings Pile in New Mexico.

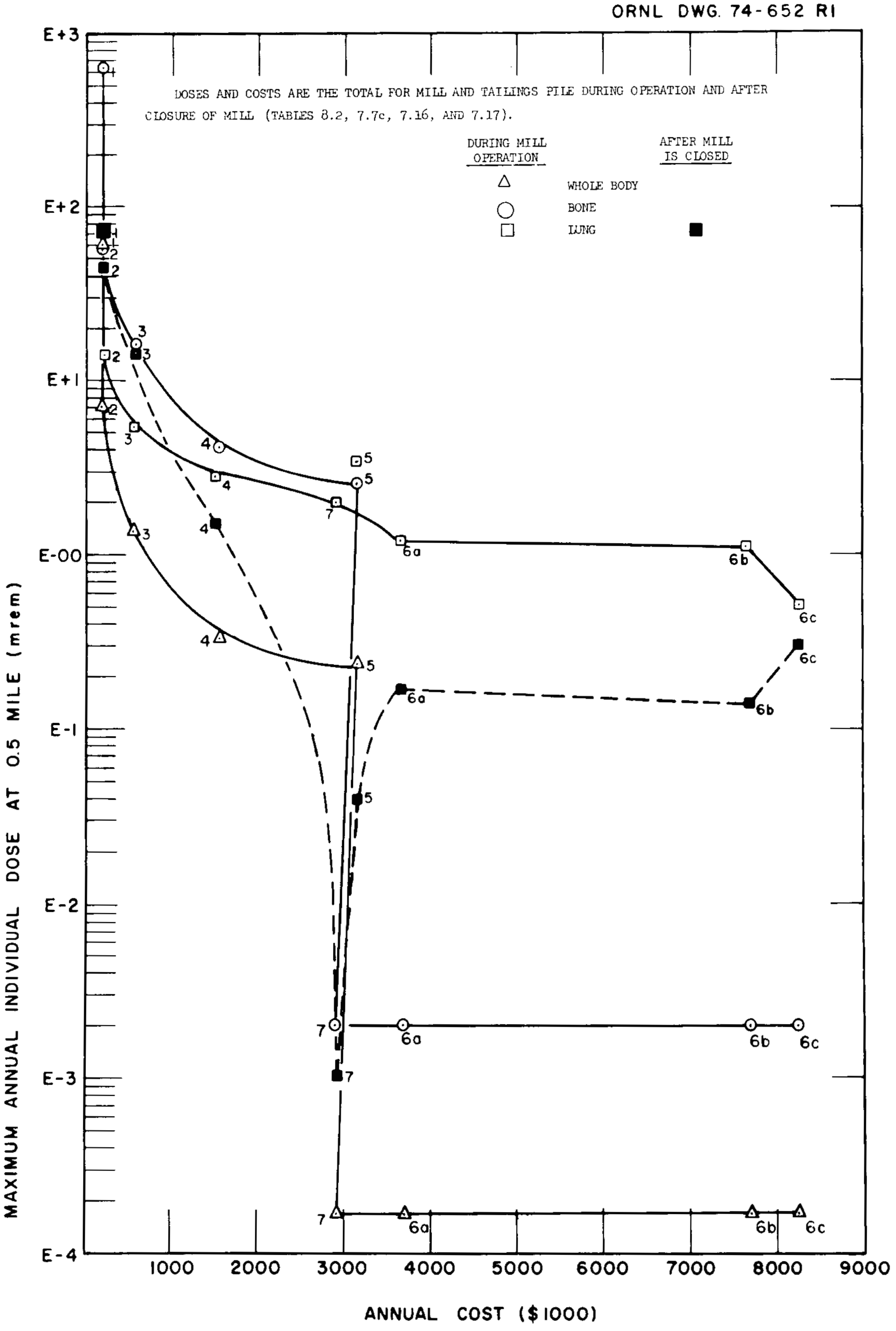


Fig. 8.3. Total Annual Cost for Reduction of Maximum Annual Dose (100% Food Ingestion) from Airborne Effluents from an Acid Leach--Solvent Extraction Mill and Tailings Pile in Wyoming.

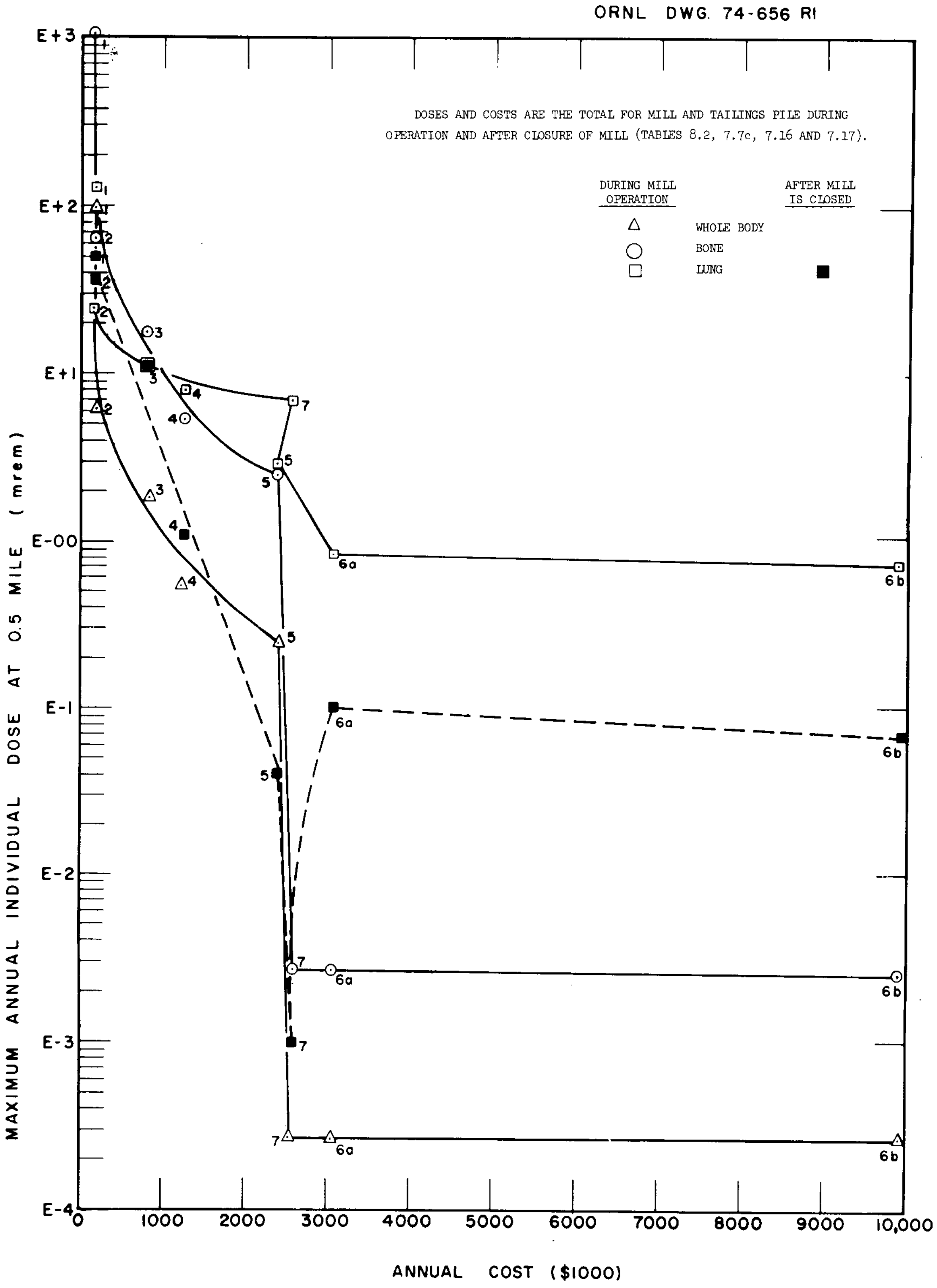
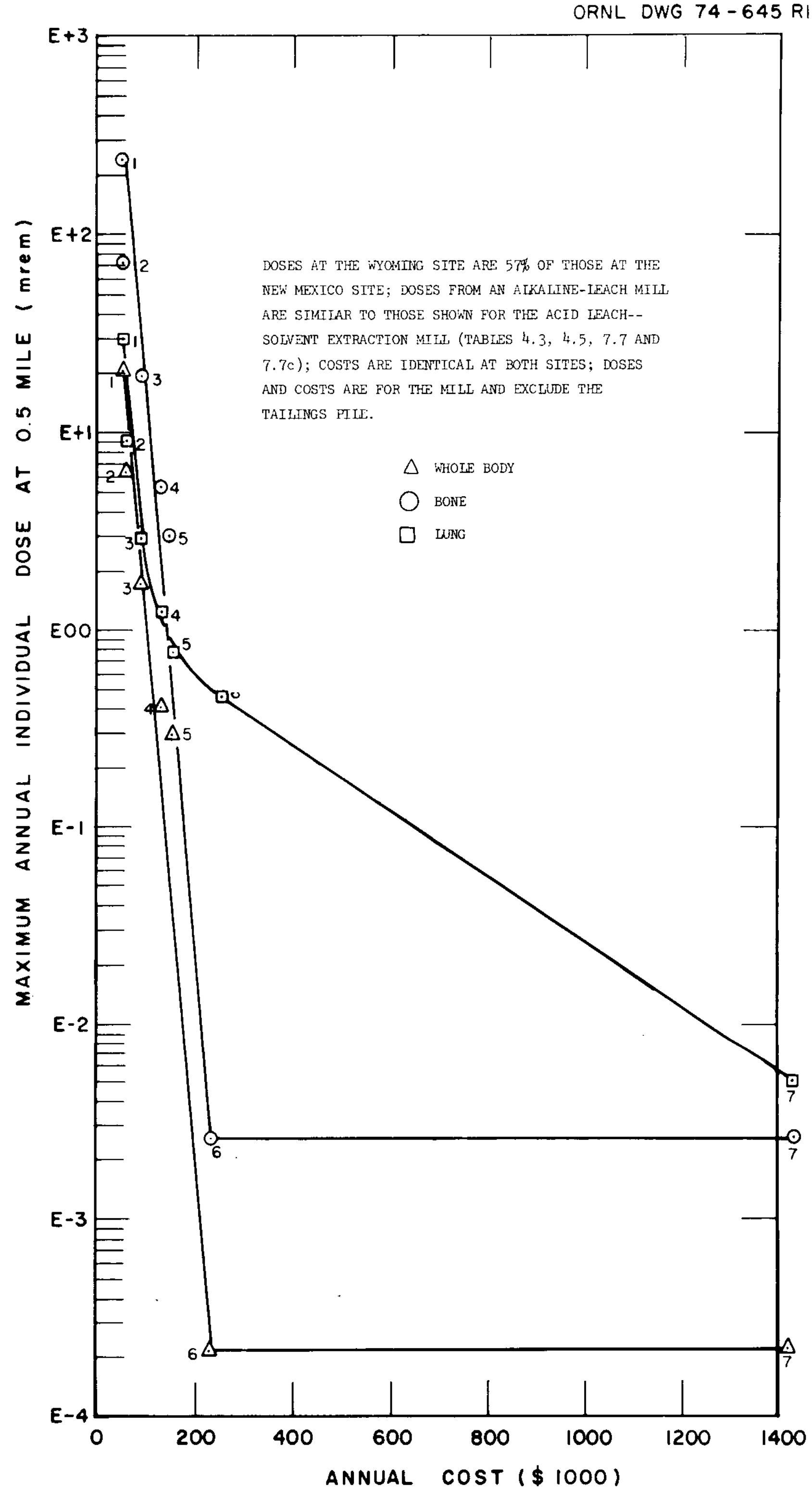


Fig. 8.4. Total Annual Cost for Reduction of Maximum Annual Dose (100% Food Ingestion) from Airborne Effluents from an Alkaline-Leach Mill and Tailings Pile in Wyoming.



DOSES AT THE WYOMING SITE ARE 57% OF THOSE AT THE NEW MEXICO SITE; DOSES FROM AN ALKALINE-LEACH MILL ARE SIMILAR TO THOSE SHOWN FOR THE ACID LEACH--SOLVENT EXTRACTION MILL (TABLES 4.3, 4.5, 7.7 AND 7.7c); COSTS ARE IDENTICAL AT BOTH SITES; DOSES AND COSTS ARE FOR THE MILL AND EXCLUDE THE TAILINGS PILE.

Fig. 8.5. Annual Cost for Reduction of Maximum Annual Dose (100% Food Ingestion) from Airborne Effluents from an Acid Leach--Solvent Extraction Mill in New Mexico - Mill Processes Only (Tailings not included).

ORNL DWG 74-650 RI

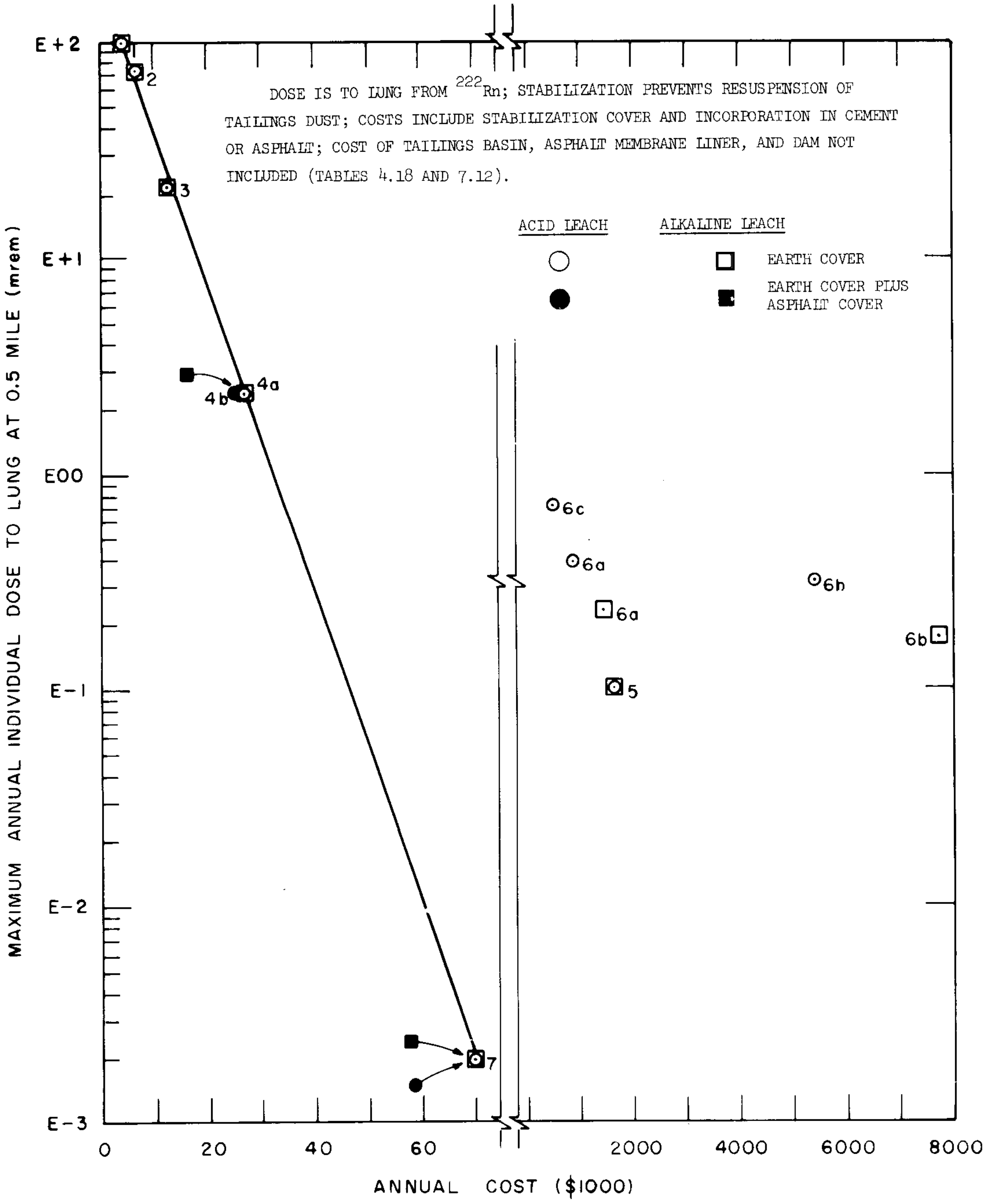


Fig. 8.6. Annual Cost for Reduction of Maximum Annual Dose from Airborne Effluents from a Stabilized Tailings Pile at an Acid Leach--Solvent Extraction Mill and an Alkaline-Leach Mill in New Mexico.

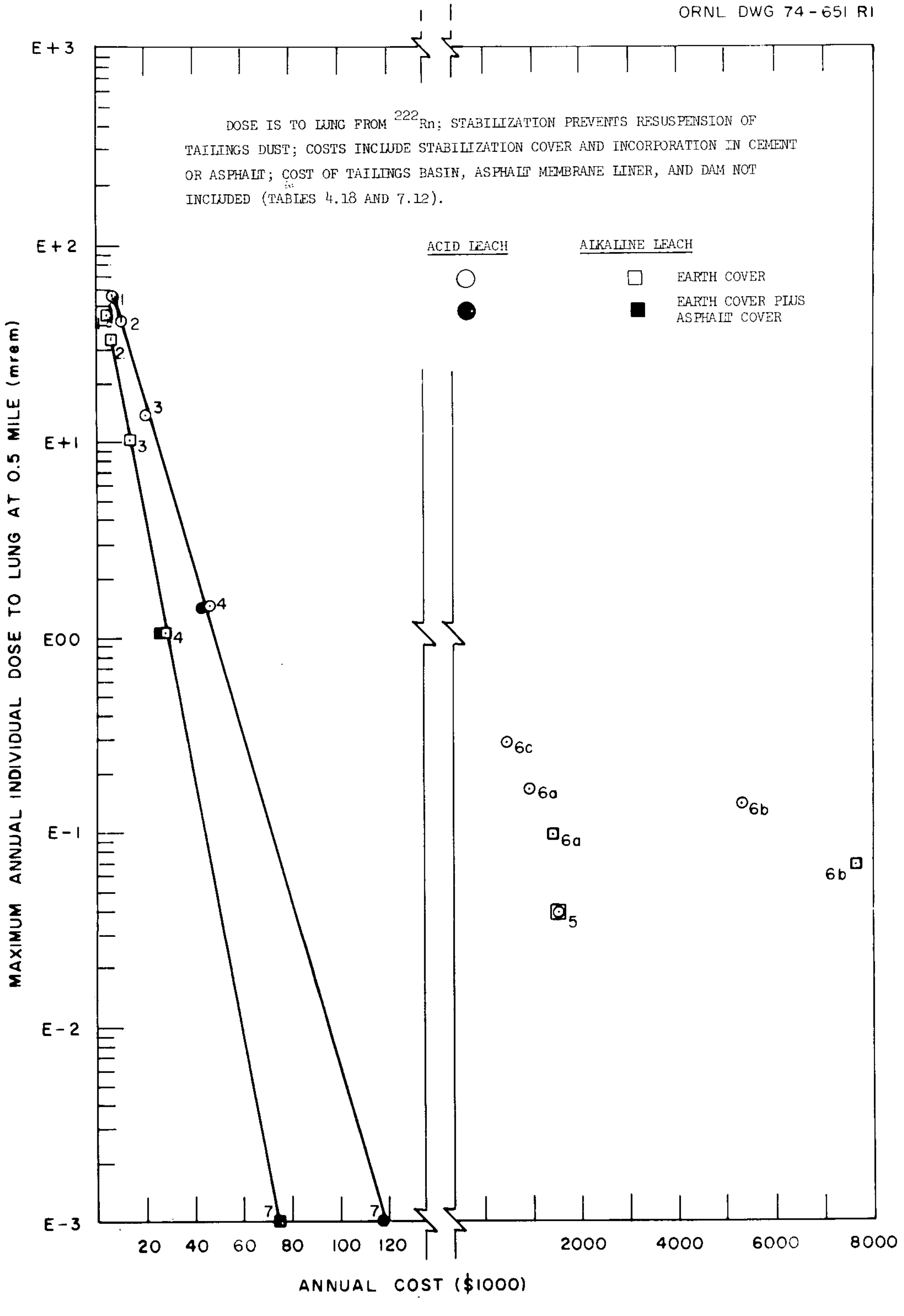


Fig. 8.7. Annual Cost for Reduction of Maximum Annual Dose from Airborne Effluents from a Stabilized Tailings Pile at an Acid Leach--Solvent Extraction Mill and an Alkaline-Leach Mill in Wyoming.

ORNL DWG. 74-649R1

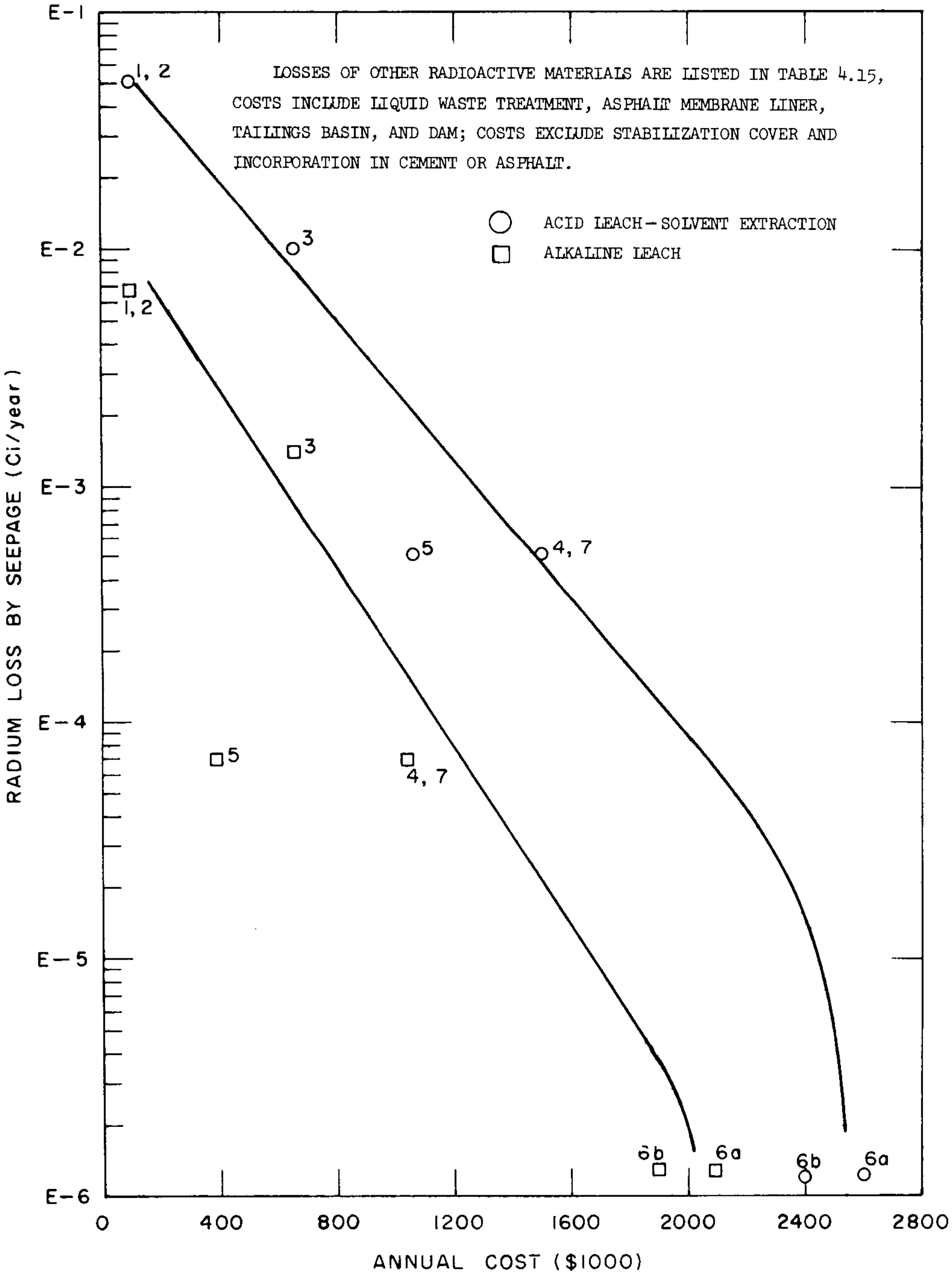


Fig. 8.8. Annual Cost for Reduction of Loss of Soluble Radium in Seepage from a Tailings Pond at an Acid Leach--Solvent Extraction Mill and an Alkaline-Leach Mill in New Mexico.

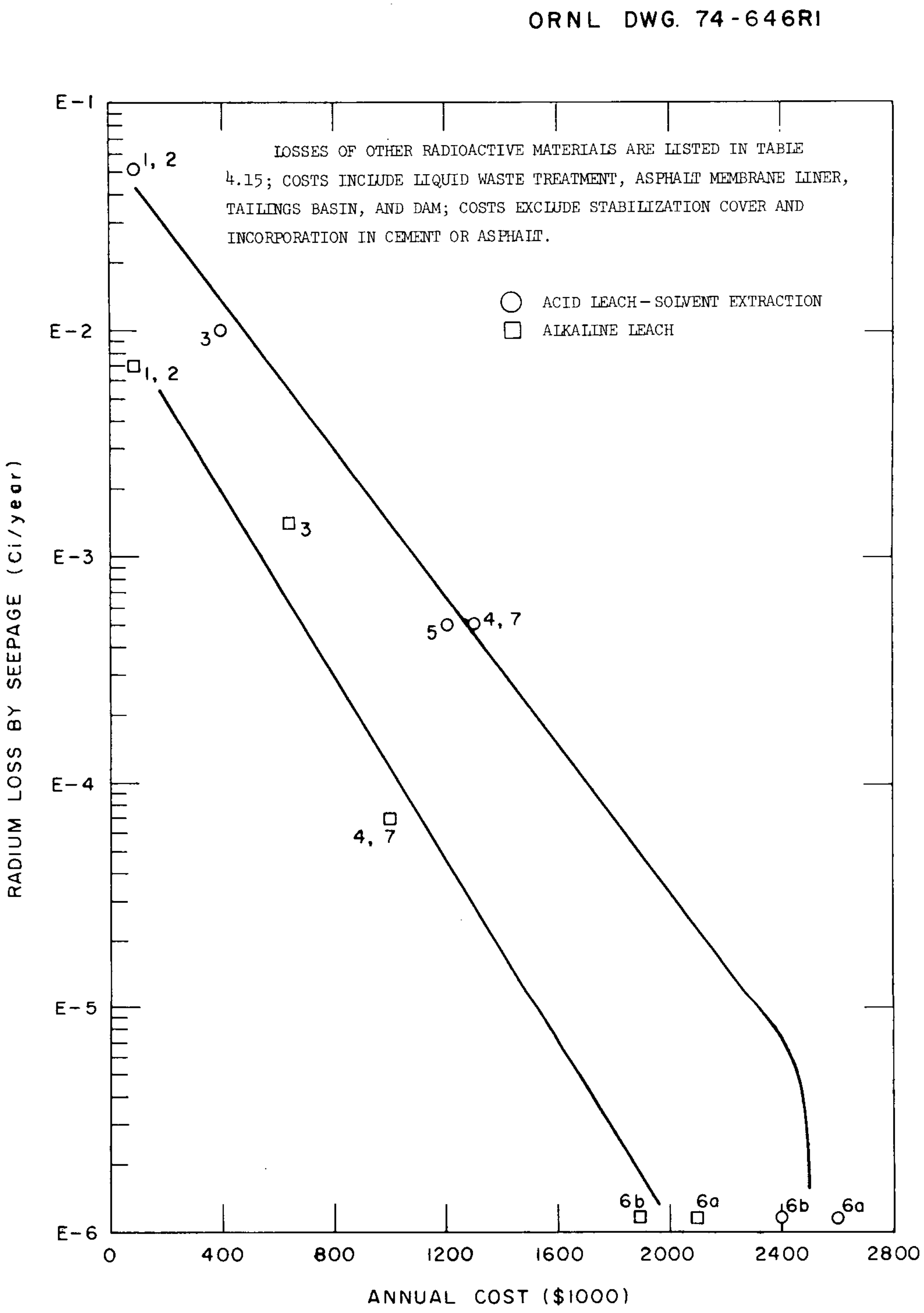
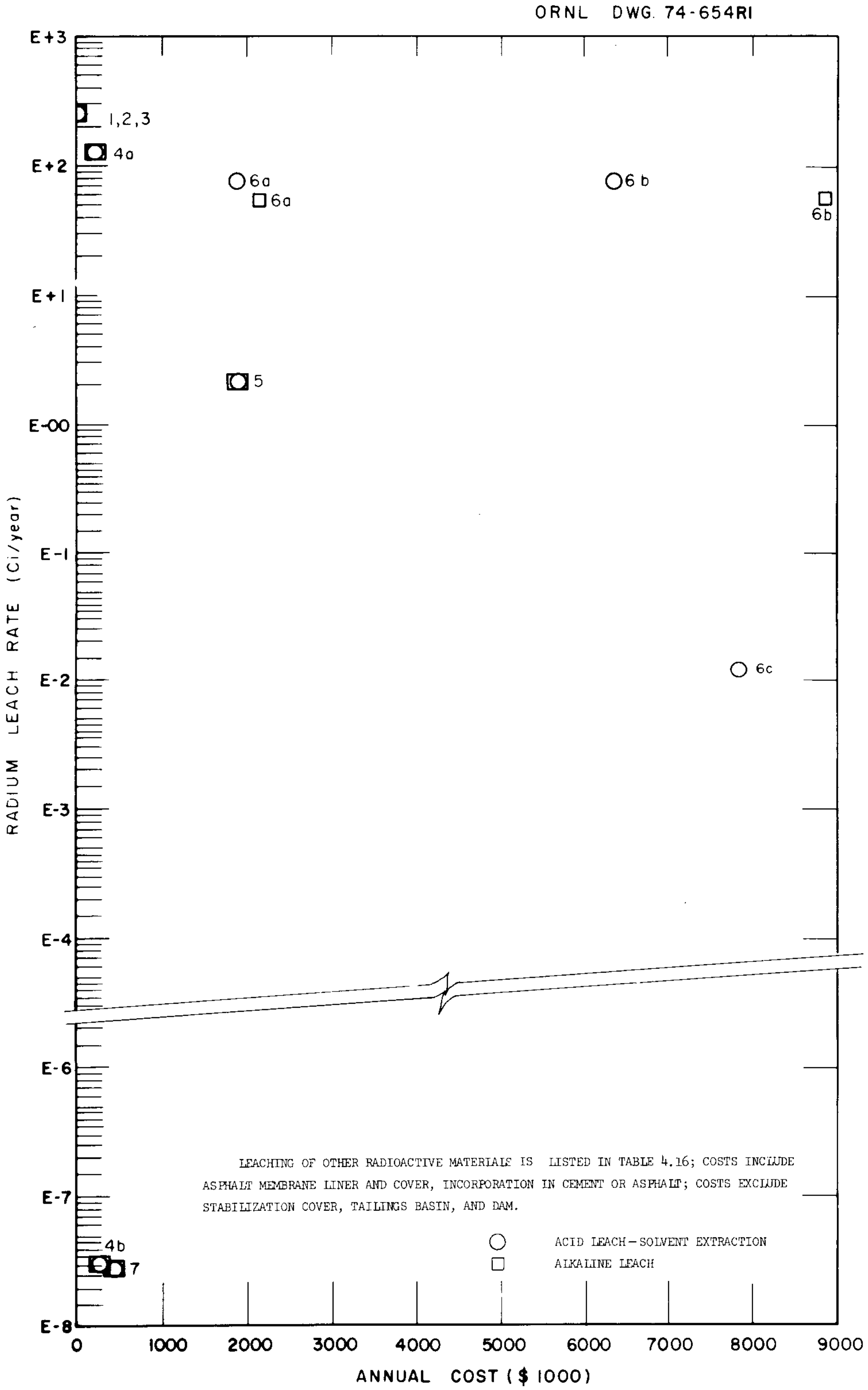
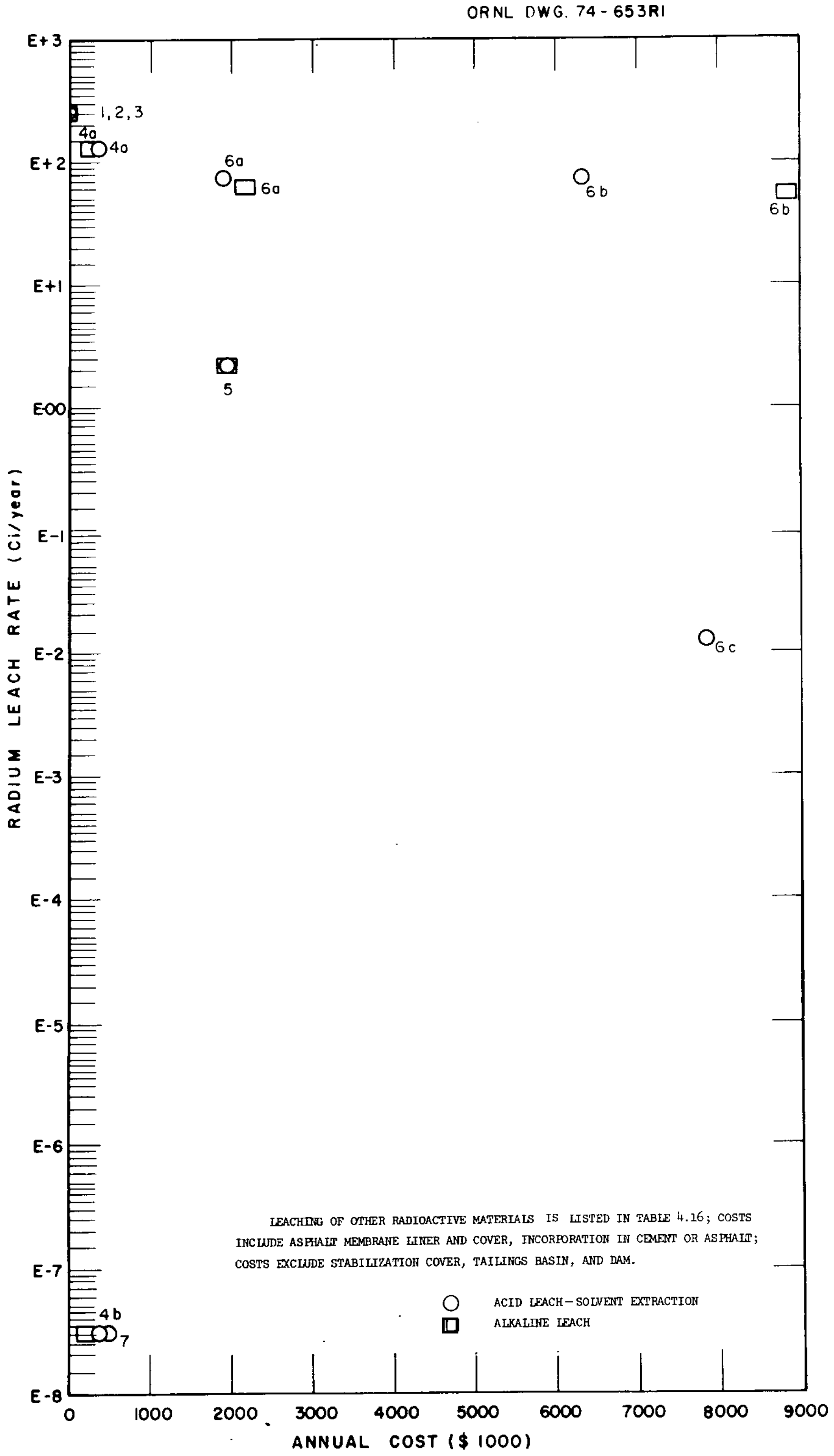


Fig. 8.9. Annual Cost for Reduction of Loss of Soluble Radium in Seepage from a Tailings Pond at an Acid Leach--Solvent Extraction Mill and an Alkaline-Leach Mill in Wyoming.



LEACHING OF OTHER RADIOACTIVE MATERIALS IS LISTED IN TABLE 4.16; COSTS INCLUDE ASPHALT MEMBRANE LINER AND COVER, INCORPORATION IN CEMENT OR ASPHALT; COSTS EXCLUDE STABILIZATION COVER, TAILINGS BASIN, AND DAM.

Fig. 8.10. Annual Cost for Reduction of Leaching of Radium from a Stabilized Tailings Pile at an Acid Leach--Solvent Extraction and Alkaline-Leach Mill in New Mexico.



LEACHING OF OTHER RADIOACTIVE MATERIALS IS LISTED IN TABLE 4.16; COSTS INCLUDE ASPHALT MEMBRANE LINER AND COVER, INCORPORATION IN CEMENT OR ASPHALT; COSTS EXCLUDE STABILIZATION COVER, TAILINGS BASIN, AND DAM.

Fig. 8.11. Annual Cost for Reduction of Leaching of Radium from a Stabilized Tailings Pile at an Acid Leach--Solvent Extraction and Alkaline-Leach Mill in Wyoming.

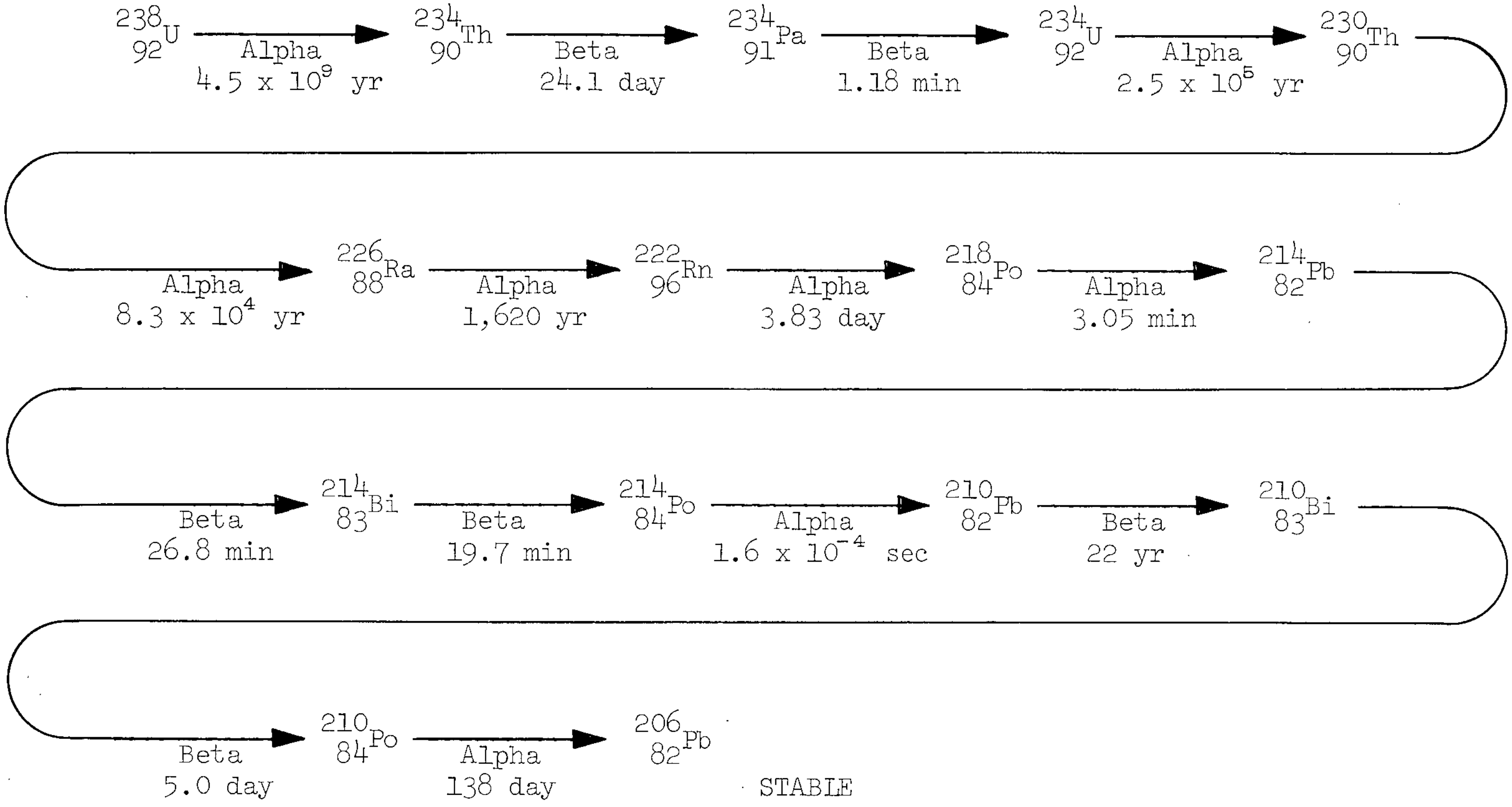


Fig. 9.1. Uranium-Radium Family — Minor Branches Not Shown.

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