United States
Environmental Protection
Agency

Office of
Radiation Programs
Washington, DC 20460

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EPA

Final Environmental Impact Statement for Standards for the Control of Byproduct Materials from Uranium Ore Processing (40 CFR 192)

Volume I

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SUMMARY

( ) Draft
(X) Final Environmental Impact Statement

Environmental Protection Agency
Office of Radiation Programs

1. This action is administrative.

2. The Environmental Protection Agency is establishing public health and environmental standards (40 CFR 192) for uranium and thorium mill tailings at licensed mill sites under the Uranium Mill Tailings Radiation Control Act of 1978 (PL. 95-604). Mills are currently located in Colorado, New Mexico, South Dakota, Texas, Utah, Washington, and Wyoming.

These standards are issued to reduce and control the hazards associated with uranium and thorium mill tailings. Controls are required both during the operational period of mills and for disposal of the tailings piles, to assure environmentally sound, long-term protection of public health and stabilization of the tailings.

These standards will be implemented by the U.S. Nuclear Regulatory Commission and its Agreement States that have approval to license uranium or thorium mills. The total cost is estimated to be about $260 million (1983 dollars) for disposal of existing tailings and about $390 million (1983 dollars) for disposal of existing tailings and those projected to be generated to the year 2000.

3. These standards will provide the following public health and environmental benefits:

(a) Under the post-closure standards, radon emissions from tailings piles will be reduced by at least 95 percent for 1,000 years, and for a lesser degree beyond that period for a time not readily estimated. We estimate that this will avoid approximately 570 lung cancer deaths per century; the total number of lung cancer deaths avoided over the effective life of the control is not calculable, but should exceed tens of thousands. Measures used to achieve these standards will also prevent spreading of tailings by wind and water erosion, protect water quality, and should discourage misuse of tailings by

providing a significant barrier against intrusion for at least a thousand years.

(b) Existing standards for operating mills are not changed (40 CFR 190, 40 CFR 440, and Federal Radiation Guidance as published in 1960, 25 FR 4402). Groundwater quality will be protected through the incorporation of Solid Waste Disposal Act (SWDA) standards (40 CFR 264) into these standards. Also, uranium and molybdenum are added to the list of hazardous constituents controlled under the SWDA standards and specific concentration limits for alpha emitters in water are added.

4. The following alternatives were considered:

(a) Institutional controls with radon emission limits of:

(B-1)	no limit
(B-2)	60 pCi/m^2s
(B-3)	20 pCi/m^2s
(B-4)	6 pCi/m^2s

(b) Passive, engineered controls designed for 1,000 years with radon emission limits of:

(C-1)	no limit
(C-2)	60 pCi/m^2s
(C-3)	20 pCi/m^2s
(C-4)	6 pCi/m^2s
(C-5)	2 pCi/m^2s

(c) Passive, engineered, below-grade controls designed for 1,000 years with radon emission limits of:

(D-2)	60 pCi/m^2s
(D-3)	20 pCi/m^2s
(D-4)	6 pCi/m^2s
(D-5)	2 pCi/m^2s

(d) Different standards for sites in remote areas.

EPA selected alternative C-3 with an admonishment to regulatory agencies that alternative D-3 should be seriously considered for any new tailings impoundments.

5. The following are the major points raised in public comments on the proposed standards and EPA's resolution of them:

(a) Estimates of health risk from radon
Some commenters thought EPA's estimates were too high. We reviewed our risk estimates and concluded the original estimates are reasonable. In any case, uncertainties in these risk estimates would not lead to different standards.

(b) Significance of risk from radon from tailings piles
Several commenters argued that EPA failed to demonstrate that the risks associated with radon emissions from tailings are significant and compared the risk from radon from tailings to that from other radon sources and from other causes of deaths, such as automobile and home accidents. We do not believe these other risks are relevant to this rulemaking. Both the individual and the population risks from radon from tailings are sufficient for EPA to consider controlling radon from tailings.

(c) Standards based on current populations
Some commenters suggested that less restrictive standards are appropriate for sites that are in currently sparsely populated areas. Other commenters raised the question of the fairness, or equity, of protecting a few people less just because of where they live. We concluded that relaxed standards for "remote" sites are not feasible based on a demographic basis, i.e., a remote site is not readily defined, on the lack of clear delineation between existing sites, and on the unpredictability of future populations. In addition, the potential cost savings do not outweigh foregone benefits.

(d) Passive vs. institutional controls
Comments on this issue ranged from strong support of passive stabilization for thousands of years to protection for only a few decades with institutional controls. We concluded that long-term protection should be provided through the use of passive control methods because the legislative history of the Act supports this approach, and because the incremental cost of passive control are well justified in terms of incremental benefits.

(e) Radon emission limit after closure
Commenters who thought the proposed 20 pCi/m^2s limit too high objected primarily to the high residual risk to individuals living very close to a pile. This risk is about 1 in 1,000. Commenters who thought the proposed limit too restrictive contended the cost was too high in view of the small contribution radon from tailings makes to total radon and their view that EPA had overestimated the risk. We selected 20 pCi/m^2s because higher values will not achieve the objectives of the rulemaking, and these objectives can be cost-effectively achieved by such a limit. We did not select a lower value since this limit is already technology forcing, and uncertainty of predictably attaining lower limits is too great to justify the benefits that will be achieved.

(f) Relationship to the Clean Air Act requirements
A few commenters argued that EPA is required to provide suitable health protection under both UMTRCA and the Clean Air Act (CAA)

and that EPA had not done so in the proposed standards. EPA therefore considered emissions of radionuclides from tailings under both UMTRCA and CAA. For the operational period, EPA has not sufficiently analyzed work practice and tailings management methods to assure radon emissions will be minimized. Therefore, EPA is issuing an Advance Notice of Proposed Rulemaking under the CAA for consideration of the control of radon emissions from tailings during the mill's operating period. For the post-closure period, we concluded that these standards fulfilled all requirements under both UMTRCA and CAA.

(g) Radon concentration vs. emission rate limits
A few commenters believed a radon concentration limit in air where people are exposed is preferable to an emission limit. EPA rejected this approach since it could be satisfied by dispersion, rather than control, through selection of boundaries and installation of fences, both institutional controls that would not provide long-term protection.

(h) Cleanup standards
Some commenters argued there is no need to clean up contaminated land that is to be turned over to a government agency, since the government can provide any needed protection. We concluded land included as part of the disposal site should be cleaned up to satisfy the same objectives of this rulemaking that apply to disposal of tailings.

(i) Choice of liner material-protection of groundwater quality
Some commenters stated that no liner technology, synthetic or clay, is capable of achieving the goal of the primary groundwater protection standard, i.e., no seepage of hazardous constituents into the groundwater or the soil underlying the tailings impoundment. During its SWDA rulemaking, EPA reviewed this matter in detail and decided to require a liner that is capable of preventing migration of wastes into the ground and water. Commenters did not establish that tailings impoundments are sufficiently different from impoundments controlled under SWDA to justify departures from SWDA rules.

(j) Secondary standard-protection of groundwater quality
Many commenters argued that past practice at uranium mill sites has led to groundwater contamination at virtually every site and, under the proposed standards, this will lead to a requirement for EPA concurrence on alternate standards at most of these sites. They argued that this amounts to duplicative licensing. We have modified the standard to authorize the regulatory agency to issue alternate limits when the secondary standards will be satisfied within the site boundary or 500 meters, whichever is less.

6. The following Federal Agencies have commented on the Draft Environmental Impact Statement:

Department of Energy
Department of Health and Human Services
Department of the Interior
Nuclear Regulatory Commission
Tennessee Valley Authority

7. This Final Environmental Impact Statement was made available to the public in October 1983. Single copies are available while quantities last from:

U.S. Environmental Protection Agency
Director, Criteria and Standards Division
Office of Radiation Programs, (ANR-460)
Washington, D.C. 20460

or the National Technical Information Service, 5285 Port Royal Road, Springfield, Va., 22161.

Chapter 1: INTRODUCTION

In the Uranium Mill Tailings Radiation Control Act of 1978, Public Law 95-604, 42 USC 7901 (henceforth designated as "the Act"), Congress directed the Environmental Protection Agency (EPA) to "promulgate standards of general application for the protection of the public health, safety, and the environment from radiological and non-radiological hazards associated with the processing and with the possession, transfer, and disposal of byproduct material...at sites at which ores are processed primarily for their source material content or which are used for the disposal of such byproduct material." The term 'byproduct material' as defined by the Act means, for these sites, "...the tailings or wastes produced by the extraction or concentration of uranium or thorium from any ore processed primarily for its source material content." The Act assigns the responsibility for implementation and enforcement of these standards to the Nuclear Regulatory Commission and its Agreement States through their licensing activities.

The Act also requires EPA to promulgate standards for cleanup and disposal of uranium tailings at inactive processing sites. EPA issued standards for cleanup of contaminated open lands and buildings and for disposal of tailings at inactive uranium processing sites on January 5, 1983 (48 FR 590).

1.1 Scope of the Standards

Standards are required for the control of effluents and emissions from the tailings both during milling operations and for the final disposal of tailings. The Act specifies that standards for non-radioactive hazards must provide protection of human health and the environment consistent with applicable standards established under Subtitle C of the Solid Waste Disposal Act, as amended.

The sites that are affected by these standards currently include about two dozen conventional uranium mills and 4 heap-leaching locations; these sites are licensed by NRC or its Agreement States. Approximately 86 percent of all uranium produced in 1980 was produced from ore mined in underground or open-pit mines and processed in conventional uranium mills. Solution mining contributed 8 percent, and about 5 percent came from heap-leach plants, mine water extraction and conventional milling of low-grade stockpiles of ore.

Only conventional uranium mills, heap-leaching operations, and above-ground wastes from solution mining are covered by these proposed standards. Phosphoric acid byproduct operations are not included because these operations do not process ore primarily for its source material (uranium or thorium) content. The Act was directed primarily toward the solution of environmental problems from the radioactive tailings piles resulting from conventional milling operations.

A number of environmental standards already apply to tailings. EPA promulgated 40 CFR Part 190, Environmental Radiation Protection Standards for Uranium Fuel Cycle Operations, on January 13, 1977 (42 FR 2858). These standards specify the radiation levels below which normal operations of the uranium fuel cycle must operate. Radiation exposures due to environmental release of and from uranium byproduct material are covered by these standards, with the exception of emissions of radon and its decay products. Under the Clean Water Act, EPA issued effluent limitations guidelines on December 3, 1982, for new source performance standards for wastewater discharges from the mining and dressing of uranium, radium, and vanadium ores (40 CRF 440, 47 FR 54598). Discharges of both radioactive and nonradioactive materials to surface waters from uranium byproduct materials are covered by these effluent guidelines. Because these guidelines and proposals have already been issued, we have not evaluated control measures for discharges to surface water in this DEIS.

EPA promulgated 40 CFR Part 261, Subpart F--Groundwater Protection, on July 26, 1982 (47 FR 32274) under the Solid Waste Disposal Act (SWDA), as amended by the Resource Recovery and Conservation Act. The Act requires that standards for nonradioactive hazards from uranium byproduct materials be consistent with standards promulgated under SWDA for such hazards. Also, the Act requires that the NRC establish general requirements which are, to the maximum extent practicable, at least comparable to requirements applicable to the possession, transfer, and disposal of similar hazardous material regulated by EPA under the SWDA. NRC Agreement States are required by the Act to adopt standards which are equivalent, to the maximum extent practicable, or more stringent than, standards adopted and enforced by the NRC. These responsibilities must be carried out by the NRC whether or not EPA promulgates standards for groundwater protection. We have included groundwater protection in this analysis to determine whether or not the SWDA standards should be supplemented or modified by the standards promulgated under the Act.

Thorium mill tailings are included in the definition of byproduct material and must be licensed by the NRC or an Agreement State under the same provisions of the Act as uranium mill tailings. However, the only thorium currently being recovered from ore is as a secondary product at the W.R. Grace Co. facility near Chattanooga. There are also thorium byproduct materials at four inactive sites located in New Jersey, Illinois, Ohio, and West Virginia. The current demand for thorium is small, and there appears to be little growth potential. The two major uses of thorium are as a source material in nuclear applications and as a thin ceramic lantern mantle that gives off a bright light. Neither of these uses is expected to increase significantly in the next few years.

There are a few other licensed sites contaminated with uranium and thorium and their decay products. Two or three of these sites may contain uranium and thorium byproduct material as defined by the Act. These sites are not included in this analysis, because the quantities of material are relatively small and would not affect the overall analysis.

There are now about 175 million tons of tailings at the licensed mill sites. Of these, about 56 million tons were generated under government contracts. Most of these 56 million tons of tailings are not separated from other tailings and are commonly designated "commingled" tailings. The Department of Energy (DOE) has recently issued a report on commingled tailings in response to Congressional concern over whether the government or industry should pay for disposal of these tailings (DOE82). The analysis for these standards is not significantly affected by this issue. However, government sharing of costs would lead to a lesser impact on the industry, as reflected, for example, in fewer mills closing under certain alternatives for environmental requirements. Thus, government sharing of costs could permit application of more stringent standards. Our economic analysis assumes the total costs of compliance will be borne by the industry. Any government sharing of disposal costs would thus improve industry's economic position compared to that projected in this analysis.

1.2 Contents of the Analysis

In this document, we examine (1) alternative standards for disposal of uranium mill tailings, and (2) alternative standards for control of environmental releases from tailings during the operational phase of uranium mills. Both radioactive and nonradioactive releases are considered. Potential effects of tailings on health are estimated, along with the effectiveness and costs of different control approaches.

In Chapter 2 we briefly describe the uranium industry and summarize projections of uranium production to the year 2000. Chapter 3 contains a description of the uranium tailings themselves, with emphasis on their hazardous components and releases of contaminants to the environment. A model site and tailings pile is described in Chapter 4 for use in carrying out the analysis of benefits and costs of control. In Chapter 5, pathways through which radioactive and hazardous materials may cause exposure to man are examined. Based on the information in Chapters 4 and 5, potential health effects are estimated on local, regional, and national populations in Chapter 6. Chapter 7 contains a review of emission control measures for the operating period of the mill and estimates of the effectiveness and costs of these systems.

In Chapter 8 we examine the efficacy and longevity of the principal methods for disposal of tailings. Chapter 9 contains cost estimates for representative disposal methods for existing and future tailings at model sites. In Chapter 10 we analyze costs and benefits for tailings disposal standards options.

REFERENCES

DOE82 Department of Energy, "Commingled Uranium Tailings Study," DOE/DP-0011, June 1982.

Chapter 2: THE URANIUM MILLING INDUSTRY[1]

2.1 History of the Uranium Milling Industry

The uranium milling industry has undergone considerable change in the last 35 years, as uranium developed from a commodity of minor commercial use to one vital for nuclear weapons and for producing electrical energy. To meet military needs in the early 1940's, uranium ore was obtained from the rich pitchblendes (greater than 10 percent U_3O_8 equivalent) of the Belgian Congo and the Great Bear Lake deposits in Canada, supplemented by production from a few small mines in the Colorado Plateau area. These high-grade ores and concentrates were refined by an ether extraction technique adapted from analytical chemistry procedures. The processes used for low-grade ores were relatively crude and reflected little change from methods used at the turn of the century. Milling costs were high and uranium recovery was relatively inefficient.

After the Atomic Energy Act was passed in 1946, strong emphasis was placed on the discovery and development of new sources of uranium and on development of improved processing techniques. The Atomic Energy Commission (AEC) purchased 3×10^5 MT[2] of U_3O_8 between 1948 and 1970, with approximately 55 percent from domestic sources. Table 2-1 illustrates the size of the industry from 1948 to the present. During the peak production years of 1960 to 1962, there were up to 26 operating mills (excluding plants producing byproduct uranium from phosphates) with an annual production rate exceeding 1.5×10^4 MT of U_3O_8 from 7×10^6 MT of ore (average grade of 0.21 percent).

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(1) Much of the information in this chapter is based on the Nuclear Regulatory Commission's "Final Generic Environmental Impact Statement on Uranium Milling," NRC80, Chapters 2 and 3 and Appendix B. Material from other sources is separately referenced.

(2) Metric ton (MT) or 1000 kg, equivalent to 2200 pounds or 1.1 short tons (ST).

Table 2-1. Uranium Production[a]

Year	U_3O_8 (1000 MT)	Year	U_3O_8 (1000 MT)
1948	0.1	1965	9.5
1949	0.2	1966	9.6
1950	0.4	1967	10.2
1951	0.7	1968	11.2
1952	0.8	1969	10.5
1953	1.1	1970	11.7
1954	1.5	1971	11.1
1955	2.5	1972	11.7
1956	5.4	1973	12.0
1957	7.7	1974	10.5
1958	11.3	1975	10.5
1959	14.7	1976	11.6
1960	16.0	1977	13.6
1961	15.7	1978	16.8
1962	15.4	1979	17.0
1963	12.9	1980	19.8
1964	10.7	1981	17.5

[a] Adapted from DOE82. Includes U_3O_8 production obtained by mine water, heap-leaching, solution mining, or as a by-product of another activity.

Reduced military requirements and the slow development of commercial nulcear power resulted in fewer operating mills and lower uranium production in the period from 1963 to 1970. About 3.4×10^5 MT of U_3O_8 had been produced by the end of 1981, resulting in about 1.8×10^8 MT of tailings. Approximately 15 percent of the tailings are at 23 inactive mill sites covered under Title I of the Act, and the balance (85 percent or about 1.5×10^8 MT) is located at currently active mill sites considered by this analysis.

Mill capacities in 1978 ranged from 360 to 6300 MT of ore per day, with an average capacity of 1800 MT per day. In early 1978, 19 mills were operating; this increased to 21 in early 1980. At the end of 1982, there were 14 mills in operation.

2.2 Conventional Milling Processes

In the uranium milling process, uranium is extracted from the crude ore and concentrated into an intermediate semirefined product called "yellowcake." The remainder of the material, essentially the total mass for low-grade ores, is disposed of in mill tailings piles. Most of the radioactivity associated with the ore goes to the tailings pile. This radioactivity consists primarily of radium and its decay products, which are not removed with the uranium during milling.

Historically, about 90 percent or more of yellowcake has been produced by conventional mills. In 1980 about 15 percent of yellowcake was produced from solution mining, mine water, copper dump-leach liquor, or wet process phosphoric acid effluents.

There are two basic conventional processes for removing uranium from ore: the acid-leach process and the alkaline-leach process. About 80 percent of the current milling capacity uses a sulfuric acid leach process. Since it is not economical to leach those ores having a high alkaline content with acid, these ores are leached with an alkaline solution. Several mills include circuits for both processes. Primary emphasis is placed on the acid-leach process in this analysis. Comments on the alkaline process are limited to differences between the processes that are pertinent to their environmental releases.

Figure 2-1 is a flow diagram of the process at a conventional mill leading up to the generation of waste tailings solids and liquids. In a conventional mill, the first step is grinding the ore to a size suitable for leaching out the uranium. Ore characteristics and the leaching process dictate the degree to which ore must be ground. For the acid leaching of sandstone ores, the ore is ground to the natural grain size.

Alkaline leaching requires much finer grinding. The ore is conveyed from the crushing circuit to the grinding circuit by belt feeders. Samples are taken at points between the crushing and grinding circuit for routine laboratory analysis. Rod and ball mills are usually used to grind the ore to approximately 28 mesh (600 microns) for the acid-leach process or to 200 mesh (74 microns) for the alkaline-leach process. The ores are wet ground (water added) with the aid of classifiers, thickeners, cyclones, or screens that size the ore and return coarser particles for further grinding, resulting in a pulp density of 50 to 65 percent solids. Water consumption is reduced by recirculating mill solutions (e.g., by recycling the clarified effluent from the grinding circuit thickener.) Wet milling can be used in place of both the crushing and fine grinding. This process uses a rotating steel cylinder. The tumbling action of the lifters, large pieces of ore, and a small charge of 8- to 10-centimeter steel balls are used to break down the ore.

After grinding, the ore is leached to remove uranium. In 1976, the acid-leach process was used by 82 percent of the industry. Acid leaching is preferred for ores with 12 percent or less limestone. Those with more than 12 percent limestone require excessive quantities of acid and, for economic reasons, are best extracted by alkaline leaching. The sulphuric-acid leaching process is compatible with several concentration and purification processes, including ion exchange, solvent extraction, or a combination of both processes. The

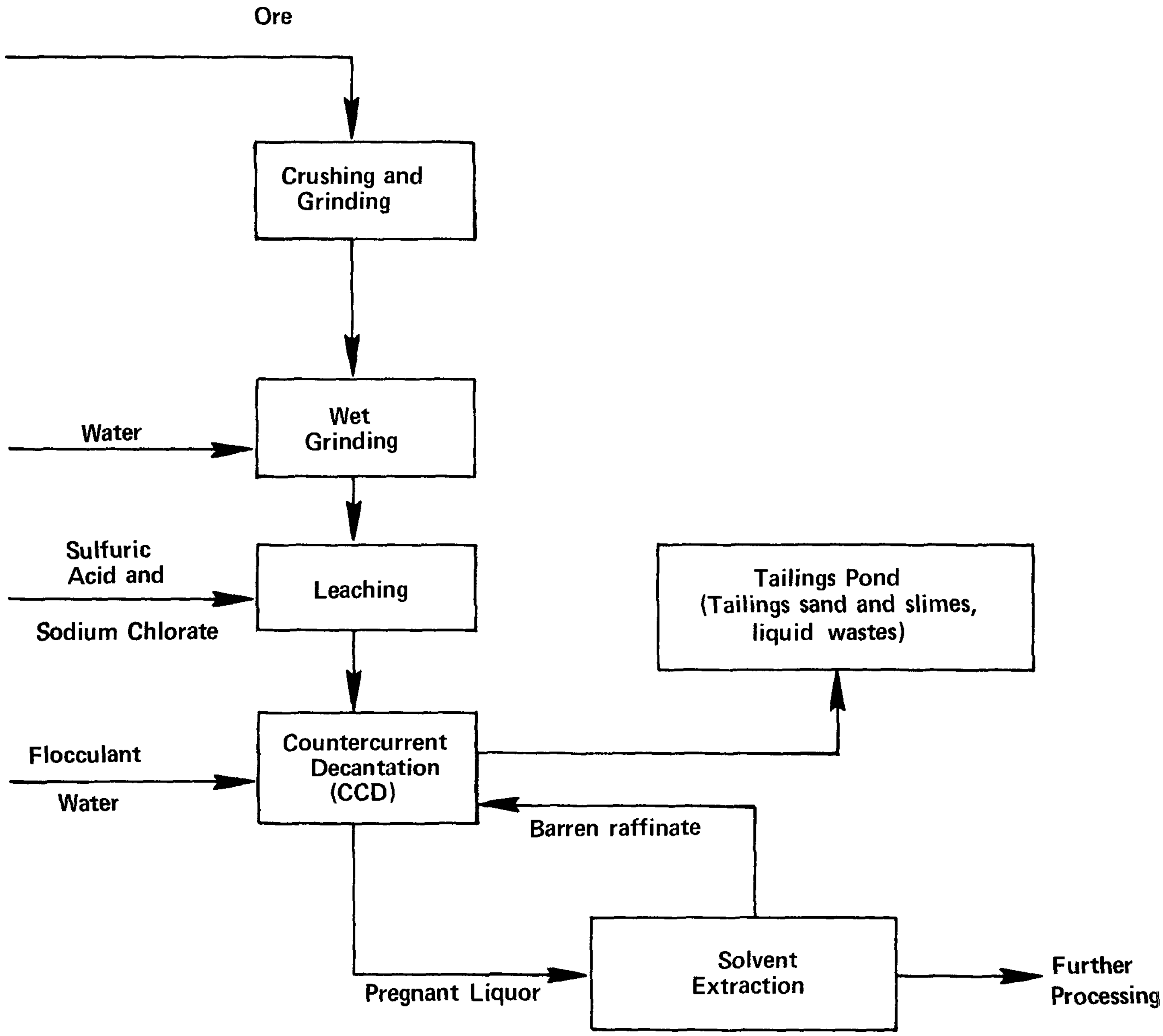

Figure 2-1. Flow Diagram of the Generation of Uranium Tailings Solids and Liquids from the Acid-Leach Process.

slurry from the grinding operation (50 to 65 percent solids) is discharged into the leaching circuit, which consists of several tanks in series. Sulfuric acid is continuously added to maintain the pH between 0.5 and 2.0. For U.S. ores treated exclusively for uranium extraction, acid consumption ranges from 20 to 60 kilograms of sulfuric acid per MT (40 to 120 lbs/tons) of ore.

An oxidant, either $NaClO_3$ or MnO_2, is also continuously added with the sulfuric acid to oxidize tetravalent uranium in the ore to hexavalent uranium, which is more soluble. Iron must be present in the solution for $NaClO_3$ or MnO_2 to be an effective oxidant for tetravalent uranium. Either oxidant acts to oxidize ferrous iron to the ferric state, and the ferric iron in turn oxidizes the uranium. Ore leaching proceeds at atmospheric pressure and a little above room temperature. Most of the uranium in the ore is dissolved, as well as some other materials, such as some uranium daughter products, iron, and aluminum. The residence time in the leaching tank is about 7 hours.

After ore leaching is completed, the "pregnant" leach liquor containing the dissolved uranium is removed from the tailings solids. This is carried out in a countercurrent decantation (CCD) circuit. In this operation, the slurry is first sent to hydrocyclones (liquid cyclone separators) that separate the coarse sand fraction as an underflow, and the sand fraction is subsequently washed in a series of classifiers. The overflows from the classifier and the hydrocyclone are combined, and the slimes are washed. Flocculants are added to promote settling of the suspended solids. The solids are washed with fresh water and recycled (barren) raffinate from the solvent extraction circuit. After thorough washing, the sands and slimes are pumped as a slurry to the tailings pond. After solid-liquid separation in the CCD circuit, the leach solution is sent to the solvent extraction and further processing.

The acid-leach and alkaline-leach processes have considerable chemical differences, and the ore is milled to a smaller size for carbonate leaching. However, this does not appear to cause any significant differences in environmental releases. A larger fraction of the thorium-230 is solubilized in the acid-leach process than in the carbonate-leach process, but the thorium is precipitated in the tailings pond when the acidity is reduced. Thus, except in the early stages of liquid discharges before the solution is neutralized, this difference is negligible.

2.3 Waste Management at Uranium Mills

During the early history of uranium milling, tailings liquids were discharged to surface waters. As late as 1975, Sears (Se75) noted that two mills were discharging liquid effluents to surface waters. In 1981, only the Uravan, Colorado, mill was still discharging treated liquid effluents directly to surface waters.

The alternative to discharging liquid effluent is the impoundment of both solids and liquids in a tailings pond. Initially, tailings ponds were located near the mill based on economics and accessibility. The pond areas were formed from dikes built with tailings sands or from soil and rock from the pond area. As the pond was filled, the dikes were raised with mill tailings sands, separated from the slurried waste with cyclone separators. This design was used for most of the inactive tailings piles (EPA80) and many of the older active piles. Current NRC regulatory practice discourages the use of tailings for dike materials (NRC80a, NRC77). However, this practice still continues for many of the existing active sites (e.g., Homestake and Kerr-McGee near Grants, New Mexico). Although the ponds were generally designed as evaporation ponds, there are instances where seepage has equaled or exceeded the evaporation rate (Ka75, EPA75). There are still seepage releases to groundwater and probably to surface water at several mills (See Chapter 3.)

It was not until 1976 that the NRC made a concerted effort to control uranium mill tailings. Performance objectives were issued in 1977 and again in revised form in Regulatory Guide 3.11 (NRC77). These objectives provide location criteria, require the elimination of wind-blown tailings, and require reducing post-reclamation gamma exposure to offsite areas to essentially background levels. Furthermore, this guidance discourages the use of upstream dam construction techniques (the dam is raised in stages on the tailings material) and specifies minimizing seepage from the tailings ponds by the use of clay or artificial liners. The guidance requires designs that improve the tailings stability and reduce the seepage from tailings disposal systems.

EPA collected information on active mills and waste disposal practices in 1978 (Ja79). Some of the notable conclusions are:

- Tailings and effluent disposal methods practiced in the United States generally consist of impoundment of mill wastes in unlined ponds. This disposal method is not state-of-the-art. It is usually inadequate, since up to 85 percent of the liquid effluent impounded may be lost by seepage and, subsequently, pollute groundwater.

- Treatment of mill effluents to reduce pollutant levels and/or to recover uranium or uranium byproducts is seldom practiced.

- Treatment and discharge as a method of effluent disposal is practiced at only one of the currently operating, conventional uranium mills in the United States.

- All effluent streams from the mills sampled in this study, were they to be discharged, would require treatment to comply with effluent limitation guidelines for point-source discharges. Currently, none of the streams sampled is being discharged.

- Unlined ponds, properly located, may be environmentally acceptable as a means of mill waste disposal under some local soil and hydrogeological conditions, because some native soils can mitigate the adverse effects of seepage, by exhibiting low permeabilities, thereby reducing seepage rates, and/or possessing characteristics that favor the uptake and fixation of seepage-borne contaminants.

- Total dependence on native soils above the water table for purification of seepage from unlined ponds is not technically sound, since uptake capacity is both unpredictable and time dependent, and anions such as sulfate, chloride, and nitrate are not removed.

- Lined ponds represent a recent advance in state-of-the-art technology for containment of millwastes, since they afford a greater degree of seepage prevention than unlined ponds and ensure protection of groundwater.

- Clay or treated clay liners are preferred for lining ponds containing mill tailings wastes.

After a mill ceases operations, the tailings impoundment will slowly dry up over a few years. In such a condition, tailings are continually vulnerable to spreading by wind and water erosion or by such uses as for fill around buildings. Some of these dry tailings piles have been the subject of a variety of stabilization schemes involving earth cover placement and revegetation. Stabilization attempts to date have not been generally successful, and none has been designed for the long term.

2.4 Uranium Recovery by Heap-Leaching

Most mills are not designed to process uranium ores of less than 0.04 percent U_3O_8. However, uranium is often extracted from such ores by a heap-leach process. Heap-leaching is also used when the ore body is small or situated far from the milling facilities. Shipping a high-grade solution or a crude bulk precipitate (the product of heap-leaching) to the mill is less expensive than hauling low-grade ore to the mill.

Uranium recovery by heap-leaching has been used for low-grade (0.01-0.03 percent U_3O_8) sandstone uranium ores. The ore to be heap leached is typically placed upon a gently sloped impermeable pad and saturated from above with a leaching solution. Pad impermeability is generally achieved by laying down a plastic sheeting, but other materials such as asphalt and concrete have been used on a pilot scale. Just above the pad, a network of pipes and drain tiles is put in place to collect the leachate that percolates to the bottom of the ore piles. The percolated leachate is collected and recirculated until the uranium concentration in the solution reaches 0.06 to 0.1 grams of U_3O_8/per liter. At this point the leachate is sent to resin ion-exchange columns for extraction of the uranium.

If mine water is used, uranium already in the water, as well as that extracted from the heap leach, is recovered. The most commonly used leach reagents are sulfuric acid and ammonium carbonate. In an efficient operation about 80 percent of the uranium will be extracted from the ore. Heap-leach piles are commonly about 100 meters long, 6 to 8 meters high, with beams separating the piles in segments about 20 meters wide. After completion of operations, the leached ore may be limed, graded, and stabilized by covering and revegetating the surface. A state-of-the-art heap-leaching operation is described in detail in a recent document (NRC78b).

2.5 Currently Licensed Uranium Mills

There were 27 licensed uranium mills, of which 14 were operating, in the United States as of December 31, 1982. These mills are listed in Table 2-2. Edgemont, South Dakota, which is not an operating mill, has been included since it is licensed and has been excluded from the designated inactive sites (EPA80). The Tennessee Valley Authority (TVA) owns the site and had planned to reactivate the mill. However, TVA is now planning to clean up the site and move the milling operation. The Ray Point, Texas, site has also been shut down for several years. The Bokum mill in New Mexico has been constructed and licensed, but it has never started operation. The data in Table 3-1 summarizes the operational features of the mills with significant tailings (NRC80a and Ja79, supplemented with private communications).

2.6 Future Uranium Supply and Demand

Uranium is required for both the nuclear power industry and defense activities. Projections of uranium needs for nuclear power can be reasonably accurate for the next 20 years, since 10 to 15 years is required from the decision to build a reactor until it is producing power. Power reactors ordered now will not be producing power until the 1990's. Uranium needs for defense purposes are much more difficult to project since they are greatly influenced by political considerations. However, it is likely that nuclear power needs will greatly

Table 2-2. Currently Licensed U.S. Uranium Mills[a]

Location	Owner
	OPERATING MILLS
Colorado	
Canon City	Cotter Corporation
New Mexico	
Milan	Homestake Mining
Ambrosia Lake	Kerr-McGee Nuclear
Texas	
Panna Maria	Chevron Resources
Utah	
Blanding	Energy Fuels Nuclear
La Sal	Rio Algom Corporation
Moab	Atlas Minerals
Wyoming	
Gas Hills	Pathfinder Mines
Gas Hills	Union Carbide
Powder River	Rocky Mountain Energy
Powder River	Exxon Minerals
Red Desert	Minerals Exploration Co.
Shirley Basin	Pathfinder Mines
Shirley Basin	Petrotomics
	SHUT-DOWN MILLS
Colorado	
Uravan	Union Carbide Corporation
New Mexico	
Bluewater	Anaconda Minerals Company
Seboyeta	Sohio-Reserve
Church Rock	United Nuclear
Marquez	Bokum Resources
South Dakota	
Edgemont	Tennessee Valley Authority
Texas	
Falls City	Conoco-Pioneer Nuclear
Ray Point	Exxon (Susquehanna-Western)

(continued)

See *footnote at end of table.*

Table 2-2. Currently Licensed U.S. Uranium Mills[a] (Continued)

Location	Owner
	SHUT-DOWN MILLS (Continued)
Utah	
Hanksville	Plateau Resources
Washington	
Ford	Dawn Mining Company
Wellpinit	Western Nuclear
Wyoming	
Jeffrey City	Western Nuclear, Inc.
Gas Hills	Federal-American Partners

[a] As of September 1982.

outstrip defense needs during the next 20 years. Thus, only demand for the nuclear power industry is projected in this analysis.

Projections of uranium demand are made for two cases. A "high" case is based on the mid-range nuclear generating capacity scenario of the U.S. Department of Energy (DOE) (DOE81). A "low" case is based on the DOE installed reactor capacity projection identified as the firm nuclear base scenario (DOE81). These estimates are presented in Table 2-3.

Yellowcake requirements are calculated by using the NRC assumptions given in their generic EIS for uranium milling (NRC80a). A conversion factor of 185 MT U_3O_8 in yellowcake per GWe-year is used. This assumes a 3 percent fuel enrichment, 0.20 percent tails assay, and an effective average nuclear generating plant capacity factor of 75 percent.

Conventional mills (as described in Section 2.2) are not assumed to satisfy the total demand for uranium. About 80 percent of the present uranium demand is supplied by conventional milling. This fraction is expected to vary during the next 20 years. The fraction of uranium assumed to be supplied by conventional milling is listed in Table 2-3 (NRC80a). The demand for conventional milling production, estimated by multiplying the total uranium demand by this fraction, is presented in Table 2-3 for the 20-year period 1980 to 2000.

Another important factor in projecting demand for uranium is the inventory held by utilities, reactor manufacturers, and fuel fabricators. A normal inventory level is about a 1-year level of consumption. Currently an abnormally large inventory of uranium is

Table 2-3. Projection of Industry Demand and Production for Uranium Yellowcake 1983-2000

Year	Industry Demand 10^3 MT U_3O_8	Conventional Production 10^3 MT U_3O_8
1983	12.7	7.5
1985	17.1	7.3
1990	18.1	9.5
1995	20.4	10.5
2000	26.9	11.3

Source: Appendix B, Regulatory Impact Analysis of Final Active Mill Tailings Standard, EPA 520/1-83-010, 1983.

being held. It is assumed that this inventory will be reduced to more normal levels over a 6-year period. This inventory reduction will result in less uranium production.

The total quantities of tailings produced by conventional milling from 1983 to 2000 is projected to be about 175 million tons. (The conversion factor used is 1,075 MT of tailings per MT of U_3O_8 as yellowcake (NRC80a) and assumes 0.1 percent uranium in ore and a 93 percent recovery rate during milling.

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Chapter 3: ENVIRONMENTAL RELEASES FROM URANIUM MILLING WASTES

In this chapter, we discuss the composition of uranium mill tailings solids (sands and slimes), tailings pond liquids, and heap-leaching wastes. We also discuss the extent to which radioactive elements, toxic substances, and other contaminants from these wastes have been released to the environment through human activity and/or by natural causes. We defer to Chapter 4 the development of projections of releases from a model site.

3.1 Composition of Tailings Solids and Pond Liquids

Uranium mill tailings solids and pond liquids contain essentially all the radioactive and toxic elements of the original uranium ore, except for about 90 percent of the uranium which is extracted during the milling process. The tailings also contain a variety of chemicals used as part of the extraction process described in the previous chapter.

3.1.1 Radioactivity in Tailings

Most of the uranium recovered from ore is uranium-238, a radioactive isotope that decays, over billions of years, to become lead-206, a stable (i.e., nonradioactive) element. The lengthy decay process includes a number of intermediate stages (called decay products). These, too, are radioactive. Figure 3-1 traces the steps in this decay process. Since the ore was formed millions of years ago, uranium has continued to decay and an inventory of all of these decay products has built up. There are also radioactive materials from two other decay processes in uranium ore, the uranium-235 series and the thorium-232 series, but these are present in much smaller amounts, and we have concluded that it is not necessary to include them in our analysis (see Section 4.1).

When ore is processed most of the uranium is removed, and most of the subsequent decay products become part of the tailings. As a result, thorium-230 is the radionuclide with the longest half-life[1]

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[1] A half-life is the time it takes for a given quantity of a radioactive isotope to decay to half of that quantity. Figure 3-1 shows the half-lives of the members of the uranium-238 decay series.

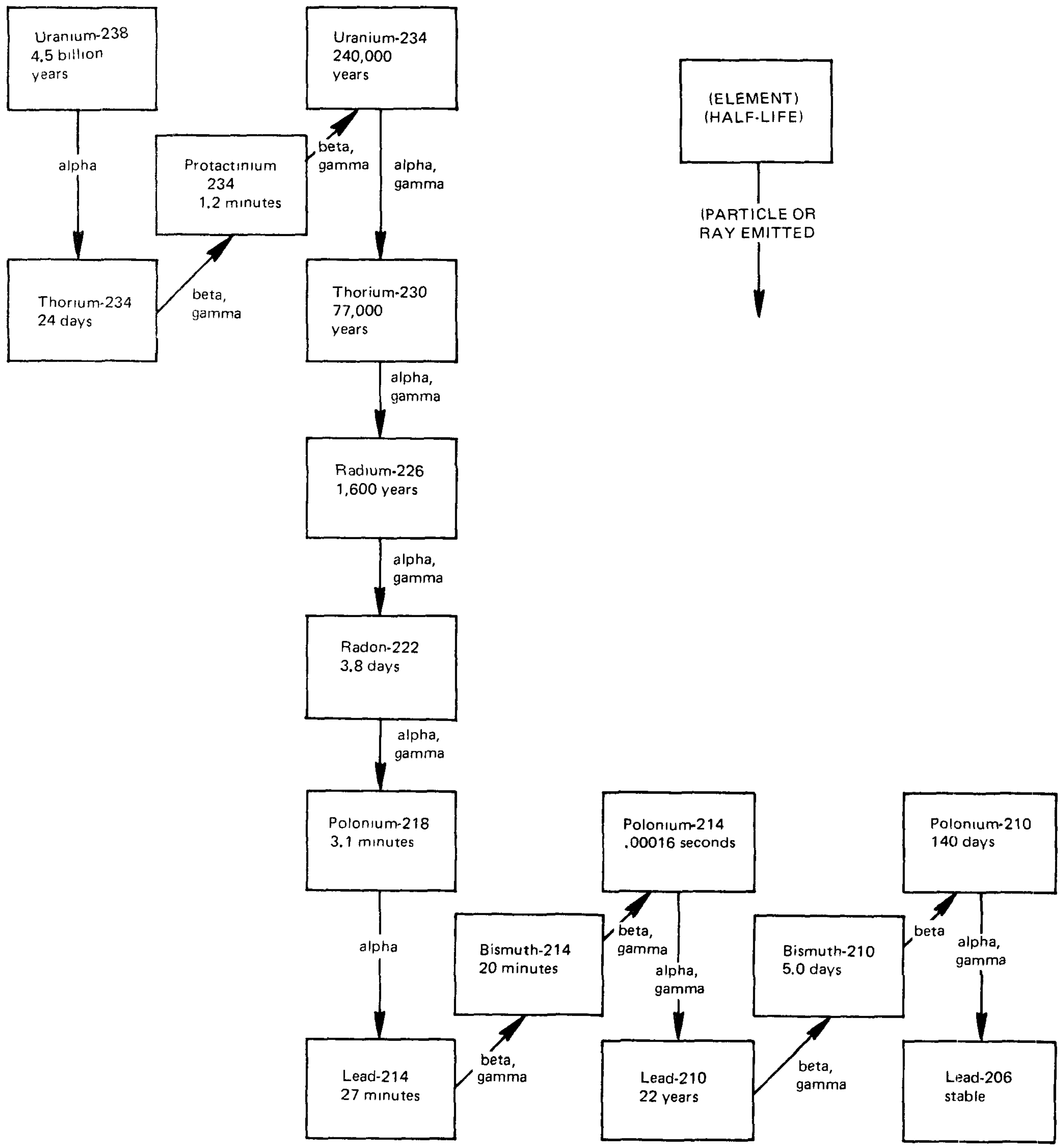

Figure 3-1. The Uranium-238 Decay Series.

of significance in tailings. Thorium decays to produce radium-226. Radium decays in turn to produce radon-222, a radioactive gas. Because radon gas is chemically inert, some of it escapes from the tailings particles in which it is produced, diffuses to the pile surface, and is carried away into the atmosphere. Airborne radon produces a series of short half-life decay products that are hazardous if inhaled. If the radon does not escape from the tailings, its decay products remain there, and the gamma radiation they produce may increase the hazard to people near tailings.

Since thorium-230 has a much longer half-life than its two immediate decay products, radium and radon, the amounts of radioactivity from radium and radon remain the same as that from thorium. The amount of radon released from a tailings pile, therefore, remains effectively constant on a year-to-year basis for many thousands of years, decreasing only as the thorium, with its 77,000-year half-life, decreases.

In Figure 3-2 we show how the yearly production rate of radon in a tailings pile will decrease with time. It falls to 10 percent of its initial value in about 265,000 years. This time scale illustrates the long-term nature of most of the significant radiological hazards associated with uranium mill tailings.

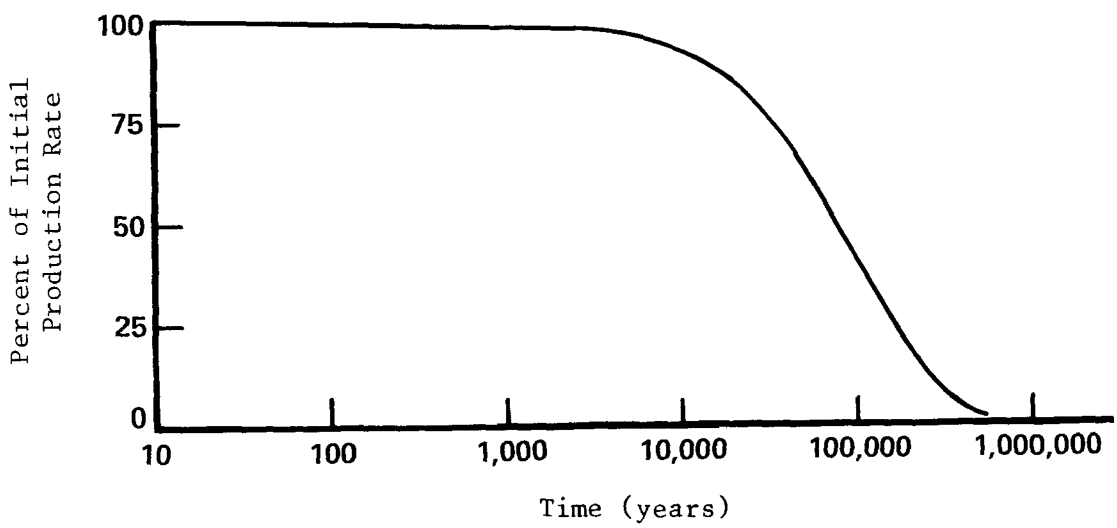

Figure 3-2. Radon Production in a Tailings Pile.

When discharged from the mill, tailings have both solid and liquid components. The solid portion of tailings is composed of particles ranging in size from coarse sands to fine slimes. In both the acid process and the alkaline process, the residual uranium and radium content of slimes is about twice that of sands. In the acid-leach process, about 95 percent of the thorium in the original ore remains with the solid tailings, while the balance is dissolved in the tailings liquids. Less than one percent of the radium is dissolved in the liquids. In the alkaline process, less than one percent of both the thorium and radium is dissolved in the tailings liquids.

In Table 3-1 we show, for licensed uranium mills (as of January 1980) with tailings piles, the quantity of tailings, area of the pile, average ore grade, and estimated average radium content in the solids. Also included are the estimated radon emissions from each pile and other factors relevant to emissions from tailings piles. Tailings at most future uranium mills are expected to fall within the range of values shown in Table 3-1. The ore grade at the different mills typically varies from 0.15 percent to 0.3 percent uranium, and the radium concentration (and presumably other radionuclides in the uranium-238 decay series) varies from 200 pCi/g to 900 pCi/g. This should be compared with the background radium concentration in average soil from 0.2 pCi/g to 3 pCi/g.

In Table 3-2 we have compiled selected available data on radioactivity and toxic element levels in tailings pond liquids. Many levels are more than two orders of magnitude above EPA drinking water standards (these are listed in Table 3-4), but large variations occur among the mills. The wide variation is caused by the characteristics of uranium ore and the process (i.e., acid- versus alkaline-leach). Again, the values in Table 3-2 are expected to characterize liquid wastes at future uranium mills.

3.1.2 Toxic Elements and Other Chemicals in Tailings

A number of toxic materials from ore or from chemicals used in processing have been found in both liquid and solid uranium mill wastes (Se75, FB76-78). The contaminants present depend on the ore source and the type of processing. In Table 3-3, we indicate the average concentration of 15 elements commonly found in the solids of 19 inactive tailings piles (Ma81a). The concentrations of these elements show wide variations among the piles, as well as wide variations above and below values for "typical soil." This data is believed to be representative of tailings at active mills as well as tailings to be generated at future mills. In Table 3-2, we showed the concentration of toxic substances and other chemicals in tailings pond liquids at existing uranium mills.

3.2 Routine Environmental Releases from Tailings

Releases from tailings wastes may occur to land, groundwater, surface water, and air. Land is contaminated chiefly by tailings transported by wind and water erosion; groundwater by the leaching of radionuclides, toxic elements, and other chemicals in solid tailings, or from seepage of tailings pond liquids; surface water from inputs from contaminated groundwater and also from runoff over contaminated areas; air from emissions of radon and fine wind-suspended tailings particles.

3.2.1 Air Contamination

Radon Emissions

In the uranium-238 decay series, radon is unique because it is a chemically inert gas and therefore freely migrates by diffusion from the tailings into ambient air. In Table 3-1 we show calculated radon emission rates(1) from the 27 active sites. These calculated rates range from 200 pCi/m^2s to 900 pCi/m^2s. Radon emission rates from uncontaminated soils are much lower, averaging close to 1 pCi/m2s, with a range of perhaps as much as a factor of 2 or 3 higher and lower. To estimate the annual radon release rates reported in Table 3-1, we assumed that the radon emission rate per unit area is 1.0 pCi/m^2s per pCi/g radium; this value was also used by NRC (NRC80, Appendix G). It is consistent with the assumption that the piles are dry, homogeneous, uncovered, and at least 3 meters deep. By way of comparison, Haywood (Ha77) has calculated values of 0.35, 0.65, and 1.2 pCi/m^2s radon per pCi/g radium for wet, moist, and dry tailings, respectively.

The radon release rates listed in Table 3-1 are likely to be greater than the actual release rates for active piles because these piles still contain significant quantities of entrapped water. Many active piles also contain large areas of standing water on their surface. Both conditions significantly inhibit the release of radon to air. In assessing the health impact from active tailings piles, we have considered the effect of the pond area in reducing radon emissions. However, with regard to assessing the impact of tailings piles when the mill is not active, we consider it more reasonable to assume that, over the time period of interest for the hazards associated with radon release (hundreds of thousands of years), the piles would be dry most of the time.

There have been few systematic ambient air measurements of radon emissions from tailings piles. However, studies to date (Mo82, PHS69) demonstrate good agreement between field measurements and the

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(1)The term emission rate is used rather than fluence rate or flux density, which, although more precise, are terms generally less familiar.

Table 3-1. Description of Mill Tailings Piles at Licensed Mills[a]

Location/ Company	Maximum Capacity (MT/day)	Ore Grade: Percent of U_3O_8	Tailings: Amount (10^6MT)	Tailings: Impoundment area (acres)	Radium Concentration[b,c] (pCi/g)	Estimated Radon Release[d] (kCi/y)	Type of Impoundment	Precipitation (in/y)	Evaporation (in/y)
COLORADO									
Canon City (Cotter)	1100	-	1.7	165	780	20	Unlined & lined	8	56
Uravan (Union Carbide)	1200	0.15	9.0	85	480	4.8	Pond unlined, collect seepage recycle or treat	11	47
NEW MEXICO									
Seboyeta (Sohio/Reserve Oil & Minerals	1500	-	1.9	140	500	11	Lined with natural clay	8	56
Church Rock (United Nuclear)	3600	0.15-0.2	3.2	200	290	7.4	Unlined, dam failed	14	50
Bluewater (Anaconda)	5400	0.34	20.7	300	620	21	Unlined	8	56
Ambrosia Lake (Kerr-McGee)	6300	-	27.6	328	620	20	Some ponds lined with PVC	8	56
Milan (Homestake Mining Co.)	3100	0.2	19.2	210	385	9.7	2-section pond, unlined	-	-
SOUTH DAKOTA									
Edgemont (TVA)	500	0.2	2.1	123	560	8.9	11 ponds, half covered with soil	14	37
TEXAS									
Falls City (CONOCO/Pioneer Nuclear)	3100	-	8.0	240	-	-	Natural clay	27	55
Panna Maria (Chevron Resources)	2300	-	3.3	160	-	-	Natural clay	-	-
Ray Point (Exxon)	800	0.18	0.4	47	520	3.1	Unlined	-	-
UTAH									
Blanding (Energy Fuels Nuclear)	1800	0.125	1.1	116	350	5.2	Synthetic liner	8	64
La Sal (Rio Algom)	700	0.2	2.3	100	560	3.2	Unlined, dug into natural clay	12	62
Moab (Atlas)	1300	-	9.3	128	540	7.8	Unlined	8	64

See footnotes at end of table.

Table 3-1. Description of Mill Tailings Piles at Licensed Mills[a] (Continued)

Location/ Company	Maximum Capacity (MT/day)	Ore Grade: Percent of U_3O_8	Tailings: Amount (10^6MT)	Tailings: Impoundment area (acres)	Radium Concentration[b,c] (pCi/g)	Estimated Radon Release[d] (kCi/y)	Type of Impoundment	Precipitation (in/y)	Evaporation (in/y)
WASHINGTON									
Ford (Dawn Mining)	400	0.3	2.9	133	850	11	Unlined and lined	12-18	50
Wellpinit (Western Nuclear)	1800	0.05-0.09	2.3	89	200	1.1	36 mil Hypalon liner	10-15	50
WYOMING									
Gas Hills (FAP)	900	-	5.4	117	420	5.6	2 ponds, unlined	10	42
Gas Hills (Pathfinder)	2300	0.15-0.26	8.6	248	420	4.0	Unlined	9	45
Jeffrey City (Western Nuclear)	1500		7.0	167	430	4.8	Unlined	10	36
Gas Hills (Union Carbide)	1300	0.15-0.18	6.5	146	310	5.9	Unlined	10	42
Powder River Exxon	2900	-	6.5	200	450	12	Unlined	-	-
Powder River (Rocky Mt. Energy)	1800	0.15	4.5	120	420	8	Unlined	12	40
Shirley Basin (Pathfinder)	1600	-	5.3	400	540	10	Unlined	-	-
Shirley Basin (Petrotomics)	1400	0.1	5.0	140	570	12	Bentonite clay,	12	43
Red Desert (Minerals Exploration Co.)	2700	0.1	10.9	174	280	6.2	30 mil polyvinylchloride (bottom liner) 30 mil Hypalon (sides liner)	6-8	40-70
Total		-	174.7	4,276	-	202.7[e]	-	-	-

(a) As of January 1980, based upon "Environmental Study on Uranium Mills," TRW Inc., for U.S. Environmental Protection Agency, Contract #68-03-2560; "Final Generic Environmental Impact Statement on Uranium Milling," NRC, NUREG-0706, Appendix T; and relevant EIS's.

(b) Some values are not consistent with the reported ore grades if radium and uranium are assumed to be in equilibrium in the ore.

(c) Also approximately equal to the estimated radon flux density in pCi/m^2s.

(d) This is a maximum estimate obtained by assuming that the emanation from the tailings pond area is 1 pCi/m^2s per pCi/g of radium -226. This relationship is well established for dry tailings (*NRC GEIS, Appendix G*), but the emanation from thoroughly wet tailings is insignificant. Therefore, the estimated emanation of active ponds should be reduced in proportion to the wetted area of the tailings.

(e) Does not include releases from piles where estimate was not obtained.

Table 3-2. Dissolved Substances in Tailings Pond Liquids at Selected Sites

Substance/ Units	Gas Hills #4[a] Wyoming (NRC77)	Moab[b] Utah (NRC79)	Gas Hills[c] Wyoming (NRC81)	Split Rock[d] Wyoming (NRC80)	Edgemont[e] Pond S .D. (FB78)	Bluewater[f] N. M. (NM80)	Grants[g] N. M. (NM80)	Seyboyeta[h] N. M. (NM80)	Church[i] Rock N. M (NM80)	Grants[j] N. M. (NM80)
Radionuclides (pCi/1)										
Uranium-238	16,000	600	6,200	3,600	18,500	13,180	4,900	3,170	3,450	11,200
Thorium-230	170,000	50	-	250,000	26,000	-	-	-	-	-
Radium-226	420	-	-	35,000	1.7	620	106	110	58	68
Toxic Metals (mg/1)										
Arsenic (As)	42	7	12.1	-	2.75	2.25	4.23	1.27	1.55	5.02
Lead (Pb)	-	-	1.76	0.51	0.153	.75	2.61	2.07	0.71	0.006
Molybdenum (Mo)	-	-	-	0.41	0.23	0.6	23.3	.44	1.89	93.7
Selenium (Se)	-	-	-	0.01	0.456	2.35	1.74	1.53	0.27	36.7
Other Substances (mg/1)										
Iron (Fe)	--	-	145	5,450	-	-	-	-	-	
Manganese (Mn)	350	-	-	-	222.8		-	-	-	-
Sulfate (SO_4)	17,000	100,000	18,000	11,590	40,000	21700	27,000	31,600	15,100	7,430
Chlorine (Cl)	1100	300	-	116	200	2,240	2,225	520	309	1,075
Total Dissolved Substances (TDS)	-	150,000	-	12,700	65,000	27,560	45,320	39,300	39,000	21,050
Acidity Index (pH)	acid	1.7	acid	3.5	2.01	1.51	1.33	0.97	1.33	10.2

(a)Owner: Utah International.
(b)Owner: Atlas.
(c)Owner: Federal American Partners.
(d)Owner: Western Nuclear.
(e)Owner: TVA.
(f)Owner: Anaconda.
(g)Owner: Kerr-McGee.
(h)Owner: Sohio.
(i)Owner: United Nuclear.
(j)Owner: United Nuclear/Homestake Partners.

prediction of mathematical models. The data in these studies support the following conclusions:

- Radon levels immediately above tailings piles typically are above 10 pCi/l.
- At 0.5 km from some piles, radon concentration may exceed the average background by 1 pCi/l.
- Significant increases above background have been measured at distances up to 1.5 km downwind of tailings piles.

Emission of Tailings Particles

Tailings piles also release fine tailings particles to the air in moderate-to-high winds. Schwendiman, et al., have studied particle release rates from an active pile (Sc80). Their data show that for wind speeds from 7 mph to 25 mph, the airborne mass loading downwind from the pile is roughly 5×10^{-4} g/m^3. This is an order of magnitude greater than the mass loading measured just upwind of the site.

The airborne concentrations of several radioactive and toxic elements were also measured, confirming that the windblown particles from a tailings pile contain a variety of radionuclides, as well as the toxic elements selenium, lead, arsenic, mercury, and molybdenum. However, the air concentrations of toxic elements observed were well below the 8-hour threshold limit values to which workers can be repeatedly exposed without suffering adverse effects. (These values for occupationally exposed workers were established by the American Conference of Governmental Industrial Hygienists (AC81).) We conclude, therefore, that the primary hazard arises from breathing radionuclides, and their buildup on land surfaces.

3.2.2 Land Contamination

The action of wind and water can erode tailings from unstabilized piles onto nearby land. To determine the extent of this contamination at inactive sites, we conducted gamma radiation surveys at most of the inactive tailings sites in the spring of 1974 (Do75). We used the measured gamma radiation levels to estimate the extent of radium contamination in the surface soil (EPA80). If levels above 5 pCi/g, averaged over the top 15 centimeters, are considered to represent significant contamination, then, typically, windblown tailings have contaminated an area near each pile that is more than three times the area of the pile itself. It is reasonable to assume that, if uncontrolled, contamination at existing uranium mills will be comparable to that at inactive sites within a decade or so after the existing mills become inactive. Little data is available concerning contamination of land with windblown toxic materials. However, because

Table 3-3. Average Concentration of Elements Found in Inactive Uranium Mill Tailings[(a)]
(in ppm)

Tailings Pile	ELEMENT													
	As Arsenic	Ba Barium	Cd Cadmium	Cr Chromium	Cu Copper	Fe Iron	Pb Lead	Hg Mercury	Se Selenium	Ag Silver	U Uranium	V Vanadium	Zn Zinc	Ra-226 Radium ($\times 10^{-6}$)
Arizona														
Monument Valley	1.5	-	-	-	-	-	--	--	0.064	--	60	1850	--	50
Tuba City	82	86	4	6	1160	7230	812	0.001	10	6	370	620	249	920
Colorado														
Durango	0.80	82	0.20	8.8	95	62	62	0.87	1.2	1.2	480	3900	304	700
Grand Junction	14	121	1.6	29	14	1170	50	0.026	3.1	0.72	180	1760	45	780
Gunnison	254	66	0.26	5.2	30	20800	137	--	1	3.8	90	80	120	420
Maybell	1.5	18	0.09	9.3	3.1	2100	13	0.09	13	0.15	120	120	17	274
Naturita	59	172	0.07	3.5	54	16400	48	--	0.47	1.1	500	2890	75	--
New Rifle	4.2	100	1.1	55	8	807	187	0.001	1.9	1.4	240	3990	31	870
Old Rifle	3.7	155	8.7	20	18	8250	38	0.25	2.7	0.46	380	520	359	1000
Slick Rock NC	34	453	0.027	4.9	35	6540	1250	109	0.76	1.7	80	620	21	780
Slick Rock UC	6.6	134	0.074	3.4	17	4080	29	0.074	2.2	0.57	50	1480	21	690
New Mexico														
Ambrosia Lake	2.6	96	3.6	8	58	90	--	0.002	68	0.15	210	1590	47	640
Shiprock	0.004	-	-	-	-	-	--	--	0.18	--	120	330	--	700
Utah														
Green River	1.9	73	0.40	17	102	1210	121	0.001	231	0.070	60	1390	21	810
Mexican Hat	63	12	0.70	1.0	488	3650	40	--	6	1.0	140	1350	57	780
Vitro Uranium[(b)]	210	2130	-	1010	310	31100	3060	--	--	0.022	180	100	340	
Vitro Vanadium[(b)]	244	3860	-	2030	1080	213000	350	--	--	0.066	50	830	350	900
Wyoming														
Spook	87	46	0.37	26	14	15299	2.5	--	262	2.2	130	350	31	340
Riverton	161	64	0.32	23	21	21800	3.2	--	391	2.4	70	240	38	560
"Typical" Soil[(c)]	6	500	0.06	100	20	38000	10	0.03	0.2	0.1	1.0	100	50	1.5

(a)Adapted from G. Markos and K.J. Bush, "Physico-Chemical Processes in Uranium Mill Tailings and Their Relationship to Contamination" (Ma81a)
(b)Two different parts of the Vitro Site, Salt Lake City, Utah.
(c)Bo66.

NC North Continent pile. UC Union Carbide pile.

whole tailings particles are transported, it is likely that the ratio of toxic materials to radioactive materials in contaminated land is in generally the same proportion as the ratio of these materials in the tailings. Surface runoff may also deposit tailings particles and, therefore, toxic materials in the vicinity of the pile. In these cases also, the amount of radioactivity should usually be a reasonably good indicator of the presence of elevated levels of toxic elements because like radioactive elements, they are, for the most part, relatively well fixed in tailings particles.

3.2.3 Water Contamination

Tailings can contaminate both surface and groundwater; we discuss what is known about each at both active and inactive tailings piles. As we shall see, the potential for water contamination at inactive piles is far less than the corresponding potential contamination at active sites.

Groundwater

Most of the potential for groundwater contamination arises from seepage of liquid waste from the tailings pile when the mill is active. Kaufmann, et al. (Ka75), estimated that 30 percent of the process water from two active tailings ponds in New Mexico had seeped into the ground. Purtyman, et al. (Pu77), estimated a 44-percent seepage loss from another pile in New Mexico during its active life. The NRC (NRC80) assumes that a model site will experience a 40-percent water loss by seepage and uses a mathematical model to estimate the movement of the seepage through unsaturated soil, formation of a seepage "bulb" in the saturated soil zone, and the movement of pollutants with groundwater. For its model mill in an arid region, where the evaporation rate far exceeds the precipitation rate, the NRC concluded that about 95 percent of the possible contamination of groundwater would be associated with the active phase of the pile and only 5 percent with with long-term loses from an inactive nonstabilized pile (NRC80). A more detailed description of groundwater contamination can be found in Appendix D.

Case histories showing water contamination problems near selected active uranium mills and mines are given in a recent report (UI80). Contamination that extends up to 8,000 feet from active tailings piles has been found, but this has been confined to shallow alluvial aquifers (UI80). Contamination of deep aquifers near these mills has not been observed. In Table 3-4 we have summarized the data from groundwater monitoring around these active tailings ponds. In general, the data support the following conclusions regarding the shallow aquifers:

- Unless pond water is contained by a natural clay or synthetic liner, contamination of groundwater near the pile may be expected. More than perhaps one-third of all active tailings piles show at least limited contamination of a shallow aquifer.

Table 3-4. Contamination in Shallow Aquifers Compared with Estimated Background Near Active Tailings Ponds[a]

Substance/ Units	EPA Drinking Water Standards[b]	Canon City, Colo.[c]		Ford, Washington[d]		Gas Hills, Wyoming[e]		La Sal, Utah[f]	
		Well (8000 ft)	Back-ground	Spring (4000 ft)	Back-ground	Monitoring Well	Back-ground	Monitoring Well	Back-ground
Radionuclides									
Uranium (Total - mg/L)	-	2.47	0.6	0.06	0.004	19.6	-	73	0.003
Thorium-230 (pCi/L)	-	1.6	-	-	-	110	-	80.1	
Radium-226 (pCi/L)	5.0	0.6	-	-	1.15	51.2	1.7-9.3	13.4	9.0
Toxic Metals (mg/L)									
Arsenic (As)	0.05	-	-	0.001	0.002	0.001	-	0.012	-
Lead (Pb)	0.05	-	-	0.005	0.016	0.3	-	0.001	-
Molybdenum (Mo)	-	16.7	1.1	-	-	-	-	0.04	-
Selenium (Se)	0.01	0.013	0.014	-	0.006	0.26	0.02	0.001	0.001
Other Substances (mg/L)									
Iron (Fe)	0.3	-	-	213	0-1.7	6.1	-	0.21	0.05
Manganese (Mn)	0.05	-	-	2.55	0.059	7	-	0.051	0.018
Sulfate (SO_4)	250	2720	-	5250	7.6	2932	120-271	4660	330
Chloride (Cl)	250	147	-	5.85	3.54	893	4.8-45	960	30
Total Dissolved Substances (TDS)	500	-	-	5836	202	5760	514-632	10,650	720

(a) Adapted from UI80.
(b) EPA primary and secondary drinking water standards.
(c) Process used: Acid and alkaline. Mill owner: Cotter Corporation.
(d) Process used: Acid. Mill owner: Dawn Mining Company.
(e) Process used: Acid. Mill owner: Union Carbide Corporation.
(f) Process used: Alkaline. Mill owner: Rio Algom Corporation.

- Contamination is accompanied by highly elevated levels of total dissolved solids, with sulfate being the chief constituent. Such water is rendered essentially useless for all puposes.

Because of the lack of background data on the aquifers and sites in question, no other general conclusions can be made. It is often difficult to prove that tailings are the cause of an elevated concentration of a substance in groundwater unless the background concentration of the aquifer is well characterized and there are no nearby potential sources of additional contamination. This situation is seldom realized. However, at one mill, heavy molybdenum contamination has been confirmed. Other sites show strong evidence of contamination from selenium and uranium (UI80).

There is evidence that groundwater in shallow aquifers is contaminated near some inactive sites, probably due to seepage of liquids from tailings ponds during and soon after their active use (Dr78). Groundwater contaminant concentrations near the inactive mills have been surveyed (FB76-78). Although it is not possible to positively ascribe the source of this contamination to tailings, some cases of elevated concentrations were found.

In Table 3-5, we summarize the toxic elements found in elevated concentrations in groundwater near inactive tailings piles. Markos has shown that many of the soluble elements in piles tend to precipitate and form a barrier when liquids move downward in the pile to the soil at the tailings-soil interface (Ma79a, Ma81b, Ma81c). This would prevent contamination of groundwater from tailings piles during the inactive phase. However, it is not known how long this barrier will last, and there could be channels through the barrier at locations other than those sampled. DOE is currently sponsoring additional studies of these potential routes of groundwater contamination.

Surface Water

Standing water with elevated concentrations of toxic materials has been reported on and adjacent to some tailings sites (Ma81c, FB76-78). Usually, these concentrations are intermediate between those reported for waters within piles and normal levels in surface water. Surface water runoff from rains and floods can wash surface salt deposits and tailings from an unprotected pile, causing spread of toxic and radioactive elements to nearby land and streams. A more likely route for the contamination of surface water is seepage of contaminated groundwater into a nearby stream or reservior. Some degradation of water quality in nearby streams has been reported at active sites. However, studies of the inactive tailings piles do not show that nearby streams are being contaminated (FB76-78).

Table 3-5. Elements Found in Elevated Concentrations in Groundwater Near Inactive Tailings Sites

Tailings Site[a]	Elements[b]
Gunnison, Colorado	Arsenic, Barium, Chromium, Iron, Lead, Selenium, Vanadium
Ambrosia Lake, New Mexico	Barium, Lead, Vanadium
Falls City, Texas	Arsenic, Barium, Chromium, Iron, Lead, Selenium, Radium, Vanadium
Green River, Utah	Arsenic, Chromium, Lead, Selenium
Ray Point, Texas	Arsenic

[a](FB76-78).
[b]At most sites there are other potential sources of this toxic material contamination; see orginal reports for details.

3.3 Nonroutine Releases

3.3.1 Accidents and Acts of God

The most credible accident that could lead to a widespread release of tailings solids and pond water is a dam failure at a tailings pond. This actually occurred at the United Nuclear mill in Church Rock, New Mexico on July 16, 1979, and 100 million gallons of tailings-pond water and 1000 tons of solid tailings were released into the Rio Puerco, a large ephemeral stream. Following the spill, abnormally high concentrations of radionuclides and toxic elements were recorded as far as 36 miles downstream. However, after several weeks, water quality of the Rio Puerco susbstantially improved to within background levels of contaminants. In addition to surface-water contamination, some groundwater contamination in shallow wells adjacent to the Rio Puerco was also detected. Contaminated sediment was found in the Rio Puerco for several miles downstream of the spill.

The spill prompted a commitment of resources from several Federal and State agencies to study the failure and to monitor the contamination. At the urging of the State of New Mexico and the Navajo Nation, United Nuclear conducted a cleanup of contaminated areas and supplied the Navajos with replacement water. The ultimate cost of the entire incident will probably be several million dollars.

Although the Church Rock tailings-dam failure occurred spontaneously, natural events could also precipitate such a failure: most notably severe flooding or an earthquake. In Chapter 8, the probabilities of such events are discussed, along with engineering and site selection options for minimizing these probabilities. Also discussed in Chapter 8 are the impacts of events such as tornadoes and glaciation on the effectivness of contaminant controls.

3.3.2 Misuse of Tailings Sands

In the recent past, uranium mill tailings have been used extensively as a building material, chiefly as fill around and under foundations and concrete slabs. The tailings sands have ideal physical characteristics for this purpose. However, such use typically results in building occupants being exposed to high levels of radon decay products and thereby incurring a significant lifetime risk of lung cancer. In Grand Junction, Colorado, over 700 buildings have been identified as contaminated and requiring remedial action. In other mill towns, it is estimated that more than 350 buildings are contaminated. In addition to buildings, many thousands of other locations have been identified (e.g., sidewalks, lawns, gardens, driveways) in mill towns where tailings have been used. These buildings and locations were contaminated by tailings from inactive mills. We have not assessed the extent of existing misuse near active mills.

3.4 Environmental Releases from Heap-Leaching Operations

The principal solid waste from heap leaching is the barren material remaining after uranium recovery. Airborne emissions from heap-leaching operations include particulates suspended by wind erosion of the pile and radon gas. The particulates will contain toxic elements and radionuclides in proportion to the ore concentrations. The amount of radon and particulates given off will be proportional to the size of the operation. These have been calculated for the heap-leaching cell covering about 0.5 acre in area described in Chapter 2.

Particulate emissions from the dry portion of a heap-leaching cell are estimated to be about 1 MT annually. The radon emanation rate from this operation is calculated to be 25 Ci/y (NRC78). This is less than one-half as much as a tailings pile per unit acre.

Releases of contaminants to groundwater could result from the seepage of leachate containing elevated concentrations of radionuclides and toxic elements. This, however, would not normally pose a problem during operations since an efficient heap-leaching operation requires an impermeable pad and all leachate is collected for processing. After termination of operations, normal rainfall could lead to some leaching from the piles, but we expect this to be no greater threat than leaching from an unstabilized conventional tailings pile.

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Chapter 4: MODEL SITE AND TAILINGS PILE

This chapter summarizes the specific characteristics of the model site and tailings pile used for the analyses presented in Chapters 5 and 6.

4.1 Model Site

The "model mill" chosen for this analysis is the one developed for the NRC's Final Generic Environmental Impact Statement on Uranium Milling (NRC80). The model mill is based on features of uranium mills in operation in the 1970's. The characteristics, operating procedures, and effluents of the model mill were derived from data for existing mills as described in the technical literature and in environmental reports (MP80). Since the Act relates only to the tailings resulting from operation of the mill, the "model site" used for the analysis in Chapters 5 and 6 is defined as the area within a radius of 80 kilometers from the center of the model mill tailings pile.

4.1.1 Meteorology

The meteorology of the model site is typical of semiarid regions of the western United States. The average annual precipitation of the model site is 31 cm (12 inches). Potential evaporation exceeds precipitation, averaging 150 cm (60 inches) per year. Joint frequency of the annual average wind speed, direction, and atmospheric stability for the model site are presented in Table 4-1.

4.1.2 Demography

Two population distributions were used for the model site to represent a range of potential impacts from the model tailings pile: (1) the population distribution from the NRC model site (NRC80), and (2) the population distribution near the tailings pile in Edgemont, South Dakota (NRC81). The NRC model site represents a location where only a few people live close to the tailings pile (referred to here as a "remote" site). The Edgemont site represents a location with a larger population living near the tailings pile (referred to here as a "rural" site). Tables 4-2 and 4-3 present these population distributions as a function of distance and direction from the model tailings pile.

Table 4-1. Annual Average Joint Frequency Distribution for Winds in the Model Mill Region

Class/ Speed[a] (m/s)	Wind Direction (Joint Percent and Frequency)																
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
ALL CLASSES	5.01	4.64	5.02	5.44	4.81	2.77	2.95	3.01	8.05	8.68	14.82	16.40	9.87	4.17	2.27	2.09	100.00
STABILITY CLASS A	0.11	0.17	0.14	0.08	0.05	0.03	0.03	0.05	0.14	0.12	0.14	0.22	0.25	0.27	0.14	0.08	2.02
0.0-1.5	0.06	0.10	0.08	0.05	0.03	0.02	0.02	0.03	0.08	0.07	0.08	0.13	0.15	0.16	0.08	0.06	1.20
1.6-3.2	0.05	0.07	0.06	0.03	0.02	0.01	0.01	0.02	0.06	0.05	0.06	0.09	0.10	0.11	0.06	0.02	0.82
STABILITY CLASS B	0.36	0.49	0.42	0.31	0.39	0.07	0.14	0.02	0.34	0.64	0.80	1.52	1.10	0.59	0.41	0.39	7.99
0.0-1.5	0.17	0.28	0.27	0.15	0.22	0.04	0.10	0.00	0.18	0.33	0.41	0.85	0.59	0.33	0.22	0.24	4.38
1.6-3.2	0.09	0.15	0.13	0.08	0.11	0.02	0.03	0.00	0.09	0.17	0.22	0.45	0.31	0.17	0.12	0.13	2.27
3.3-5.1	0.10	0.06	0.02	0.08	0.06	0.01	0.01	0.02	0.07	0.14	0.17	0.22	0.20	0.09	0.07	0.02	1.34
STABILITY CLASS C	0.55	0.64	0.67	0.67	0.44	0.08	0.14	0.13	0.72	1.07	1.93	2.10	1.88	0.79	0.35	0.38	12.54
0.0-1.5	0.08	0.11	0.14	0.11	0.06	0.00	0.02	0.02	0.12	0.10	0.20	0.21	0.26	0.10	0.06	0.05	1.64
1.6-3.2	0.20	0.26	0.34	0.26	0.14	0.01	0.06	0.05	0.29	0.23	0.45	0.52	0.62	0.25	0.14	0.11	3.93
3.3-5.1	0.24	0.24	0.14	0.30	0.23	0.07	0.05	0.06	0.25	0.52	0.74	0.85	0.71	0.34	0.10	0.21	5.05
5.2-8.2	0.03	0.03	0.05	0.00	0.01	0.00	0.01	0.00	0.06	0.13	0.43	0.31	0.23	0.10	0.05	0.01	1.45
8.3-10.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.09	0.21	0.05	0.00	0.00	0.00	0.43
Greater than 10.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.00	0.01	0.00	0.00	0.00	0.04

See footnote at end of table.

Table 4-1. Annual Average Joint Frequency Distribution for Winds in the Model Mill Region (Continued)

Class/Speed[a] (m/s)	Wind Direction (Joint Percent and Frequency)																
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
STABILITY CLASS D	1.15	0.99	0.77	1.39	1.05	0.27	0.59	0.73	2.19	3.49	6.88	7.13	3.75	1.53	0.64	0.49	33.04
0.0-1.5	0.16	0.13	0.11	0.11	0.06	0.02	0.09	0.09	0.18	0.19	0.22	0.31	0.25	0.06	0.04	0.06	2.08
1.6-3.2	0.30	0.23	0.20	0.21	0.10	0.03	0.13	0.16	0.33	0.36	0.38	0.54	0.39	0.10	0.07	0.10	3.63
3.3-5.1	0.45	0.32	0.31	0.68	0.52	0.09	0.18	0.31	0.84	1.39	1.78	1.93	1.02	0.44	0.14	0.21	10.61
5.2-8.2	0.22	0.24	0.14	0.37	0.36	0.10	0.16	0.14	0.68	1.17	3.37	3.13	1.60	0.80	0.36	0.11	12.95
8.3-10.8	0.02	0.06	0.01	0.02	0.01	0.02	0.02	0.03	0.14	0.31	1.00	1.01	0.47	0.13	0.03	0.01	3.29
Greater than 10.8	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.02	0.07	0.13	0.21	0.02	0.00	0.00	0.00	0.48
STABILITY CLASS E	2.12	1.74	2.35	2.33	2.22	1.92	1.54	1.52	3.58	2.56	3.72	3.77	2.05	0.74	0.57	0.56	33.29
0.0-1.5	1.39	1.15	1.66	1.53	1.58	1.54	1.11	1.00	2.31	1.38	2.18	2.37	1.23	0.41	0.31	0.34	21.49
1.6-3.2	0.52	0.44	0.53	0.50	0.46	0.36	0.37	0.38	0.75	0.56	0.71	0.79	0.48	0.15	0.11	0.08	7.19
3.3-5.1	0.21	0.15	0.16	0.30	0.18	0.02	0.06	0.14	0.52	0.62	0.83	0.61	0.34	0.18	0.15	0.14	4.61
STABILITY CLASS F	0.72	0.61	0.67	0.66	0.66	0.40	0.51	0.56	1.08	0.80	1.35	1.66	0.84	0.25	0.16	0.19	11.12
0.0-1.5	0.45	0.37	0.47	0.42	0.42	0.25	0.31	0.32	0.64	0.43	0.65	0.79	0.40	0.10	0.06	0.07	6.15
1.6-3.2	0.23	0.17	0.14	0.14	0.18	0.13	0.16	0.17	0.31	0.15	0.30	0.37	0.24	0.07	0.06	0.06	2.88
3.3-5.1	0.04	0.07	0.06	0.10	0.06	0.02	0.04	0.07	0.13	0.22	0.40	0.50	0.20	0.08	0.04	0.06	2.09
5.2-8.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8.3-10.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Greater than 10.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[a] Frequencies for unlisted windspeed groups are 0.0 percent. The average windspeed for each interval is as follows:

Windspeed interval (w/s)	Average windspeed (w/s)
0. - 1.5	.671
1.6 - 3.2	2.46
3.3 - 5.1	4.47
5.2 - 8.2	6.93
8.3 - 10.8	9.61
Greater than 10.8	12.5

Table 4-2. Population Distribution at a Remote Uranium Mill Tailings Site

Distance (km)	Wind Direction N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0.5 - 1.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0 - 2.0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	8
2.0 - 3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.0 - 4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.0 - 5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.0 - 10.	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	8
10. - 20.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20. - 30.	1008	8	0	8	0	0	0	0	0	8	0	0	8	0	8	0	1048
30. - 40.	2000	500	0	8	0	0	0	0	0	0	8	8	0	0	500	500	3524
40. - 50.	0	0	13000	0	0	0	0	0	1000	8	0	0	0	0	1000	1000	16016
50. - 60.	0	0	3500	0	0	0	0	0	0	0	0	0	8	0	0	500	4008
60. - 70.	0	0	0	500	2000	0	0	0	0	0	2000	500	8	4000	0	500	9508
70. - 80.	0	0	0	0	0	0	0	0	0	0	8	1000	10000	12000	300	0	23308
Total																	57428

Table 4-3. Population Distribution at a Rural Uranium Mill Tailings Site

Distance (km)	Wind Direction																
	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0.5 - 1.0	22	17	0	0	0	0	2	54	19	0	108	184	248	262	105	64	1085
1.0 - 2.0	81	76	8	0	0	0	0	0	3	54	79	80	343	162	27	10	915
2.0 - 3.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.0 - 4.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.0 - 5.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.0 - 10.	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	129	144
10. - 20.	0	0	0	0	0	0	0	0	103	0	0	0	0	0	26	0	129
20. - 30.	0	0	0	0	0	0	0	190	0	0	0	0	0	0	0	0	190
30. - 40.	0	86	0	4725	0	0	0	14	0	0	0	193	0	0	0	106	5124
40. - 50.	0	1025	24	0	0	0	0	40	57	45	0	0	0	0	0	0	1191
50. - 60.	839	1615	3500	0	0	0	0	0	114	0	0	0	8	0	0	500	2568
60. - 70.	0	345	108	0	0	0	0	242	418	0	0	474	0	0	0	4033	5620
70. - 80.	560	857	0	0	0	0	0	1371	141	250	1495	182	0	0	0	0	4856
Total																	21822

To obtain better information on populations at mill sites, EPA contracted with Battelle Pacific Northwest Laboratories to count the number of people within 5 km of these sites. These data are presented in Appendix E. EPA also obtained data on the number of people living between 5 and 80 km of these sites based on 1970 census data (Ew73). These values were then used to estimate the total health risk to local and regional populations (see Chapter 6) by various weighting techniques.

4.1.3 Hydrology

The surface waters near the model pile are short-lived streams and small ranch impoundments used for livestock watering. These ephemeral streams have their maximum flows in June and July and are dry from September to February. Rivers and reservoirs are several miles away from the model pile. In some cases, the nearby surface water is good (of drinking water quality), but nearby surface water will contain relatively high concentrations of dissolved solids, making it unsuitable for many purposes. The groundwater resources near the model uranium mill tailings pile are an unconfined surface aquifer (often alluvial) plus deep aquifers separated from the surface by an impermeable layer. For calculating the movement of contamination from the model pile, the NRC assumed the water table (the top of the surface aquifer) is 25 meters below ground level. The deep aquifers often lie below 300 meters. The surface aquifer is the most commonly used, chiefly for domestic and stock water.

The deep aquifers are used for large industrial applications. Uranium mills, for example, often obtain mill process water from deep aquifers. Water quality of both the surface and deep aquifers is variable.

4.1.4 Agricultural Productivity

Uniform agricultural productivity rates for vegetables, meat, and milk in units of $kg/y\text{-}km^2$ were applied over the entire area of the model site except the controlled areas occupied by the mill and tailings pile. The production rates used are:

Product	$kg/y\text{-}km^2$
Vegetables	1020
Meat	1180
Milk	1140

These production rates are averages of production rates in States where uranium milling takes place (NRC80), weighted by the expected uranium development activity in each state.

4.2 The Model Tailings Pile

The tailings are assummed to be generated by an acid-leach mill. We generally assume the same characteristics as chosen by the NRC for their generic assessment of the uranium milling industry (NRC80).

4.2.1 Physical Description

The model tailings pile is typical of uranium mills in operation in the 1970's. The model mill generates 1800 MT of solid tailings slurried in water to about 50 percent solids by weight. When discharged from the mill, the slurried tailings material is pumped through pipes to the tailings pond impoundment. The pond is initially a square basin formed by building low earthen embankments. The initial embankment is assumed to be 3 meters high, 3 meters broad at the top, and 15 meters wide at the base. Each side of the square is assumed to be 947 meters long at the centerline of the embankment. The final embankments are assumed to be 10 meters high, 13 meters wide at the top, and 53 meters at the base; the initial centerline dimensions are unchanged. The total tailings disposal area is about 100 hectares (250 acres) of which 80 hectares contain tailings. It is assumed that, during operations, one fourth of the tailings area is covered by water, and another one-eighth is wet.

After milling operations cease, it is assumed a few years pass before the tailings have dried and settled sufficiently to accommodate heavy equipment. The ultimate height of the tailings pile is assumed to be about 8 meters. In this post-operational phase, the emissions from tailings and the controls are different from those during the operational phase.

The principal physical characteristics of the model tailings pile are summarized in Table 4-4.

Table 4-4. Summary of Principal Physical Characteristics of the Model Tailings Pile

Parameter	Value
Operational life of tailings pile	15 years
Operating days per year	310
Dry solid waste generated (tailings)	1800 MT/day
Tailings density (slurry)	1.6 g/cm^3
Gross water flow to tailings pond	1800 MT/day
Tailings pond water recycled	30%
Net water consumption for tailings slurry	1260 MT/day
Area of tailings impoundment	100 ha
Area of tailings	80 ha
Ponded area on tailings (operational)	20 ha
Ponded area on tailings (post-operational)	0 ha
Wet beaches	10 ha
Average depth of tailings (post-operational)	8 m

4.2.2 Contaminants Present

The ore grade processed by the model mill from 1982 to 2000 is assumed to average 0.1 percent. The uranium recovery efficiency is assumed to be 93 percent. These values result in the tailings radioactivity listed in Table 4-5. Also listed are the assumed concentrations of toxic substances and other chemicals in the tailings pond liquids of the model pile (NRC80). The values in Table 4-5 are representative of tailings piles generated by acid leach mills. For an alkaline-leach mill, the most significant difference is that the concentration of thorium-230 in tailings liquids would be more than an order of magnitude lower.

4.2.3 Radioactive Emissions to Air

Radionuclides are released into air from tailings piles in the form of small dust particles and radon gas. Table 4-6 lists the assumed annual release rates of radionuclides from the model tailings pile. Particulate emissions are listed in two particle size distributions with characteristic diameters of 5 and 35 microns, respectively, and a density of 2.4 g/cm^3. The Activity Median Aerodynamic Diameters (AMADs) for these particle size distributions are 7.75 and 54.2 μm, respectively. A detailed description of the methods used for estimating these release rates is given in Appendix G-1 of the Generic Environmental Impact Statement on Uranium Milling (NRC80).

4.2.4 Emissions of Contaminants to Water

For the model pile, it is assumed that there are no routine releases to surface water. This is achieved through proper siting of the pile along with the minimal engineered controls required to substantially eliminate surface water runoff from the tailings pile.

The assumed routine emissions to groundwater are more substantial. NRC calculates a seepage rate of 0.22 million MT of water per year during the operational phase, and 5 percent of this value during the post-operational phase. We have made no estimates of the specific contaminants released with this water because they will vary with the ore used, the milling process, the geochemistry of the soil, and other factors.

Table 4-5. Chemical and Radiological Properties of Tailings Wastes Generated by the Model Mill[a]

Parameter	Unit	Value[a]
Dry Solids		
U_3O_8	wt%	0.007
Uranium (natural)[b]	pCi/g	39
Radium-226	pCi/g	280
Thorium-230	pCi/g	280
Tailings Liquid		
pH		2
Aluminum	mg/L	2,000
Ammonia	mg/L	500
Arsenic	mg/L	0.2
Calcium	mg/L	500
Cadmium	mg/L	0.2
Chloride	mg/L	300
Copper	mg/L	50
Fluoride	mg/L	5
Iron	mg/L	1,000
Lead	mg/L	7
Manganese	mg/L	500
Mercury	mg/L	0.07
Molybdenum	mg/L	100
Selenium	mg/L	20
Sodium	mg/L	200
Sulfate	mg/L	30,000
Vanadium	mg/L	0.10
Zinc	mg/L	80
Total dissolved solids	mg/L	35,000
Uranium (natural)	pCi/L	3,300
Radium-226	pCi/L	250
Thorium-230	pCi/L	90,000
Lead-210	pCi/L	250
Polonium-210	pCi/L	250
Bismuth-210	pCi/L	250

[a](NRC80).
[b]A 1.5 microgram mass of natural uranium has activities of 0.49 pCi each of uranium-238 and uranium-234 and 0.023 pCi of uranium-235.

Table 4-6. Radioactive Emissions to Air from Model Tailings Pile

Radionuclide	Operational Phase		Post-Operational Phase	
	Particulate Emissions,(mCi/y) Particle size			
	5 μm	35 μm	5 μm	35 μm
Uranium-238	2.6	6.1	4.2	9.8
Uranium-234	2.6	6.1	4.2	9.8
Thorium-230	36	84	58	134
Radium-226	36	84	58	134
Lead-210	36	84	58	134
Polonium-210	36	84	58	134
	Gaseous Emissions (Ci/y)			
Radon-222	4400		7000	

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Chapter 5: ENVIRONMENTAL PATHWAYS

In this Chapter the pathways through which radioactive and toxic materials from mill tailings may cause exposure of man are examined and, where possible, quantified. While consideration of the impact of tailings piles on man depends on the status--operational or postoperational--of the mill, the contaminants which are expected to be present are the same. The projected health impacts of these materials are developed for the various pathways in Chapter 6, using the results obtained in this chapter for the model site.

5.1 Contaminants

The pathway analysis considers three general forms of contaminants. They are particulates (dust), radon (gas), and liquids (leachate). An introductory discussion of each form is given first, and the actual transport mechanisms are presented in the following sections. The model mill has been described in Chapter 4. The source terms and other model parameters are more fully described in the Final Generic Environmental Impact Statement on Uranium Milling (NRC80). Since the Act addresses only the tailings resulting from mill operations, only the model mill source terms applicable to the tailings pile are employed.

5.1.1 Particulates

The mechanism of movement of tailings particles by wind is similar to the movement of soil and is dependent on wind velocity, physical properties of the tailings, and the nature of the tailings surface. Wind forces can generate three basic modes of particle movement: surface creep, saltation, and airborne suspension. Surface creep, which spreads the tailings pile, involves particles ranging in size from 500 to 1000 μm. These particles are rolled along the surface by the push of strong winds and the exchange of momentum after impact with smaller particles in saltation. Saltation causes individual particles to jump and lurch within a few centimeters of the ground. Particles that saltate are from 100 to 500 μm in size, depending on shape and density, and are quickly brought back to the ground by gravitational force. The resulting exchange of momentum with other particles can initiate surface creep, saltation, or suspension. Particles in suspension are small enough (less than about 100 μm) to have a gravitational velocity of fall lower than the upward velocity of the turbulent wind. These particles may be carried through the atmosphere for long time periods and to distances far from their original location. While airborne, these suspended particles contribute to the inhalation pathway of exposure of man; when deposited, they contribute to the ingestion and external surface exposure pathways.

5.1.2 Radon

As shown in Figure 3-1, the radon decay process involves seven principal decay products before ending with nonradioactive lead. The four short half-life radioactive decay products immediately following radon are the most important sources of cancer risk. These decay, for the most part, within less than an hour. Members of the decay chain with relatively long half-lives (beginning with lead-210, which has a 22-year half-life) are more likely to be ingested than breathed and pose much smaller risks.

The principal short half-life products of radon are polonium-218, lead-214, bismuth-214, and polonium-214. Polonium-218, the first decay product, has a half-life of just over 3 minutes. This is long enough for most of the electrically-charged polonium atoms to attach to microscopic airborne dust particles that are typically less than a millionth of a meter (μm) across. When breathed, these small particles have a good chance of sticking to the moist epithelial lining of the bronchial tubes in the lung.

Exposure to radon decay products is expressed in terms of a specialized unit called the Working Level (WL). A Working Level is any combination of short half-life radon decay products that emits 130,000 million electron volts (MeV) of alpha-particle energy in 1 liter of air. The unit of cumulative exposure to radon decay products is the Working Level Month (WLM), which is exposure to air containing 1 WL of radon decay products for a working month, which is defined as 170 hours. (These units were developed to measure radiation exposure of workers in uranium mines.) Continuous exposure of a member of the general population to 1 WL for 1 year is equivalent to about 27 WLM. For exposures occurring indoors, we assume a 75 percent occupancy factor. Thus, an indoor (residential) exposure to 1 WL for 1 year is equivalent to about 20 WLM (EPA79a).

5.1.3 Liquid Contaminants

Airborne transport of tailings, with subsequent deposition on the ground and on surface waters, and transport or leaching of tailings by water used for drinking or irrigation can lead to exposure of man to radioactive and toxic substances. Future contamination of surface or groundwater is also likely if there is erosion of toxic elements from a pile by rain, by flooding, or, possibly, by the flushing action of seasonal changes in the water table when it can reach a pile from below. Severe floods have a greater, but difficult to evaluate, potential for producing significant contamination of streams and rivers. Future groundwater contamination from the seepage and flushing action of seasonal changes in the water table is uncertain. The degree of detail with which we can accurately treat these potential pathways varies. Modeling of water pathways requires site-specific data on sources and uses of water. The existence of actual water pathways for radioactive and toxic materials from tailings piles has not yet been verified, so we discuss these pathways in general terms only. Concentrations of dissolved substances in the tailings pond water at the model mill are shown in Table 4-5.

5.2 Atmospheric Transport

Airborne particulates and radon are analyzed using essentially the same calculational procedure. For the purpose of evaluating environmental impact, the analysis has been performed for both regional and national populations, using appropriate meteorological models for each. Because of the short half-life of radon, the worldwide impact is not significantly greater than the sum of the impacts of these two groups, and is therefore not calculated for this analysis. The term "regional" is defined to include local and regional populations at distances up to 50 miles (80 km) from the tailings site and "national" to cover the remainder of the contiguous United States.

5.2.1 Near the Tailings

We estimated radon concentrations over and close to the edge of generic, uncovered tailings piles, which, for calculational convenience, we take as circular in shape. For these calculations we assumed that the radon emission rate is a uniform 280 pCi/m^2s from the tailings. Concentrations for other emission rates would be proportionately higher or lower. The concentration calculations were made using generic wind data from the NRC GEIS (NRC80) and the AIRDOS-EPA dispersion model (EPA79b).

5.2.2 Regional

Meteorology

Airborne transport within the region is governed by meteorological conditions at the model mill site. These are detailed in Chapter 4. The transport mechanisms considered are described below.

Dispersion

The AIRDOS-EPA code (EPA79b) uses a modified Gaussian plume equation to estimate airborne dispersion of radionuclides from the pile. Calculations are site-specific and require detailed knowledge of the joint wind direction, wind speed, and stability frequencies. Since the accuracy of these projections decreases with distance, we limit calculations with this method to regional (less than 50 miles distant) locations. Values calculated are annual averages, since we are not concerned with diurnal or seasonal variations.

Deposition

AIRDOS-EPA estimates the annual average concentration of each radionuclide in air at ground level (corrected for deposition) as a function of direction and distance from the source. Deposition rates at each location are calculated for each radionuclide, and from these, the ground concentration levels at the desired locations. The radionuclides are deposited on the ground in the model by both precipitation and direct dry deposition.

Ingrowth of Radon Decay Products

At the point where radon diffuses out of the tailings, the atmospheric concentration of associated radon decay products is zero, because those decay products generated prior to diffusion from the surface have been captured in earth. As soon as radon is airborne, atmospheric decay product ingrowth commences and a secular equilibrium between the amount of radon and the amount of each decay product is approached. At such secular equilibrium, there is equal activity of all the short half-life radon decay products in air, and alpha radiation per unit of radon concentration is maximized. To account for incomplete equilibrium before this state is achieved, we define the "equilibrium fraction" as the ratio of the potential alpha energy from those decay products actually present to the potential alpha energy that would be present at complete equilibrium. As radon and its decay products are transported by the wind, the equilibrium fraction increases with distance from the pile approacing the theoretical maximum value. However, depletion processes, such as dry deposition or precipitation scavenging, selectively remove decay products (but not radon), so complete equilibrium with the radon is seldom, if ever, reached.

When radon and its daughters enter a structure, they remain for a mean time that is inversely proportional to the ventilation rate and proportional to its half-life. Since the former is much smaller than the latter, the building ventilation rate is a principal factor affecting further changes in the equilibrium fraction. It can also be affected by other considerations, such as the indoor surface-to-volume ratio and the dust loading in indoor air (Po78).

We have also assumed that, on the average, Americans spend approximately 75 percent of their time indoors, mostly in their homes (Mo76, Oa72). We have weighted the indoor and outdoor equilibrium fractions for a given location by factors of 0.75 and 0.25, respectively, to estimate an effective value for calculating exposure to radon decay products from tailings piles. Since indoor exposure is the dominant form of exposure due to radon, this effective equilibrium fraction does not depend strongly on the distance from the tailings pile. We assume an effective equilibrium fraction of 70 percent for exposure of populations, since the majority of all affected individuals are not close to piles. For maximum exposed individuals close to a pile, we assume half this value.

5.2.3 National

The inert radon gas emitted from tailings piles can be transported beyond the 50-mile regional cutoff. A trajectory dispersion model developed by NOAA (Tr79) has been used to estimate the national impact of radon emissions from the model pile. This model calculates the potential radiation exposure to the United States population for radon released from four typical mill site locations. (Descriptions of these typical mill sites--Casper, Wyoming; Falls City, Texas; Grants, New Mexico; and Wellpinit, Washington--are given in (Tr79).) Only exposures taking place beyond the 50-mile regional limit are considered. Details of the model are given in He75. The model yields radon concentrations (pCi/L) in air which were converted to decay product concentrations by assuming that 100 pCi/L of radon corresponds to a decay product concentration of 0.7 WL.

5.3 Hydrological Dispersion

There are two basic types of water resources considered in the impact assessments: (1) surface water (water on the surface of the earth, such as in lakes and rivers) and (2) groundwater (water occurring below the surface of the earth in a zone of saturation). The impacts on these two types of water resources in the model region are discussed in the following subsections for the case of an unlined tailings disposal area.

5.3.1 Surface Water

Operational

During operation of the mill, seepage from tailings ponds could add heavy metals, suspended solids, radioactive contaminants, and soluble salts to surface waters. Three routes of contamination might occur as a result of this seepage:

1. Seepage water from the tailings pond could intercept an aquifer and contaminate groundwater. This contamination could also degrade surface water quality under certain conditions. Irrigation wells or water supply wells could also penetrate aquifers that have been contaminated by seepage from tailings ponds. Water pumped from such wells would normally discharge into a surface water irrigation ditch or canal and ultimately into a stream. Contaminated water extracted via such wells would remain contaminated when it entered a surface water stream.

2. Seepage water could form surface pools downgrade from the tailings pond. Consideration of the transport time and concentration data for the seepage pools indicates that the trace materials in the pools would have the same initial composition as the tailings pond.

This surface water would be subject to a high rate of evaporation, which would result in a concentration of the soluble ions as the volume of seepage water decreases. During periods of local precipitation and spring runoff, this contaminated water could enter surface streams or rivers.

3. During dry periods, seepage water might reach the ground surface and be subject to a high evaporation rate, which would result in salt deposits. These areas would be exposed to surface runoff during periods of precipitation or during periods of snowmelt, at which time the precipitates again would be subject to dissolution and transport, resulting in a pulse of contaminated water reaching surface waters. Depending on the amount of materials in the runoff and the dilution capacity of the existing streamflow, the water quality of some streams, on rare occasions, could reach toxic levels.

Post-Operational

After mill operations cease, seepage from the tailings would be substantially reduced since discharge of water from the mill ends. The permanent seepage rate caused by precipitation falling on uncovered, abandoned tailings is estimated to be about 5 percent of the rate during the 15-year operational period (NRC80).

5.3.2 Groundwater

The impacts of uranium milling operations on groundwater are generally site-specific (because of regional and local variations in geology and hydrology) and thus are difficult to discuss on a generic basis. For illustrative purposes, however, a set of geological and hydrological characteristics has been assumed for the model region.

The effects of mining on groundwater can be fairly extensive and in many cases cannot be logically separated from the effects of nearby milling operations. For the model mill, however, we assume that the mines will be sufficiently far from the tailings pond to have no effect on effects due to tailings pond seepage.

Operational

By far the greatest impact on groundwater resulting from operation of a model mill would be from seepage from the tailings pond. The term "tailings pond" is used in the general sense in this context, and is intended to include evaporation ponds or any other type of unlined facility which receives mill waste water. The model mill contains an unlined tailings disposal area. The principal contaminants in the acidic tailings pond liquid are radium, thorium, sulfate, iron, manganese, and selenium (Table 4-5).

Post-Operational

After mill operations cease, seepage from the tailings would be substantially reduced because of the cessation of discharge of water from the mill. It should be emphasized that this analysis assumes that no new wells are permitted which would withdraw contaminated groundwater from the aquifer affected by the seepage.

During the post-operational period, an advancing front of seepage water containing nonradioactive contaminants would be moving downgradient. In this analysis, contaminant concentrations have been calculated on the assumption that there would be no lateral dispersion; this is a conservative assumption in that it results in overestimation of downgradient concentrations of contaminants. As these contaminants disperse downgradient, their concentrations would be reduced.

5.4 Environmental Concentrations

We calculate environmental concentrations, radiation doses, and health risks due to airborne releases using three computer codes--AIRDOS-EPA (EPA79b), RADRISK (Du80), and DARTAB (Be81).

AIRDOSE-EPA estimates, for a given source term, the amount of intake of each radionuclide, or the external concentration, at the point of exposure. RADRISK calculates the radiation dose and risk from unit intake of a given radionuclide. DARTAB is a control code that scales the unit estimates of RADRISK to match the actual exposure levels calculated by AIRDOS-EPA and then displays the results in a useful format.

5.4.1 Calculational Procedures

The regional environmental concentrations resulting from airborne emissions presented in this Chapter are obtained using the AIRDOS-EPA code. The RADRISK and DARTAB health risk calculations are described in Chapter 6 and Appendix C.

The AIRDOS-EPA code was developed for EPA by the Oak Ridge National Laboratory. It is a modification of AIRDOS-II, a code in use for many years, also developed by ORNL. Terrestrial food chain models used by the code are based on those used by the U.S. Nuclear Regulatory Commission, as provided in Regulatory Guide 1.109.

A modified Gaussian plume is used to estimate dispersion of as many as 36 radionuclides from point or area sources. Radionuclide concentrations in air, rates of deposition on ground surfaces, ground surface concentrations, and intake rates due to inhalation and ingestion (meat, milk, fresh vegetables) are then calculated. Meteorological, population, and other data characteristics of the site can be used to give more accurate assessments of a specific source.

When a source continually emits long half-life radionuclides, the environmental concentration levels build up for as long as the source continues to emit. This is not a significant consideration for air concentrations, but is for those concentrations which result from deposition on the ground surface. Our calculations assume that the particulates which deposit on the ground surface are removed by environmental processes, such as leaching, at a rate of 2 percent per year. (In addition, only 20 percent of the radon which results from the decay of deposited radium is assumed to escape). Since the environmental concentrations are not constant, they are calculated for specific times appropriate to the analysis. For the operational period, this is at the end of 15 years (the expected duration of mill operation) for the assessment of individual exposure and at the end of 100 years for the assessment of population exposures. The release rates used for these calculations are those shown in Table 4-6.

For the post-operational period, the enviromental concentrations are calculated at the end of 100 years of releases. The release rates for this period assume the tailings pond no longer exists and that the entire tailings pile area (80 ha) contributes to the releases. Because of the 2 percent per year removal rate assumed for deposited particulates, these concentrations are close to equilbrium.

Radon decay product concentrations (WL) are calculated from the atmospheric radon concentration (Ci/m^3) using an effective equilibrium fraction as described in Section 5.2.1.

5.4.2 Air Concentrations

Near the Pile

Average concentrations near the pile are shown in Figure 5-1 for a small (5 hectares or 12 acres), a medium (20 hectares or 49 acres), and a large (80 hectares or 196 acres) tailings pile. Our calculations show that the average concentration near the center of the pile and at the edge of the pile are relatively insensitive to the size of the pile. For the 20-hectare pile, Figure 5-1 also shows the results in the directions for which the concentration is maximum or minimum. The wind data (and therefore the dispersion) and the shape of the pile at actual sites would differ from the one used for these calculations. Although we have not performed site-specific calculations, we believe that the higher wind direction asymmetry at actual tailings sites would increase the maximum concentration at the edge of the tailings to about 4 pCi/L. This is the only calculation which uses dimensions different from those of the model pile described in Chapter 4.

Regional

Regional air concentrations for particulates and radon are shown in Table 5-1. These concentrations are based on the operational phase source terms given in Table 4-6. In Table 5-1 and subsequent tables, the column heading "average" refers to the arithmetic average over the sixteen directions for which concentrations are calculated. The heading "maximum" is the value for the direction of maximum risk (see

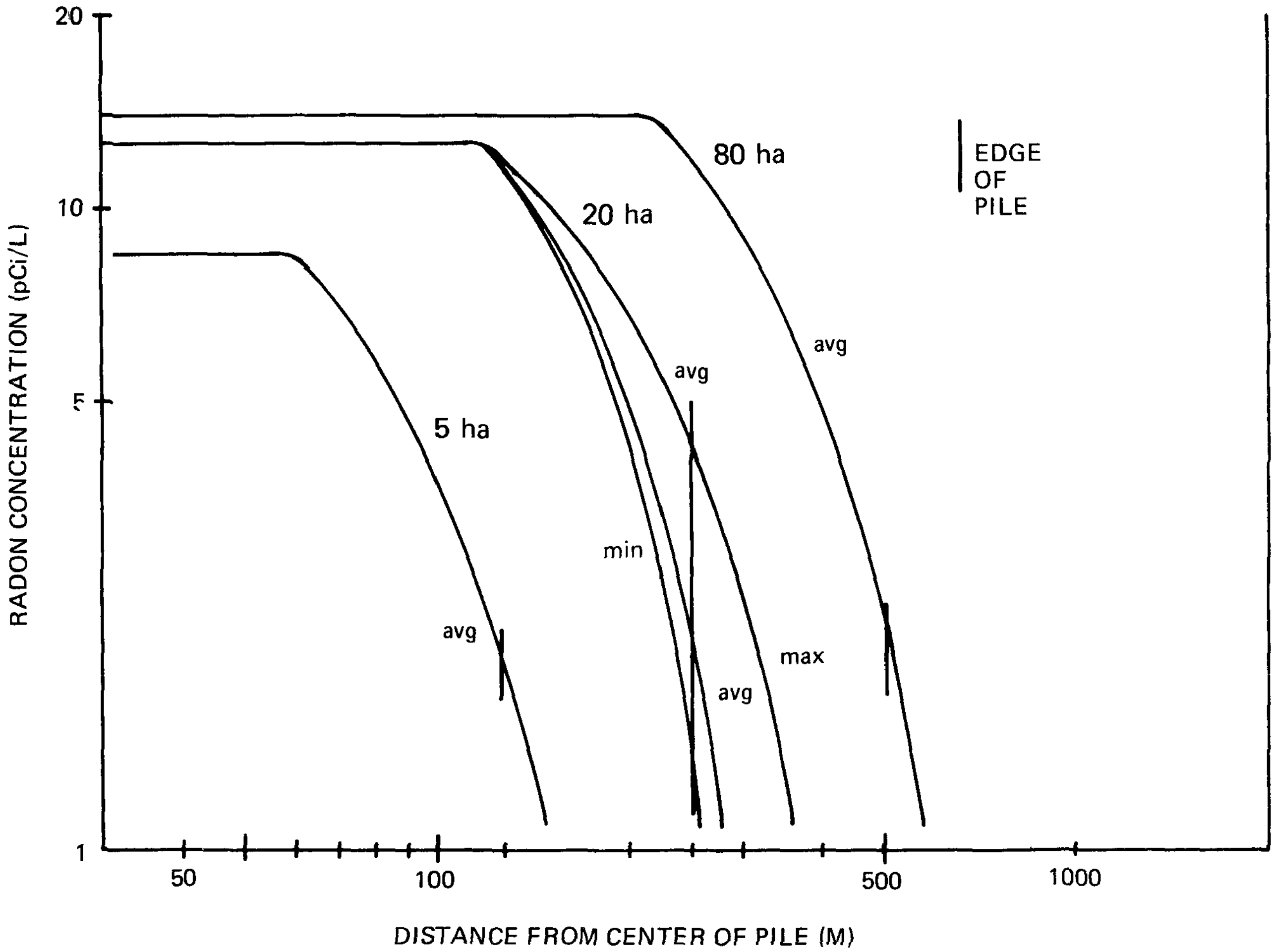

Figure 5-1. Radon Concentration Near the Tailings Pile.
Radon Emission Rate is 280 pCi/m^2s.

Chapter 6) at that distance. The directions may differ since "risk" implies that an individual or population is present. In general, the direction of maximum concentration is the same as that of maximum risk; in those situations where it is not, the concentration for the direction of maximum risk does not differ in any practical sense from that in the direction of maximum concentration. Data in Table 5-1 and subsequent tables are presented to two significant figures to facilitate comparisons and not to indicate that environmental values can be calculated to that level of accuracy.

Table 5-2 shows population inhalation intakes of particulates and radon decay product exposures, calculated for a year's release during the operational period. The population distributions are shown in Tables 4-2 and 4-3. Note that the total intake/exposure values for the remote site are less than those for the rural one even though the remote site has a larger regional population. The larger nearby population of the rural site substantially increases the regional intakes and exposures for that site. Post-operational regional concentrations for particulates and radon are shown in Table 5-4. The entire tailings pile area is assumed to be dry in this period, so the emissions are 80/50 times the values for the operational phase.

National

National population exposures during the post-operational phase of the model mill are calculated in the same way as those for the operational phase. The radon source term, Table 4-6, during this phase is 7000 curies per year and the exposures shown in Table 5-5 are the total exposures for each year that the tailings pile continues to exist.

Annual national population exposures to radon emissions during the operational phase of the model mill are shown in Table 5-3. The total source term of 4400 curies per year (from Table 4-6) is attributed to each site in turn; the average value for all sites is also shown. These exposures assume an equilibrium fraction of 0.7 and exclude the population living within 50 miles of the sites. The values represent the total exposure to this population which results from each year's operation of the mill.

5.4.3 Ground Surface Concentrations

Operational

Table 5-6 shows the regional ground surface concentrations of radionuclides for the operational phase of the mill. These values are calculated after 15 years of operation. The "average" and "maximum" headings again refer to the average for all directions and the direction of maximum risk for all pathways.

Table 5-1. Regional Air Concentration (Ci/m^3) of Radionuclides by Distance and Particle Size (Operational Phase)

Distance (meters)	Average[a] 5 μm	Average[a] 35 μm	Maximum[b] 5 μm	Maximum[b] 35 μm
		^{238}U, ^{234}U		
600	3.7E-16	6.5E-17	6.3E-16	1.5E-16
1000	1.1E-16	1.8E-17	2.2E-16	5.6E-17
2000	2.8E-17	3.5E-18	6.3E-17	1.3E-17
3000	1.2E-17	1.4E-18	2.9E-17	5.5E-18
4000	7.0E-18	6.9E-19	1.7E-17	2.8E-18
5000	4.6E-18	4.2E-19	1.1E-17	1.7E-18
10000	1.2E-18	7.5E-20	3.0E-18	3.1E-19
20000	3.2E-19	1.3E-20	8.8E-19	5.4E-20
		^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po		
600	5.2E-15	9.3E-16	9.0E-15	2.2E-15
1000	1.6E-15	2.5E-16	3.1E-15	7.9E-16
2000	3.9E-16	5.0E-17	9.0E-16	1.9E-16
3000	1.8E-16	2.0E-17	4.2E-16	7.8E-17
4000	1.0E-16	9.8E-18	2.4E-16	4.0E-17
5000	6.6E-17	6.0E-18	1.6E-16	2.4E-17
10000	1.6E-17	1.1E-18	4.2E-17	4.4E-18
20000	4.6E-18	1.9E-19	1.3E-17	7.7E-19
		^{222}Rn		
600	1.3E-09		2.0E-09	
1000	4.4E-10		7.7E-10	
2000	1.4E-10		2.7E-10	
3000	7.0E-11		1.4E-10	
4000	4.6E-11		9.5E-11	
5000	3.4E-11		6.9E-11	
10000	1.3E-11		2.6E-11	
20000	5.6E-12		1.1E-11	

[a] Value averaged over all directions.
[b] Value for direction of greatest risk.

Table 5-2. Regional Population Inhalation Intake and Exposure (per Operational Year)

Distance (km)	Number of Persons	Inhalation (person-pCi): ^{238}U, ^{234}U 5 μm	^{238}U, ^{234}U 35 μm	^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po 5 μm	^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po 35 μm	Radon Decay Product Exposure (person-WLy)
			Remote Site[a]			
20	16	6.9	1.5	1.0E+02	2.2E+01	2.4E-02
20-40	4,572	4.9	7.5E-02	6.9E+01	1.1	1.5E-01
40-80	52,840	2.6E+01	7.3E-01	3.7E+02	1.0E+01	7.3E-01
Total	57,428	3.8E+01	2.3	5.4E+02	3.3E+01	8.9E-01
			Rural Site[a]			
20	2,273	2.0E+03	1.8E+02	2.8E+04	2.5E+03	7.0
20-40	5,314	1.2E+01	4.4E-01	1.8E+02	6.3	2.0E-01
40-80	14,235	2.8	3.6E-02	4.0E+01	5.1E-01	1.4E-01
Total	21,822	2.0E+03	1.8E+02	2.8E+04	2.6E+03	7.3

[a] See Chapter 4 for description of sites.

Table 5-3. National Population Exposures and Intakes (per Operational Year)

Release Site	Exposures: ^{222}Rn (person-Ci-y/m^3)	Exposures: Radon Decay Product (person-WLy)	^{210}Pb Intakes: Inhalation (person-Ci)	^{210}Pb Intakes: Ingestion (person-Ci)
New Mexico				
Grants	3.1E-07	2.2	7.7E-07	4.4E-06
Texas				
Falls City	4.8E-07	3.3	8.2E-07	2.7E-06
Washington				
Wellpinit	2.6E-07	1.9	7.9E-07	5.3E-06
Wyoming				
Casper	3.7E-07	2.6	9.4E-07	4.8E-06
Average	3.5E-07	2.5	8.3E-07	4.4E-06

Table 5-4. Regional Air Concentration (Ci/m^3) of Radionuclides by Distance and Particle Size[(a)] (Post-Operational Phase)

Distance (meters)	Average[(a)] 5 µm	Average[(a)] 35 µm	Maximum[(b)] 5 µm	Maximum[(b)] 35 µm
		^{238}U, ^{234}U		
600	5.9E-16	1.0E-16	1.0E-15	2.4E-16
1000	1.8E-16	2.8E-17	3.5E-16	8.9E-17
2000	4.4E-17	5.6E-18	1.0E-16	2.1E-17
3000	2.0E-17	2.2E-18	4.7E-17	8.7E-18
4000	1.1E-17	1.1E-18	2.7E-17	4.4E-18
5000	7.4E-18	6.7E-19	1.8E-17	2.7E-18
10000	1.8E-18	1.2E-19	4.8E-18	4.9E-19
20000	5.2E-19	2.1E-20	1.4E-18	8.6E-20
		^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po		
600	8.4E-15	1.5E-15	1.4E-14	3.5E-15
1000	2.6E-15	4.0E-16	5.0E-15	1.3E-15
2000	6.3E-16	8.0E-17	1.4E-15	3.0E-16
3000	2.8E-16	3.2E-17	6.7E-16	1.2E-16
4000	1.6E-16	1.6E-17	3.9E-16	6.3E-17
5000	1.1E-16	9.6E-18	2.6E-16	3.9E-17
10000	2.6E-17	1.7E-18	6.8E-17	7.0E-18
20000	7.3E-18	3.0E-19	2.0E-17	1.2E-18
		^{222}Rn		
600	2.0E-09		3.2E-09	
1000	7.1E-10		1.2E-09	
2000	2.2E-10		4.4E-10	
3000	1.1E-10		2.3E-10	
4000	7.4E-11		1.5E-10	
5000	5.4E-11		1.1E-10	
10000	2.0E-11		4.1E-11	
20000	9.0E-12		1.8E-11	

(a) Value averaged over all directions.
(b) Value for direction of greatest risk.

Table 5-5. National Population Exposures and Intakes Per Year (Post-Operational Phase)

Release Site	Exposures: ^{222}Rn (person-Ci-y/m^3)	Exposures: Radon Decay Products (person-WLy)	^{210}Pb Intakes: Inhalation (person-Ci)	^{210}Pb Intakes: Ingestion (person-Ci)
New Mexico				
Grants	4.9E-07	3.5	1.2E-06	7.0E-06
Texas				
Falls City	7.6E-07	5.3	1.3E-06	6.4E-06
Washington				
Wellpinit	4.2E-07	3.0	1.3E-06	8.4E-06
Wyoming				
Casper	5.8E-07	4.1	1.5E-06	7.7E-06
Average	5.7E-07	4.0	1.3E-06	7.0E-06

Table 5-6. Regional Ground Surface Concentrations (Ci/m^2) for Radionuclides[(a)] (Operational Phase)

Distance (meters)	^{238}U, ^{234}U Average	^{238}U, ^{234}U Maximum	^{230}Th, ^{226}Ra Average	^{230}Th, ^{226}Ra Maximum	^{210}Pb, ^{210}Po Average	^{210}Pb, ^{210}Po Maximum
600	3.9E-09	8.1E-09	5.5E-08	1.2E-07	5.3E-08	1.1E-07
1000	1.1E-09	2.9E-09	1.6E-08	4.2E-08	1.5E-08	4.0E-08
2000	2.4E-10	7.4E-10	3.5E-09	1.0E.08	3.3E-09	1.0E-08
3000	1.0E-10	3.2E-10	1.5E-09	4.6E-09	1.4E-09	4.4E-09
4000	5.5E-11	1.7E-10	7.8E-10	2.5E-09	7.5E-10	2.4E-09
5000	3.5E-11	1.1E-10	5.0E-10	1.6E-09	4.8E-10	1.5E-09
10000	7.7E-12	2.4E-11	1.1E-10	3.5E-10	1.1E-10	3.3E-10
20000	1.9E-12	5.9E-12	2.7E-11	8.4E-11	2.6E-11	8.1E-11

(a) Average: value averaged over all directions.
Maximum: value for direction of greatest risk.

Table 5-7. Regional Population Ground Surface Exposure (person-Ci/m^2) for Radionuclides (per Operational Year)

Distance (km)	Number of Persons	^{238}U, ^{234}U	^{230}Th, ^{226}Ra	^{210}Pb, ^{210}Po
		Remote Site[(a)]		
20	16	3.3E-08	4.7E-07	4.2E-07
20-40	4,572	9.9E-09	1.4E-07	1.2E-07
40-80	52,840	5.9E-08	8.4E-07	7.4E-07
Total	57,428	1.0E-07	1.5E-06	1.3E-06
		Rural Site[(a)]		
20	2,273	5.8E-06	8.3E-05	7.3E-05
20-40	5,314	2.9E-08	4.1E-07	3.6E-07
40-80	14,235	5.9E-09	8.4E-08	7.5E-08
Total	21,822	5.8E-06	8.3E-05	7.3E-05

[(a)] See Chapter 4 for description of sites.

Table 5-8. Regional Ground Surface Concentrations (Ci/m^2) for Radionuclides by Distance[(a)] (Post-Operational Phase)

Distance (meters)	^{238}U, ^{234}U Average	^{238}U, ^{234}U Maximum	^{230}Th, ^{226}Ra Average	^{230}Th, ^{226}Ra Maximum	^{210}Pb, ^{210}Po Average	^{210}Pb, ^{210}Po Maximum
600	2.1E-08	4.3E-08	2.9E-07	6.2E-07	2.6E-07	5.5E-07
1000	5.9E-09	1.6E-08	8.4E-08	2.2E-07	7.4E-08	2.0E-07
2000	1.3E-09	3.9E-09	1.8E-08	5.6E-08	1.6E-08	4.9E-08
3000	5.5E-10	1.7E-09	7.8E-09	2.4E-08	6.9E-09	2.2E-08
4000	2.9E-10	9.2E-10	4.2E-09	1.3E-08	3.7E-09	1.2E-08
5000	1.9E-10	5.9E-10	2.7E-09	8.4E-09	2.4E-09	7.4E-09
10000	4.1E-11	1.3E-10	5.9E-10	1.8E-09	5.2E-10	1.6E-09
20000	1.0E-11	3.2E-11	1.5E-10	4.5E-10	1.4E-10	4.4E-10

[(a)] Average: value averaged over all directions.
Maximum: value for direction of greatest risk.

Regional population surface exposures for the operational phase corresponding to these concentrations are shown in Table 5-7. These values give the total exposure to the population for each year's operation of the mill.

The national population dose resulting from deposition of radon decay products, primarily the long-lived lead-210, is dominated by the ingestion pathway. For this reason, separate ground surface exposures are not given here. Intakes due to ingestion are discussed in Section 5.4.4.

Post Operational

Post-operational regional ground surface concentrations are given in Table 5-8. These representative values are calculated for the end of a 100-year release period.

Since only the magnitude of the source term is different, post-operational surface exposures are not listed separately. They may be obtained by multiplying the values in Table 5-7 by factor 1.6.

Separate national ground exposures are not shown, since they are not significant compared to ingestion doses, which are given below.

5.4.4 Dietary Intake

Food consumption fractions for the regional population are shown in Table 5-9. We have assumed that the mill is sited in a region of low agricultural productivity and that area residents produce the same amount of their own food supply as urban residents.

Table 5-9. Regional Food Utilization Factors for An Individual

Type of Food	Home Produced (Percent)	Total Annual Consumption
Leafy vegetables	7.6	18 kg
Other produce	7.6	176 kg
Milk	0.0	112 L
Meat	0.8	85 kg

Annual ingestion intakes for an individual residing in the region are given in Table 5-10 for the operational phase and in Table 5-11 for the post-operational phase. Annual regional population ingestion values for the operational phase are given in Table 5-12. Since the only difference is in the source term, values for the post-operational phase are a factor of 1.6 larger than those in Table 5-12.

Annual national population exposures due to the ingestion of long-lived radon decay products are dominated by lead-210. Dose and risk calculations take account of the lead decay products as they build up within the body following lead-210 intake. Table 5-3 gives the annual population exposure resulting from dietary intake of lead-210 during the operational phase of the model mill. Post-operational exposures are shown in Table 5-5.

5.4.5 Water Concentrations

In general, meaningful modeling of water pathways can be done only on a site-specific basis, since any model depends strongly on the hydrological and geological characteristics of the area. NRC (NRC80) has performed a detailed analysis for the model mill based on a set of assumed parameters. However, the environmental impact of a given tailings pile depends on so many factors, i.e., wind erosion, floods, slides into nearby streams, seepage through the pile, runoff of rainwater, etc., that each must be evaluated on an ad hoc basis.

Surface Water

During operation of the mill, the pathways noted in Section 5.3 could cause the transfer of contaminants to surface waters. However, based on the rainfall in the model mill region, the quantities of material washed or leached into flowing surface waters could be so dispersed and rapidly diluted that it is unlikely that surface water would pose a significant health problem. Since the moisture content of the tailings is reduced after mill operations cease, the potential for surface water contamination is even less.

Under the Clean Water Act, effluent guidelines are already in effect for uranium mills. In addition, EPA has New Source Performance Standards for new uranium mills that would eliminate the discharge of process waste water. In view of this comprehensive regulatory program for surface water discharges from the uranium milling industry, surface water contamination is not addressed in this analysis.

Groundwater

The modeling of groundwater contamination by tailings piles depends strongly on the chemical and physical properties of the underground environment. The NRC model predicts that, in spite of the initial presence of radioactive materials in the seepage, no

Table 5-10. Regional Individual Annual Ingestion (pCi) for Radionuclides[a]
(Operational Phase)

Distance (meters)	^{238}U, ^{234}U Average	^{238}U, ^{234}U Maximum	^{230}Th Average	^{230}Th Maximum	^{226}Ra Average	^{226}Ra Maximum	^{210}Pb Average	^{210}Pb Maximum	^{210}Po Average	^{210}Po Maximmum
600	3.3E+01	6.9E+01	4.6E+02	9.6E+02	7.3E+02	1.5E+03	4.7E+03	1.0E+03	4.1E+02	8.6E+02
1000	9.4	2.5E+01	1.3E+02	3.4E+02	2.1E+02	5.5E+02	1.3E+02	3.6E+02	1.2E+02	3.1E+02
2000	2.1	6.3	2.8E+01	8.6E+01	4.6E+01	1.4E+02	3.0E+01	9.0E+01	2.6E+01	7.8E+01
3000	8.7E-01	2.7	1.2E+01	3.8E+01	1.9E+01	6.0E+01	1.3E+01	3.9E+01	1.1E+01	3.4E+01
4000	4.7E-01	1.5	6.4	2.0E+01	1.0E+01	3.2E+01	6.7	2.1E+01	5.8	1.8E+01
5000	3.0E-01	9.4E-01	4.1	1.3E+01	6.6	2.1E+01	4.3	1.3E+01	3.7	1.2E+01
10000	6.6E-02	2.1E-01	9.1E-01	2.8	1.4	4.5	9.4E-01	3.0	8.2E-01	2.6
20000	1.6E-02	5.0E-02	2.3E-01	6.9E-01	3.6E-01	1.1	2.4E-01	7.2E-01	2.0E-01	6.3E-01

(a)Average: value averaged over all directions.

Maximum: value for direction of greatest risk.

Table 5-11. Regional Individual Annual Ingestion (pCi) for Radionuclides (Post-Operational Phase)[a]

Distance (meters)	^{238}U, ^{234}U Average	Maximum	^{230}Th Average	Maximum	^{226}Ra Average	Maximum	^{210}Pb Average	Maximum	^{210}Po Average	Maximmum
600	5.7E+01	1.2E+02	7.3E+02	1.5E+03	2.2E+03	4.5E+03	8.2E+02	1.7E+03	6.6E+02	1.4E+03
1000	1.6E+01	4.3E+01	2.1E+02	5.5E+02	6.1E+02	1.6E+03	2.3E+02	6.2E+02	1.9E+02	5.0E+02
2000	3.6	1.1E+01	4.6E+01	1.4E+02	1.4E+02	4.1E+02	5.1E+01	1.6E+02	4.1E+01	1.3E+02
3000	1.5	4.7	1.9E+01	6.1E+01	5.7E+01	1.8E+02	2.2E+01	6.8E+01	1.7E+01	5.5E+01
4000	8.0E-01	2.5	1.0E+01	3.3E+01	3.0E+01	9.6E+01	1.2E+01	3.6E+01	9.3	2.9E+01
5000	5.1E-01	1.6	6.6	2.1E+01	2.0E+01	6.2E+01	7.4	2.3E+01	6.0	1.9E+01
10000	1.1E-01	3.6E-01	1.5	4.6	4.3	1.4E+01	1.6	5.1	1.3	4.1
20000	2.8E-02	8.7E-02	3.6E-01	1.1	1.1	3.3	4.1E-01	1.2	3.3E-01	1.0

(a)Average: value averaged over all directions.

Maximum: value for direction of greatest risk.

radioactive contamination of groundwater would be expected during or after mill operation. Based on their parameters, many of the contaminants present in the acidic tailings pond water would precipitate out or undergo ion exchange and be removed by soil from the tailings seepage water. Potential contamination, as indicated by this model, would be limited to toxic materials having relatively high mobility. The health aspects of these materials are discussed in Chapter 6.

Since control of groundwater pollution is already required for conformance with existing water protection regulations, we have not performed a detailed analysis for this pathway.

Table 5-12. Regional Population Ingestion (person-pCi) for Radionuclides (per Operational Year)

Distance (km)	Number of Persons	^{238}U, ^{234}U	^{230}Th	^{226}Ra	^{210}Pb	^{210}Po
			Remote Site[a]			
20	16	1.4	1.8E+01	5.6E+01	2.3E+01	2.7E+01
20-40	4,572	4.1E+02	5.3E+03	1.6E+04	6.5E+03	7.8E+03
40-80	52,840	4.7E+03	6.0E+04	1.8E+05	7.5E+04	9.0E+04
Total	57,428	5.1E+03	6.5E+04	2.0E+05	8.2E+04	9.8E+04
			Rural Site[a]			
20	2,273	3.0E+02	3.9E+03	1.2E+04	4.7E+03	5.0E+03
20-40	5,314	7.1E+02	9.1E+03	2.8E+04	1.1E+04	1.2E+04
40-80	14,235	1.9E+03	2.4E+04	6.9E+04	2.9E+04	3.1E+04
Total	21,822	2.9E+03	3.7E+04	1.1E+05	4.5E+04	4.8E+04

(a) See Chapter 4 for description of sites.

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Chapter 6: HEALTH IMPACT OF TAILINGS BASED ON MODEL TAILINGS PILES

In this chapter we consider the health impact of material coming from the model pile. When feasible, projections, based on these results, for the total impact of the industry are developed in Chapter 10. Data on the concentrations of radioisotopes for individuals or populations at various distances from the model pile, taken from Chapter 5, were combined with the risk coefficients described in Appendix C to estimate the risks to individuals and populations living around the model pile. Potential effects on local, regional, and national populations are estimated.

6.1 Introduction

Among metallic ore wastes, uranium tailings piles are unusual because of the amount of radioactivity they contain. Radioactivity probably constitutes the principal source of hazard to health from these wastes, although nonradioactive toxic chemicals, such as arsenic, lead, selenium, mercury, sulphates, and nitrates are usually present. Milling of uranium ore removes about 90 percent of the uranium in the ore. The remainder, along with most other radioactive materials and toxic chemicals, is discarded in the liquid and solid wastes discharged to tailings piles.

The principal isotope of uranium, uranium-238, decays over billions of years to become lead, a stable nonradioactive element. This lengthy decay process involves a series of intermediate radioactive decay products, such as thorium-230, radium-226, and radon-222. The decay of uranium since the ore was formed millions of years ago has built up an inventory of these decay products, which are present in uranium mill tailings in various concentrations.

The dominant hazard from tailings is due to the radioactive decay products of uranium-238, particularly radium-226 and its short half-life decay products. Each gram of natural uranium ore contains about 490 pCi each of uranium-238 and uranium-234 and additionally about 23 pCi of uranium-235 and 2 pCi of thorium-232. Because they occur in relatively small proportions and/or pose much less risk to health, uranium-235 and thorium-232 and their radioactive decay products may usually be ignored in evaluating the hazard of uranium tailings.

Uranium tailings emit three kinds of radiation: alpha particles, beta particles, and gamma rays. All are forms of ionizing radiation, which breaks up molecules into electrically charged fragments called ions. In biological tissues, this ionization can produce harmful cellular changes. At the low radiation levels usually encountered in the environment, we expect the effects of such changes to be difficult to detect. Studies show, however, that people exposed to radiation have a greater chance of developing cancer. If the ovaries or testes are exposed, the health or development of future generations of children may also be impaired due to genetic damage. This genetic damage includes gene mutations and chromosome aberrations. Effects of the damage may be conspicuous or invisible, serious or trivial, with a possibility of occurring in the first generation after exposure or hundreds of generations in the future (NAS80). Only effects causing serious handicap at sometime during the lifespan are addressed in this document.

One cannot predict with precision the increased chance of cancer or genetic damage after exposure to radiation. We have based our risk estimates on studies of persons exposed at doses higher than those usually resulting from tailings and the assumption that at lower doses the effects will be proportionally less. This assumption may overestimate or underestimate the actual risk, but it is the best that can be done at present (EPA76).

Alpha, beta, and gamma radiations from mill tailings can cause cancer or genetic damage. However, the major threat comes from breathing air containing radon decay products with short half-lives--polonium-218, for example--and exposing the lungs and other internal organs to the alpha radiation these decay products emit. In addition, people may be directly exposed to gamma rays from radioactive material in the tailings pile, and radioactive tailings particles may be transported into the body by breathing or ingestion.

The body's internal organs would still be exposed to radiation from radionuclides even if uranium tailings piles suddenly disappeared, because radon, radium, uranium, thorium, and other radioactive elements occur naturally in the air, rock, and soil. One picocurie of radium per gram of soil is a typical concentration; outdoor air contains a few tenths of a picocurie of radon per liter (UN77). Normal eating and breathing introduce these and other radioactive materials into the body, increasing the potential for cancer and genetic damage. This discussion, therefore, also compares the health risks from tailings to those from normal exposure--not to justify the tailings risk, but to provide a realistic context for comparison.

Tailings also contain toxic elements that could eventually be inhaled or ingested by man and animals or absorbed by plants. Windblown tailings inhaled by man or animals are unlikely to cause any toxicity problems because the mass of inhaled material is so small. However, the toxic elements in windblown tailings could be absorbed by plants growing near a pile and could be a potential pathway leading to chronic toxicity diseases in men or animals eating those plants. Moreover, toxic elements from tailings could leach or seep into water supplies used for irrigation or drinking. Finally, windblown tailings and radon decay products could be deposited directly onto some foods, such as lettuce and spinach.

It is important to distinguish between acute and chronic toxicity. Acute toxicity (or poisoning) occurs when enough of the toxic element is consumed to interfere with a vital body or organ function. The severity of the poisoning is usually proportional to the amount of the toxic element consumed, and in extreme cases death or permanent injury will occur. Chronic toxicity is more insidious. It occurs when small amounts of a toxic element are consumed over a prolonged period of time. A small fraction of each intake may be deposited in tissues or organs. Toxic symptoms appear when the cumulative deposit exceeds a critical level. Alternatively, each intake of a toxic element may cause a small increment of organ damage. Symptoms of toxicity become apparent when this damage accumulates to a critical extent. Symptoms of chronic toxicity may be reversible if consumption of the toxic element is stopped, or they may be irreversible, progressive, or both.

In the case of tailings, acute toxicity would be a problem only if standing water adjacent to or on a pile is consumed. Chronic toxicity is more likely and is therefore examined in later discussions.

6.1.1 Radon and its Immediate Decay Products

Since the milling and extraction processes have removed most of the uranium from the ore, the longevity of the remaining radioactive members of the uranium series is determined by the presence of thorium-230, which has a 77,000-year half-life. The thorium-230 decay product, radium-226, has a 1,600-year half-life. Both thorium and radium are relatively insoluble and immobile in their usual chemical forms. However, the decay product of radium-226 is radon-222, an inert radioactive gas, that readily diffuses through interstitial spaces to the surface of the tailings pile where it becomes airborne. The half-life of radon-222 is 3.8 days, so some radon atoms can travel thousands of miles through the atmosphere before they decay.

As shown in Figure 3-1, the radon decay process involves seven principal decay products before ending with nonradioactive lead. The four short half-life radioactive decay products immediately following radon are the most important sources of cancer risk. These decay, for the most part, within less than an hour. Members of the decay chain with relatively long half-lives (beginning with lead-210, which has a 22-year half-life) are more likely to be ingested than breathed and represent much smaller risks.

The principal short half-life products of radon are polonium-218, lead-214, bismuth-214, and polonium-214. Polonium-218, the first decay product, has a half-life of just over 3 minutes. This is long enough for most of the electrically charged polonium atoms to attach themselves to microscopic airborne dust particles that are typically less than a millionth of a meter across. When breathed, these small particles have a good chance of sticking to the moist epithelial lining of the bronchi.

Most inhaled particles are eventually cleared from the bronchi by mucus, but not quickly enough to keep the bronchial epithelium from being exposed to alpha radiation from polonium-218 and polonium-214. This highly ionizing radiation passes through and delivers radiation doses to several types of lung cells. The exact doses delivered to cells that eventually become cancerous cannot be characterized adequately. Also, we do not have detailed knowledge of the deposition pattern of the radioactive particles in the lung and the distances from them to cells that are susceptible. Further, there is some disagreement about the types of bronchial cells where cancer originates. Therefore, we have based our estimates of lung cancer risk on the amount of inhaled radon decay products to which people are exposed, rather than on the dose absorbed by the lung.

6.2 Estimated Effects on Health Due to Radioactive Releases from the Model Tailings Pile

Risk factors from Tables C-3 to C-10 (see Appendix C) were used in the DARTAB computer code to determine individual and population lifetime risks for continuous exposure to emissions from the model tailings pile. The calculated health impact on individuals and populations is shown in Tables 6-1 through 6-6. The risk averages given are population averages over the indicated sector. As shown in these tables, about 99 percent of the inhalation risk is due to radon and its daughters.

Values in these tables are shown to two significant figures solely to facilitate comparisons and additional calculations; these projections have overall uncertainties of at least a factor of 2 or 3. The individual health risks are for a lifelong exposure to the environmental concentrations discussed in Chapter 5. A shorter period of exposure may be assessed by assuming that the risk due to that exposure or intake had been spread over the individual's lifetime. For example, the risk from a 15-year exposure would be approximated as 15/70.76 times the lifetime (70.76 years is the expected lifespan of an individual in the RADRISK cohort). The population health effect values are the number of cancer deaths per year calculated at equilibrium for a stationary population living at the calculated environmental concentration levels. These values are equivalent to the number of health effects committed per year of operation. (The age distribution of the stationary population is that for the U.S. life table population in 1970, assuming a constant birth rate, and no external migration.)

Table 6-1. Regional Individual Lifetime Risk of Fatal Cancer (Operational Phase)

Distance (meters)	Ingestion		Particulates--Inhalation		Ground Surface Exposure		Radon Decay Products		Total	
	Average[a]	Maximum[b]	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum
1000	3.2E-06	8.5E-06	1.9E-05	3.8E-05	2.2E-05	5.9E-05	5.3E-03	9.2E-03	5.3E-03	9.3E-03
2000	7.0E-07	2.1E-06	4.6E-06	1.1E-05	4.9E-06	1.5E-05	1.6E-03	3.2E-03	1.6E-03	3.2E-03
3000	3.0E-07	9.3E-07	2.0E-06	5.0E-06	2.1E-06	6.5E-06	8.3E-04	1.7E-03	8.3E-04	1.7E-03
4000	1.6E-07	5.0E-07	1.1E-06	2.8E-06	1.1E-06	3.5E-06	5.5E-04	1.1E-03	5.5E-04	1.1E-03
5000	1.0E-07	3.2E-07	7.6E-07	1.9E-06	7.1E-07	2.2E-06	4.0E-04	8.2E-04	4.0E-04	8.2E-04
10000	2.2E-08	7.0E-08	1.9E-07	4.9E-07	1.6E-07	4.9E-07	1.5E-04	3.1E-04	1.5E-04	3.1E-04
20000	5.6E-09	1.7E-08	5.2E-08	1.4E-07	3.9E-08	1.2E-07	6.6E-05	1.3E-04	6.6E-05	1.3E-04

[a] Average population weighted dose over all wind directions.

[b] Dose to individual in direction of maximum exposure

Table 6-2. Regional Individual Lifetime Risk of Fatal Cancer (Post-Operational Phase)

Distance (meters)	Ingestion		Particulates--Inhalation		Ground Surface Exposure		Radon Decay Products		Total	
	Average[(a)]	Maximum[(b)]	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum
1000	7.2E-06	1.9E-05	3.0E-05	6.1E-05	1.2E-04	3.1E-04	8.4E-03	1.5E-02	8.6E-03	1.5E-02
2000	1.6E-06	4.8E-06	7.3E-06	1.7E-05	2.6E-05	7.9E-05	2.6E-03	5.2E-03	2.6E-03	5.3E-03
3000	6.7E-07	2.1E-06	3.2E-06	7.9E-06	1.1E-05	3.4E-05	1.3E-03	2.7E-03	1.3E-03	2.7E-03
4000	3.6E-07	1.1E-06	1.8E-06	4.5E-06	5.8E-06	1.8E-05	8.8E-04	1.8E-03	8.9E-04	1.8E-03
5000	2.3E-07	7.2E-07	1.2E-06	3.0E-06	3.7E-06	1.2E-05	6.4E-04	1.3E-03	6.5E-04	1.3E-03
10000	5.0E-08	1.6E-07	3.0E-07	7.8E-07	8.2E-07	2.6E-06	2.4E-04	4.9E-04	2.4E-04	4.9E-04
20000	1.3E-08	3.9E-08	8.2E-08	2.3E-07	2.1E-07	6.3E-07	1.1E-04	2.1E-04	1.1E-04	2.1E-04

(a) Average population weighted dose over all wind directions.

(b) Dose to individual in direction of maximum exposure.

Table 6-3. Number of Fatal Cancers per Operational Year for the Regional Population

Distance (km)	Number of Persons	Radioactive Particulates: Ingestion	Inhalation	Ground Surface	Subtotal	Radon Decay Products	Total
				Remote Site[a]			
20	16	1.0E-08	2.0E-06	9.4E-06	1.1E-05	5.7E-04	5.8E-04
20-40	4,572	2.9E-06	1.3E-06	2.8E-06	7.0E-06	3.5E-03	3.5E-03
40-80	52,840	3.4E-05	6.9E-06	1.7E-05	5.8E-05	1.7E-02	1.7E-02
Total	57,428	3.7E-05	1.0E-05	2.9E-05	7.6E-05	2.1E-02	2.1E-02
				Rural Site[a]			
20	2,273	2.1E-06	5.4E-04	1.6E-03	2.1E-03	1.7E-01	1.7E-01
20-40	5,314	4.9E-06	3.3E-06	8.3E-06	1.7E-05	4.8E-03	4.8E-03
40-80	14,235	1.3E-05	7.5E-07	1.7E-06	1.5E-05	3.3E-03	3.3E-03
Total	21,822	2.0E-05	5.5E-04	1.7E-03	2.3E-03	1.8E-01	1.8E-01

[a] See Chapter 4 for description of sites.

Table 6-4. Number of Fatal Cancers per Post-Operational Year for the Regional Population

Distance (km)	Number of Persons	Radioactive Particulates: Ingestion	Inhalation	Ground Surface	Subtotal	Radon Decay Products	Total
				Remote Site[a]			
20	16	1.6E-08	3.2E-06	1.5E-05	1.8E-05	9.1E-04	9.3E-04
20-40	4,572	4.6E-06	2.1E-06	4.5E-06	1.1E-05	5.6E-03	5.6E-03
40-80	52,840	5.4E-05	1.1E-05	2.7E-05	9.2E-05	2.7E-02	2.7E-02
Total	57,428	5.9E-05	1.6E-05	4.6E-05	1.2E-04	3.4E-02	3.4E-02
				Rural Site[a]			
20	2,273	3.4E-06	8.6E-04	2.6E-03	3.5E-03	2.7E-01	2.7E-01
20-40	5,314	7.8E-06	5.3E-06	1.3E-05	2.6E-05	7.7E-03	7.7E-01
40-80	14,235	2.1E-05	1.2E-06	2.7E-06	2.5E-05	5.3E-03	5.3E-03
Total	21,822	3.2E-05	8.8E-04	2.7E-03	3.6E-03	2.9E-01	2.9E-01

[a] See Chapter 4 for description of sites.

Table 6-5. U.S. Collective Risks due to ^{222}Rn Release per Operational Year (Fatal Cancers)

Release Site	^{210}Pb Intake: Inhalation	^{210}Pb Intake: Ingestion	^{210}Pb Intake: Total	Radon Decay Product Exposure
New Mexico				
Grants	1.0E-04	2.1E-04	3.2E-04	5.2E-02
Texas				
Falls City	1.1E-04	1.3E-04	2.4E-04	8.0E-02
Washington				
Wellpinit	1.1E-04	2.5E-04	3.6E-04	4.4E-02
Wyoming				
Casper	1.3E-04	2.3E-04	3.5E-04	6.1E-02
Average	1.1E-04	2.1E-04	3.2E-04	5.9E-02

Table 6-6. U.S. Collective Risks due to ^{222}Rn Release per Post-Operational Year (Fatal Cancers)

Release Site	^{210}Pb Intake: Inhalation	^{210}Pb Intake: Ingestion	^{210}Pb Intake: Total	Radon Decay Product Exposure
New Mexico				
Grants	1.6E-04	3.3E-04	5.0E-04	8.2E-02
Texas				
Falls City	1.8E-04	2.1E-04	3.8E-04	1.3E-01
Washington				
Wellpinit	1.7E-04	4.0E-04	5.7E-04	7.1E-02
Wyoming				
Casper	2.0E-04	3.7E-04	5.7E-04	9.8E-02
Average	1.8E-04	3.3E-04	5.1E-04	9.5E-02

6.2.1 Effects of Radioactive Particulate Releases from the Model Tailings Pile

Individuals and Regional Populations

Windblown tailings from the model tailings pile may be inhaled by persons in the vicinity of the pile. They may also be deposited on soil or vegetation, be transferred to edible plants and ingested by members of the population around the pile. The contribution of these two pathways is included in the risk estimates listed in Tables 6-1 to 6-4. The period for greatest risk from windblown particulates is during the post-operational phase of the mill after the tailings pile has been allowed to dry (Tables 6-2, 6-4).

The risk (expectation of developing a fatal cancer) to an individual for a lifelong exposure is shown in Tables 6-1 and 6-2 as a function of distance from the center of the pile. Risks from all pathways of exposure are listed for the maximum exposed individual at each distance. Depending on whether the local population density is high or low, e.g., a rural site versus a remote site, the expected number of fatal cancers in the regional population may vary by orders of magnitude as shown in Tables 6-3 and 6-4.

Genetic effects from windblown particulates were also calculated for the two site populations. For the rural site, we calculate a commitment of 7×10^{-4} genetic effects per operational year and 1×10^{-3} genetic effects per year after operations cease. The corresponding values for the remote site are 1×10^{-4} genetic effects per operational year and 2×10^{-4} thereafter. As indicated in Appendix C these are order-of-magnitude estimates of the genetic effects to all future generations.

6.2.2 Effects of Radon Emissions from Tailings Piles

Individuals and Regional Populations

Detailed information is needed to determine the exposure due to radon decay products in a population. An accurate calculation of the collective exposure from a particular pile would require, in addition to the number of people exposed, the site and ventilation characteristics of each person's residence and work place, the length of time a person spends at each place, and the average annual distribution of wind speed and direction.

We have estimated local and regional exposure at the model site using the methods to estimate exposures described in Section 5.4. The population data used are those presented in Chapter 4, although future changes are almost certain. Some population data are updated in Section 6.6 below.

The excess risk to people due to exposure to radon decay products depends on their distance from the pile. Tables 6-1 and 6-2 list estimated excess risks to individuals for lifetime residency, as a function of distance from a model pile during operational and post-operational phases of the pile, respectively. The decay product concentrations are based on a dispersion factor that depends on the area of the pile out to a distance of several pile diameters. Beyond that distance the theoretical pile can be considered as a point source for the purpose of estimating concentration levels. The estimates for this pile are based upon the <u>relative</u> risk model and assume a stationary population. We estimate the maximum lifetime risk of fatal cancer to an individual living 600 meters from the center of the pile is 1.2×10^{-2} during the operational period and 1.9×10^{-2} during the post-operational period.

The estimated risk of lung cancer from naturally-occurring radon decay products found in homes that are not near mill tailings or any other specifically identified radon source is 0.004 to 4 chances in 1,000 (EPA82). National data on radon decay products in homes (EPA82) are scanty and vary widely among individual houses. These estimates are based on the assumption that the average radon decay product concentration is 0.004 WL in homes and that they are occupied 75 percent of the time. This assumed average level of radon decay products is based on recent data on 21 houses in New York and New Jersey (Ge78) and on 26 houses in Florida (EPA79) and is consistent with data obtained in other countries (UN77). For comparison, these risks are about 10 percent of the expected lifetime risk of lung cancer death from all causes (0.029) in a stationary population having 1970 U.S. lung cancer mortality rates.

Effects on the U.S. Population

Radon emissions from a tailings pile may affect the health of populations beyond 80 kilometers from tailings piles. The aggregate effect on persons living more than 80 kilometers from the pile is summarized in Tables 6-5 and 6-6. These results are estimates of the total risk committed over 100 years to an exposed population of 200 million persons. Although the U.S. population increase has not been uniform, an increased risk on the order of 20 percent should provide a rough estimate of the risk to the current population.

Effects from Long-Lived Radioactive Decay Products of Radon

The long-lived decay products of radon, beginning with lead-210 (see Figure 3-1), are also potential hazards. A quantitative estimate of the impact of eating and breathing long-lived decay products from the model pile cannot be established without site-specific information--on food sources (Tr79), for example. The only detailed study available was prepared by Oak Ridge National Laboratory (Tr79) for the four sites listed in Chapter 5. We used these results in an input to our risk models to compare their importance to that of the short-lived decay products of radon. These comparisons are shown in Tables 6-5 and 6-6. These results should not be taken as quantitative estimates of the actual risk at specific active sites.

The four sources of exposure in this analysis are shown in Tables 6-1 to 6-4. The largest risk is from breathing short-lived radon decay products; the risk is 100 to 1000 times greater than the next highest risk, for both individuals and for the regional population. Persons living more than 80 kilometers from a model pile are less exposed, and their risk would be considerably below that indicated in Tables 6-1 to 6-4. But again, the risk from breathing short-lived radon decay products is about 100 times greater than from other pathways (Tables 6-5 and 6-6). We conclude that the risks from these pathways can be ignored compared to that from breathing short-lived radon decay products.

6.2.3 Effects of Gamma Radiation Emissions from Tailings Piles and Windblown Tailings

Gamma radiation exposure of individuals depends on how close to the edge of a pile people live or work and how tailings from the pile are distributed by the wind. The collective gamma radiation dose depends on both the number of people exposed and their doses. Potential individual doses can be approximated from available data, but accurate estimates cannot be made without a variety of detailed information, such as where people live and work and the amount of shielding provided by buildings.

Gamma radiation from tailings exposes the entire body so that all organs are at risk. The estimated frequency of fatal cancer and serious genetic effects due to exposure of 1 mrad/y are listed in Tables C-1 and C-2 in Appendix C. People who live or work near tailings piles will incur additonal risk from long-term exposures in proportion to the excess of their average lifetime annual dose rate above the normal background rate (approximately 100 mrem per year). The estimated contribution of gamma radiation emissions to individuals and populations in the vicinity of the model tailings pile is shown in Tables 6-1 to 6-4 in the column headed "Ground Surface."

6.3 Effects from Misuse of Tailings

When tailings are used in building construction, there can be serious risks to the health of those who live in such buildings. The Grand Junction experience is an example of what can happen when this kind of misuse occurs. There, about 700 buildings are contaminated with enough tailings to increase average indoor radon decay product levels by at least 0.01 WL; a few houses have levels higher than 0.5 WL. Assuming that the useful lifetime of these buildings is 70 years, we estimate about an additional 70-150 lung cancers would occur if remedial measures were not taken.

The estimated risks to individuals exposed to these high levels of radon decay products are very large. For persons living in a house with a concentration of 0.1 WL, the potential excess lifetime risk of lung cancer is 0.5 to 1 chance in 10.

Other misuses of tailings, e.g., tailings used in gardens or underneath detached buildings, can cause effects on health, but these cannot be estimated easily. The risks depend on the particular way in which the tailings are used, and effects on health may be due to gamma radiation, ingestion of radionuclides through food chains, or inhalation.

6.4 Estimated Effects on Health Due to Toxic Releases from the Model Tailings Pile

Toxic materials have been considered in this EIS if they are in substantially greater concentration in tailings than in native rocks or soils or in a relatively mobile form (as either anions or cations). We have included materials that are harmful to livestock and plants as well as those potentially affecting humans directly. Evaluating the potential risks from nonradioactive toxic substances in tailings requires different methods from those used for radioactive substances.(1) With nonradioactive toxic materials the type of effect varies with the material; the severity of the effect--but not its probability of occurring--increases with the dose. Moreover, because the body can detoxify some materials or repair the effects of some small doses, often no toxic effects occur below a threshold dose.

We cannot construct a numerical risk assessment for nonradioactive toxic substances because we do not have enough information. We can, however, qualitatively describe risks of toxic substances in terms of their likelihood of reaching people (or animals, or agricultural products), concentrations at which they may be harmful, and their toxic effects.

No acute effects--death in minutes or hours--could occur except by drinking liquid directly from a tailings pond. Severe sickness, or death within days to weeks, from the use of highly contaminated water is possible, but very unlikely.

Chronic toxicity from the continuous consumption of contaminants at low concentrations could be a problem. Toxic substances can accumulate slowly in tissues, causing symptoms only after some minimum amount has accumulated. Such symptoms of chronic toxity develop slowly, over months or years.

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(1)Many nonradioactive substances can induce cancer in experimental animals (Go77, Ve78). However, for nonradioactive substances found in uranium mill tailings, we do not feel that dose-response relationships adequate for estimating such risks for oral intake have been developed.

In Table 4-5 we listed many chemical elements and ions that have been found in tailings piles. Many of these occur in tailings in only slightly higher concentrations than in background soils, and they also have low toxicity when taken orally (Ve78). The following elements are in this category: lanthanides, including cerium, europium, lanthanum, and terbium; silicates; and zirconium, scandium, boron, gallium, and aluminum. Some other elements may be in elevated concentrations in tailings, but they, too, are not very toxic. These include copper, manganese, magnesium, cobalt, iron, vanadium, zinc, potassium, chloride, and sulfate. Some elements and ions at concentrations well below levels toxic to humans and animals will cause water to have an objectionable taste and color. Examples are iron, copper, manganese, chloride, and sulfate.

Other substances are both present in tailings and are regulated under the National Interim Primary Drinking Water Regulations (NIPDWR). Listing in the NIPDWR is an indication of a significant need to limit direct human consumption of these substances. The NIPDWR cover the following elements: arsenic, barium, cadmium, chromium, lead, mercury, nitrate, selenium, and silver. The toxicologies of these substances are discussed in Appendix C. Molybdenum is both toxic and present in tailings in elevated concentrations; its toxicity is also discussed in Appendix C. Appendix C also discusses both the chemical and radiological toxic effects of ingesting radium, thorium, and uranium. Tailings are not known to be significant sources of other toxic materials regulated under the NIPDWR, such as organic substances, microbiological organisms, and man-made radioactivity.

6.5 Effects Expected in Plants and Animals

No significant adverse effects are expected in plants or animals from radioactive emissions from the model tailings pile.

No attempt to estimate health effects from toxic materials released from the model tailings pile is made since such estimates require site-specific data on concentrations in water used for irrigation or watering livestock, agricultural practices, and so forth. Data on toxicity and an approach to estimating levels toxic to plants and animals are detailed in Appendix C. In a properly controlled tailings pile, there should be no hazard to plants or animals.

6.6 Total Radon Decay Product Population Risk from the Uranium Milling Industry

The estimate of the total population risk from radon emissions from all active tailings piles is presented in this section.

The number of people living within a 5-km radius of each tailings pile was counted by Battelle Pacific Northwest Laboratories (PNL) and is presented in Appendix E. The total number of people living within each annulus is:

Annulus (km from centroid of piles)	Number of People
0-0.5	31
0.5-1.0	211
1.0-2.0	1,812
2.0-3.0	1,109
3.0-4.0	6,070
4.0-5.0	5,504
Total	14,737

The population risk to these people was estimated by multiplying the number of people in each annulus by the average individual risk of fatal cancer at the enter of each annulus. This risk was extrapolated from the values given in Table 6-2, except for the 0-0.5 km annulus where the maximum individual risk was used. The total risk to the population within 5 km of tailings piles is estimated to be 0.38 deaths per year.

The number of people (3,649,271) living within the 5- to 80-km annulus of each tailings pile was calculated from 1970 Bureau of Census data (Ew73). A large part of this population was due to six sites: 2 in Texas which are within 80 km of San Antonio, 2 in Washington which are about 40 km from Spokane, 1 in New Mexico which is within 80 km of Albuquerque, and 1 in Colorado which includes Pueblo and Colorado Springs within 80 km. While the total number of people was greater than an equivalent number of model remote sites (see Table 4-2), the distribution was similar with most of the people located in the 40 and 80 km annulus. Therefore, it was considered reasonable to estimate the risk using the model remote site and correcting for the difference in total populations.

The population risk to the people living in the 5 to 80 km annuli of the 26 active piles is then:

$$(26 \text{ piles})\ (0.034\ \frac{\text{deaths}}{\text{pile/y}})\ (\frac{3,649,271}{26 \times 57,420}) = 2.1\ \frac{\text{deaths}}{\text{year}}$$

where the risk conversion factor is taken from Table 6-4.

The nationwide collective risk is:

$$(26 \text{ piles})\ (0.095\ \frac{\text{deaths}}{\text{pile/y}}) = 2.47\ \frac{\text{deaths}}{\text{year}}$$

where the risk factor is from Table 6-6.

The total collective risk from existing piles is

0.-5.0 km	0.38
5.0-80 km	2.1
Nationwide	2.47
	4.95 deaths/year

The collective risk from new tailings piles is considered to be most like the risk from remote sites. Most future uranium milling is likely to occur in New Mexico, Utah, and Wyoming, the currently developed areas. Thus, the likelihood of a large regional population is vanishingly small; Albuquerque is the only large city in these areas. Also, current siting practice prevents locating uranium mills near heavily populated area, so the local (within 5 km) population should be very small. Therefore, the population risk from new piles is estimated using the remote site risk factor from Table 6-4, the nationwide risk factor from Table 6-6, and nine new piles as projected in the RIA:

$$(9 \text{ piles})\ (0.034\ \frac{\text{deaths}}{\text{pile/y}}) + (9)(0.095\ \frac{\text{deaths}}{\text{pile/y}}) = 1.16\ \frac{\text{deaths}}{\text{year}}$$

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Chapter 7: CONTROL OF TAILINGS DURING MILLING OPERATIONS

Releases of radioactive and nonradioactive hazardous materials from tailings during milling operations are controlled by existing standards and regulations, for the most part. Control of radioactive emissions and effluents from tailings is required by the Atomic Energy Act (AEA) and the Clean Water Act (CWA). Also, UMTRCA requires that environmental standards for nonradioactive hazardous materials be consistent with standards under the Solid Waste Disposal Act (SWDA), as amended. Therefore, we briefly summarize existing standards and regulations applicable to releases from uranium tailings before we analyze controls for such releases during the operational phase of uranium byproduct material management.

EPA promulgated Environmental Radiation Protection Standards for Nuclear Operations on January 13, 1977 (40 CFR Part 190). These standards specify the radiation levels below which normal operations of the uranium fuel cycle are determined to be environmentally acceptable. Radiation exposure due to releases from uranium byproduct material is included under these standards with the exception of emissions of radon and its decay products. Alternative standards for radon emissions from uranium byproduct material are considered in this Chapter. We also briefly review controls for radioactive releases other than radon for the purpose of determining if the existing standards remain cost effective in requiring their specific protection levels.

EPA promulgated standards for discharges of process waste water from uranium mills on December 3, 1982, as Ore Mining and Dressing Point Source Category; Effluent Limitations Guidelines and New Source Performance Standards, Subpart E - Uranium, Radium and Vanadium Ores Subcategory (40 CFR Part 440). The purpose of these rules is to establish new source performance standards (NSPS) under the Clean Water Act. The NSPS require that "...there shall be no discharge of process wastewater from mills using the acid leach, alkaline leach or combined acid and alkaline leach process for the extraction of uranium or from mines and mills using in situ leach materials."

EPA promulgated Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities under Subtitle C of the Solid Waste Disposal Act (SWDA) on July 26, 1982, (40 CFR Part 264). Radioactive materials controlled under the Atomic Energy Act of 1954, as amended, are not included under the Solid Waste Disposal Act. However, UMTRCA requires that standards for nonradioactive hazards under UMTRCA shall provide for the protection of human health and the environment consistent with the standards required under Subtitle C of the Solid Waste Disposal Act, as amended, which are applicable to such hazards.

The Act also required the NRC to insure that management of uranium byproduct materials is carried out in such a manner as conforms to general requirements established by the NRC, with the concurrence of EPA, which are, to the maximum extent practicable, at least comparable to requirements applicable to the possession, transfer, and disposal of similar hazardous material regulated by EPA under the SWDA, as amended.

EPA standards under the SWDA, as amended, specify concentration limits for toxic materials in groundwater and also specify that there shall be no increase in background levels in groundwater for hazardous constituents listed in Appendix VIII of 40 CFR Part 261. For the operating these rules basically require that: 1) a plastic liner should be placed on the bottom of a tailings pond to prevent seepage of leachate into the groundwater; 2) an active leachate management program should be conducted to treat, process, recycle, etc., the leachate collected from the tailings pond; 3) groundwater adjacent to the liner should be monitored; and 4) a corrective action plan should be implemented if hazardous constituents are detected above background levels in the groundwater.

The Nuclear Regulatory Commission issued rules on October 3, 1980, which specify licensing requirements for uranium and thorium milling activities, including tailings and wastes generated from these activities (10 CFR Part 40). These rules specify technical, surety, ownership, and long-term care criteria for the management and final disposition of uranium byproduct material. Certain of these rules were suspended in August 1983 following publication of EPA's proposed standards as required by UMTRCA amendments passed in January 1983.

The NRC also enumerated the authorities reserved to the NRC in Agreement States under the provisions of UMTRCA, and specified requirements for Agreement States to implement UMTRCA (10 CFR Part 150). Under the Agreement State program, Agreement States can issue licenses for uranium processing activities, including uranium byproduct material generated from these activities.

7.1 Objectives of Control Measures

Releases of radionuclides and toxic elements to air and water from uranium mill tailings piles during milling operations can be reduced or eliminated by a variety of control measures. Some of these are appropriate for temporary control, and others have a more lasting effect. Releases to air are in the form of windblown tailings dust and radon gas. Releases to water are primarily from seepage from tailings ponds into underlying aquifers. However, best practicable technology (BPT) for existing mills permits the discharge of pollutants to surface waters. New source performance standards (NSPS) prohibit the discharge of pollutants to surface waters except in areas where annual precipitation exceeds annual evaporation; then the difference between precipitation and evaporation may be discharged (40 CRF 440). This section discusses available methods for controlling these releases and the benefits achievable.

7.1.1 Wind Erosion

Wind can erode exposed tailings embankments and dry beach areas and transport small tailings particles away from the site. These releases cause radiation exposures to people living near the tailings pile, primarily through inhaling the airborne tailings particles. Radiation exposures can also occur, but to a lesser extent, from ingesting food contaminated with tailings particles or from external exposure to offsite tailings deposited on the ground. Tailings also contain toxic elements that could be ingested eventually by man and animals or absorbed by plants.

7.1.2 Radon

Since radon-222 is an inert gas, it diffuses through the interstitial spaces of a tailings pile to the surface, where it escapes into the air. Radon-222 decay products can cause large radiation doses to the lungs of people living near tailings piles and, because radon can travel long distances through the atmosphere before decaying, it also causes small radiation doses to large numbers of people distant from tailings piles. Control measures can reduce radon emissions from the tailings.

7.1.3 Water Contamination

Wind and water flowing over or through tailings can carry radionuclides and toxic elements to surface or underground water. The primary concern during milling operations is when water seeps from the tailings ponds into an underground aquifer, contaminating the water with radionuclides and toxic elements and presenting potential health risks to people using the water. The objectives of control measures for water protection are to eliminate seepage from tailings ponds and to prevent the contamination of water resources.

7.2 Control Methods

7.2.1 Wind Erosion

Wind erosion can be controlled by stabilizing tailings by any of the following methods:

1. Physical Methods--wetting the tailings or covering the tailings with soil or other restraining materials.

2. Chemical Methods--treating the tailings with a chemical which interacts with the fine-sized materials to form a crust.

3. Vegetative Methods--growing plants in the tailings or in cover materials.

4. Staged or below-grade disposal.

During the operational phase of a mill tailings pile, airborne-dust is usually controlled by wetting the surface of the tailings or by treating the dry surfaces with chemicals. During the post-operational phase more permanent methods can be used, either physical or vegetative methods, or a combination of these methods. However, vegetative procedures are unsuitable for many locations because of the low rainfall and the high alkalinity or acidity of the tailings.

Keeping tailings surfaces wet with tailings solution or sprinkling them with water can suppress dusting. This can be done, for example, by discharging tailings slurry from multiple discharge points, as opposed to a single point. Alternatively, sprinkling systems or tank trucks can spray dried areas. Because surfaces of the tailings impoundment can dry out rapidly, this method of dust suppression requires continuous attention.

Chemical stabilization involves interaction of a reagent with tailings to form an air- and water-resistant crust or layer that will effectively stop dust from blowing. Resinous adhesives; lignosulfonates; elastomeric polymers; milk of lime; mixtures of wax, tar, and pitch; potassium and sodium silicates; and neoprene emulsions have been used for such purposes (De74). In tests by the U.S. Bureau of Mines, resinous adhesives, lignosulfonates, and elastomeric ploymers were shown to be the most promising chemicals for stabilizing tailings. Calcium lignosulfonate (Norleg A) and an elastomeric polymer (DCA-70) were tested on the tailings at Tuba City, Arizona, with reasonably good results, although periodic maintenance was needed (Ha69). More recently, wood-fiber-based materials (Conwed-200) and magnesium chloride (Dust Guard) have been used effectively for tailings dust control (Ma82). Table 7-1 lists chemicals that have been used for suppressing tailings dust and their estimated unit costs.

Various cover materials have been used or tested for stabilizing tailings and controlling wind erosion, including soil, rock, slag, bark or straw, vegetation, and synthetic covering such as asphalt. The most common cover materials used are soil and vegetation because of their relative ease of application and economy. Although vegetative cover can sometimes be used by itself, it is normally used in conjuntion with soil

Table 7-1. Chemical Stabilization Agents Used for Dust Suppression (1983 dollars)

Product	Type	Application Rate	Unit Cost ($/acre)
Aerospray-70	elastomeric polymer	230 gal/acre	$1400
Soil Gard	elastomeric polymer	420 gal/acre	1900
Dust Binder Concentrate	elastomeric polymer	240 gal/acre	1700
Coherex	resinous adhesive	730 gal/acre	950
Norlig A	lignosulfonate	2.4 tons/acre 1.5 tons/acre	280[a] 190[b]
Conwed-200	wood fiber	0.75 tons/acre	260
Conwed-200 & Terra-Tac 1	wood fiber	0.75 tons/acre 40 lbs/acre	370
Dust Guard	Magnesium Chloride	12 tons/acre	890

[a] Based on application rate used by Bureau of Mines (Ha69).
[b] NRC estimate (NRC80).

cover or with a chemical stabilizing agent. However, for areas of low rainfall, vegetative cover will require irrigation.

Several recent tailings impoundment designs have incorporated progressive reclamation schemes into overall tailings management programs. These schemes segment large tailings areas into a number of smaller cells, with sequential construction, filling, and reclamation. Such schemes substantially reduce dust emissions by reducing the available surface area of exposed tailings.

Tailings can also be stored and disposed of through the use of existing open mine pits or special excavations, so that the tailings are below grade, thus virtually eliminating exposure of the tailings to surface erosional effects.

7.2.2 Control of Radon

Radon releases from uranium mill tailings can be controlled by minimizing the exposed dry beach areas of tailings by keeping the tailings covered with water, soil, or some type of synthetic material. Management practices involving staged reclamation of the tailings are also a practical way of limiting the area of exposed tailings.

Radon diffusion through tailings is significantly affected by the moisture content of tailings. Tailings covered by water do not release any significant quantity of radon to air, and the release rate of radon from wet beach areas is only about 30 percent of the release from dry beach areas (NRC81). For most existing older tailings piles, this method of controlling radon is dependent on the design of the tailings pile and appears to have limited application. Although radon emissions can be reduced somewhat by discharging tailings slurry onto the pile and keeping it wet, large areas of exposed tailings will still exist because of upstream construction methods and the need to maintain adequate freeboard. However, for new or future tailings piles, design and management techniques can be used that will keep all but a small area of the tailings either wet or covered with water (NRC80).

Radon emissions to the atmosphere can be controlled by covering the exposed tailings with soil (see Section 8.3). Relatively thick covers (one meter or more) are needed to reduce radon emissions significantly (see Figure 8-1). Soil covers to reduce radon emissions are more applicable to final disposal of the tailings than as an interim measure to reduce radon emissions during milling operations. Applying soil covers to tailings beach areas during operations is not practical because new beach areas are constantly being formed. Several recent tailings impoundment designs have incorporated progressive reclamation schemes into overall tailings management programs. These schemes segment large tailings areas into a number of smaller cells, with sequential construction, filling, and reclamation. Such schemes substantially reduce radon emissions by reducing the of exposed surface area of tailings.

Land restrictions can prevent people from living near tailings piles and thus reduce the health risks from radon emissions from tailings. The greatest risks occur to people living close to the tailings piles (i.e., 0.5 to 1 mile), with the individual risks decreasing significantly with distance from the pile (see Table 6-1).

7.2.3 Control of Groundwater Contamination

The principal available means for controlling groundwater contamination from uranium mill tailings is using liners in the tailings pond to prevent seepage. This method is primarily applicable to new tailings piles because the liners must be installed when the tailings impoundment is originally constructed, unless the pile is removed and replaced. Other methods for controlling potential groundwater contamination involve removing the pollutants from the tailings liquids or dewatering the tailings before disposal. These methods also are most applicable to new mills. Methods for controlling seepage to groundwater under existing tailings piles are limited to pumping contaminated water back to the tailing pond or to separate, lined evaporation ponds.

Placing compacted clay over the ground surface under a tailings pile will act as a sealant and inhibit seepage from the tailings pond. Furthermore, the ion-exchange characteristics of the clay will further retard the transport of contaminants to the underlying aquifer. The sealing property of clay results from its ability to expand when wet. The expanded clay particles decrease the pore space of the soil, decreasing its permeability.

Many types of synthetic materials can be used as liners to prevent seepage from tailings ponds, including plastics, elastomers, and asphalt coatings. Plastics and elastomers are usually used with polyester or nylon reinforcement and are flexible liners. Careful preparation of the tailings pond base and of the protective soil layer placed after installation of the liner is necessary to avoid damage to the liner.

Chemical processes which remove pollutants from the tailings solution could be used to control groundwater contamination. For example, removing contaminants from the water by lime neutralization or ion exchange are two such processes (NRC80). Lime neutralization precipitates radionuclides and most toxic elements as insoluble hydroxides. Ion-exchange resin can absorb contaminants from the solution. Information on the practicability of these processes is limited, and such processes generally have not been used in the uranium milling industry in the United States (We80).

Based on available information, using liners appears to be the most practical method for preventing groundwater contamination from tailings piles.

7.3 Cost and Effectiveness of Control Measures for Model Tailings Pile

7.3.1 Control of Wind Erosion of Tailings

During the operational phase of uranium mill tailings piles, wind erosion of tailings may be most easily controlled by spraying the dry beach areas with water or treating those areas with a chemical stabilization agent. During the post-operational phase of a mill tailings pile (i.e., before final disposal), a thin cover may be used to prevent wind erosion. Although many types of cover material are available, soil appears to be the most practicable cover for this purpose. The cost and estimated efficiency of these control methods are shown in Table 7-2.

For new tailings piles, efficient design and management practices can reduce the amount of airborne dust released from the piles. Staged disposal (see Appendix B) can reduce the amount of tailings dust by about 70 percent (NRC80). Below-grade disposal will shield the dry tailings areas from wind erosional effects and significantly reduce the amount of tailings dust. We assign a control efficiency of 90 percent to the below-grade disposal option described in Appendix B. No direct costs are assigned to dust control for these management options, since dust control is obtained at no additional cost when these management options are selected based on disposal considerations. Appendix B contains a discussion of the costs of these management options.

7.3.2 Control of Radon

Methods for reducing radon emissions to air from tailings are not easily applied to existing tailings piles during the operational phase. Using cover materials is not practical since new tailings beach areas are continuously being formed. Although radon emissions can be reduced by enlarging the area of tailings covered by water, such an approach is affected by the design of the tailings pile and is a complex function of seepage, evaporation and recycling rates, and tailings embankment strength and stability. For purposes of subsequent analyses, we conclude that using water covers to obtain large reductions in radon emissions is not generally applicable to existing tailings piles. By wetting the tailings surfaces with tailings liquids or by sprinkling with water, a small reduction (20 percent of the total radon emitted over the operating life of the pile) in the radon emissions can be achieved (NRC80).

For new tailings piles, the use of staged disposal can reduce radon emissions by about 70 percent. Designs that maximize the amount of tailings covered by water can achieve a greater-than 90 percent reduction of the radon emissions (NRC80). No direct costs are assigned to these methods for controlling radon, since the control is obtained at no additional cost when the management option is selected based on disposal considerations.

7.3.3 Control of Seepage to Groundwater

During the operational phase of the mill, contamination of groundwater can be controlled by using a plastic or clay liner on the bottom and sides of the tailings pond. Estimated costs for a synthetic liner at a new tailings pond are presented in Appendix B for the model tailings pile as $11.5 million (1983 dollars), which includes 25 percent for overhead and profit. The estimated cost for a synthetic liner at a new tailings pile using the staged disposal method is $8.1 million, which includes 25 percent for overhead and profit. The staged disposal method has a lower estimated cost primarily because the tailings are arranged in a thicker layer than they are for surface storage, thereby reducing the area requiring a liner.

Table 7-2. Costs and Effectiveness of Methods for Controlling Wind Erosion at a Model Tailings Pile (1983 dollars in thousands)

Control Method	Capital Costs	Annual Costs	Present Worth	Estimated Control Efficiency (%)
		OPERATIONAL PHASE		
Water Spray (Truck)	--	35	260	50 (NRC80, PE82)
Water Spray (Piped)	420	168	1,280	90 (PED82)
Chemical Stabilization[a]	--	53	400	80 (NRC80, PE82)
		POST-OPERATIONAL PHASE		
Chemical Stabilization[a]	--	84	318	80 (NRC80, PE82)
Soil Cover (1 foot)	525	--	525	90-100 (PE82)

[a]Cost based on an annual application of the chemical agent, Norlig A.

Chemical treatment of tailings at a new tailings pond by the addition of lime is estimated to cost $12.4 million at an acid-leach mill and $11.3 million at an alkaline-leach mill (We80). The alkaline-leach tailings are assumed to be blended with acid-leach tailings before treatment with lime. The key cost item is the sludge storage lagoon for both acid- and alkaline-leach tailings.

Options for protecting groundwater at existing tailings ponds varies from site to site. The control costs for groundwater protection at existing tailings ponds can range from zero, where no action is needed, to the costs of constructing a new, lined tailings pond as presented in Appendix B. An intermediate-cost remedial action is being applied at the Homestake mill in New Mexico. Two rows of wells were drilled across the groundwater hydraulic gradient down from the tailings pond. Water is pumped from wells in the first row, closest to the pond, and recycled. Fresh water is injected into the wells in the second row to dilute any contaminated groundwater. During September 1978, 3.7 million gallons were injected. The estimated present value of the future costs for this pumping is about $89,000, which includes capital costs for 15 pumps and drilling 15 wells and an annual operating cost corrected to present value at a 10 percent discount rate.

The effectiveness of plastic liners results from the physical barrier that these liners provide. A plastic liner will retain all the liquid in the tailings pond, including the dissolved hazardous and toxic materials. This is advantageous since it prevents the seepage into groundwater of chemical forms of these materials that are highly soluble and difficult to remove with chemical processes. It also avails us of the option to issue standards requiring control of materials that are currently not listed under Subtitle C of the SWDA, as amended. Protection of groundwater achieved with plastic liners controls both the hazardous materials listed under Subtitle C of the SWDA, as amended, and other potential pollutants found in uranium tailings.

Molybdenum is found in some uranium ores and is present in tailings after the ore is processed (see Chapter 3). Molybdenum is estimated to be potentially toxic to humans and also has a narrow safety margin, e.g., a low ratio of toxic intake to adult required intake, as discussed in Appendix C. This inorganic has been found in a shallow aquifer at the Cotter mill, Canon City, Colorado, at estimated potentially toxic concentrations, as shown in Chapter 3. Also, molybdenosis has been observed in cattle grazing on land contaminated with molybdenum from the processing of uranium ores in North Dakota and Texas, as noted in Appendix C. All this, in addition to the fact that molybdenum will be controlled by the same methods used to control toxic and hazardous materials, allows us to consider control of molybdenum seepage from uranium tailings storage areas.

Radioactive materials are not included under the SWDA regulations since most of them are controlled under the Atomic Energy Act and thus are exempted by the SWDA, as amended. Tailings contain large quantities of radioactive materials as shown in Chaper 3. Contamination of groundwater by radioactive materials is controlled since they are potentially the most hazardous constituents of tailings. The same methods used to protect groundwater from other toxic and hazardous constituents will also prevent contamination by radioactive materials.

Concentration limits for toxic materials in the SWDA regulations were adopted directly from the National Interim Primary Drinking Water Regulations (40 CFR Part 141). Thus, the concentration limits for radionuclides, as specified in the drinking water standards, can be adopted for application to tailings since this is consistent with standards under SWDA, as amended. These include limits of 5 pCi of radium-226 and radium-228 per liter of water and of 15 pCi of gross alpha particle activity per liter of water. The gross alpha particle limit excludes uranium which is present in large quantities in tailings and has been found in high concentrations in shallow aquifers as shown in Chapter 3. However, uranium is indigenous in groundwater in many uranium producing areas. Therefore, rather than specifying a concentration limit for uranium, a nondegradation approach is more suitable. This requires that there would be no increase in the concentration of uranium above background levels in the local area of the tailings.

Protecting groundwater by controlling seepage from tailings with a plastic liner would eliminate seepage as a discharge pathway for excess wastewater. At some sites this is a significant discharge pathway. New Source Performance Standards (NSPS) under the Clean Water Act prohibit the discharge of process wastewater from uranium mills as the degree of effluent reduction currently attainable. Taken together, these controls may pose a problem of what to do with excess waste water at certain locations where average annual precipitation approaches or exceeds average annual evaporation. At these locations the only discharge pathway for excess wastewater would be evaporation. It appears from Table 3-1 that Texas is the only currently developed uranium producing region where this may be a problem.

However, future uranium producing locations may be developed in regions where the average annual precipitation exceeds annual average evaporation. For these situations the NSPS may not apply since these standards were developed for environmental conditions where the average annual evaporation exceeds the average annual precipitation. These standards also contain provisions in the event that the annual precipitation exceeds the annual evaporation. This potential problem may also arise for a new tailings impoundment at an existing uranium processing site. In this case a determination would be required as to whether a new impoundment would be considered a new source.

7.4 Cost-Effectiveness Analyses

7.4.1 Wind Erosion

The levels of risk to the public from dust particle emissions from uncontrolled tailings piles are relatively low. During the operational phase of the model pile, the average lifetime risk of fatal cancer to the nearest individuals is estimated to be about 3×10^{-5}, and the number of cancer deaths in the population from 15 years of dust emissions range from 0.03 for a rural site to 0.001 for a remote site. These risks can be reduced to even lower levels through the use of dust control measures.

Costs and benefits (health risk reductions) for various levels of dust control for the model tailings pile for the operational phase are presented in Table 7-3. A combination of chemical stabilization and water sprinkling can achieve a 90-percent reduction in dust emissions. This would result in a reduction from 3 x 10^{-5} to 3 x 10^{-6} in the lifetime risk of fatal cancer to the nearest individual and will prevent up to 0.03 fatal cancers (in the population living around the tailing pile at a rural site) during the operation phase of the tailings pile, at a cost of $660 thousand. For new tailings, the use of staged disposal in combination with chemical stabilization can achieve a 94 percent reduction in dust emissions. This would result in a reduction of the risks similar to those just described, but at a smaller incremental cost of $120 thousand.

7.4.2 Control of Radon

Costs and benefits for controlling radon emissions during the operational phase of the model pile are presented in Table 7-4. For existing tailings, keeping the tailings surface wet is the only practical control method. Water sprinkling would achieve about a 20-percent reduction in the radon emissions. Over the term of the operational phase this would prevent about 0.7 fatal cancers in the population at a rural site and 0.2 fatal cancers at a remote site, but would result in only a small reduction in the lifetime risk of fatal cancer to the nearest individuals (i.e., from 1.6 x 10^{-3} to 1.3 x 10^{-3}).

Table 7-3. Costs and Benefits of Various Levels of Control of Dust Emissions for Model Tailings Pile During Operational Phase (1983 dollars)

Controls	Emission Reduction (%)	Present Worth Cost ($1000)	Lifetime Risk to Individual	Fatal Cancers (Cancers/15y) Rural Site	Fatal Cancers (Cancers/15y) Remote Site
None	0	0	3.0E-5	3.0E-2	1.0E-3
A	50	260	1.5E-5	2.0E-2	5.0E-4
B	80	400	6.0E-6	6.0E-3	2.0E-4
A & B	90	660	3.0E-6	3.0E-3	1.0E-4
B & D	94	120	1.5E-6	2.0E-3	6.0E-5

A=Water spray (truck).
B=Chemical Stabilization (Norlig A).
D=Staged Disposal (applicable to new tailings piles only).
Note: See Chapter 4 for description of rural and remote sites.

Table 7-4. Costs and Benefits of Various Levels of Control of Radon Emissions from Model Tailings Pile During Operational Phase (1983 dollars)

Controls	Emission Reduction (%)	Present Worth Cost[a] ($1000)	Lifetime Risk[b] to Individual	Fatal Cancers[c] (Cancers/15y) Rural Site	Remote Site
None	0	0	1.6E-3	3.6	1.2
A	20	260	1.3E-3	2.9	1.0
D	70	0	4.8E-4	1.1	4.0E-1
E	90	0	1.6E-4	4.0E-1	1.0E-1
D & E	95	0	8.0E-5	2.0E-1	6.0E-2

A=Water Sprinkling.
D=Staged Reclamation (applicable to new tailings piles only).
E=Below grade disposal in excavated pit with tailing covered with water (applicable only to new mills).
Note: See Chapter 4 for description of rural and remote sites.

(a) Costs for Controls D and E are not listed since they are inherent in the disposal method.
(b) Lifetime risk to the average individual located 600 meters from the center of the pile.
(c) Fatal cancers include those occurring in local, regional, and national populations (see Tables 6-1 through 6-6 for the proportions in each).

For new tailings, using staged disposal in combination with below-grade disposal would allow most of the tailings to be covered with water during the operational phase. This method can achieve a high level of radon control (i.e., greater than 95 percent). This would result in a reduction of the lifetime risk of fatal cancer to the average individuals at 600 m from 1.6×10^{-3} to 8.0×10^{-5} and would prevent 3.4 fatal cancers in the population at a rural site and 1.1 fatal cancers at a remote site.

Using water covers or wetting the tailing surfaces are not appropriate radon control methods during the post-operational phase. The purpose of this predisposal period is to allow the tailings to dry out to allow final disposal. The only way to reduce radon emissions during the post-operational phase is to minimize the amount of exposed tailings through the application of staged reclamation. This method is applicable to new tailings only and would reduce the radon emissions during the 5-year post-operational phase by 70 percent for the model tailings pile. This would result in a reduction of from 1.7×10^{-3} to 5×10^{-4} in the lifetime risk to the average individual at 600 m (See Table 6-2) and would prevent 1.3 fatal cancers in the population at a rural site and 0.5 fatal cancer at a remote site.

7.4.3 Control of Seepage to Groundwater

The benefits of groundwater protection are not easily quantifiable. Maintaining the quality of the groundwater for future uses is the primary benefit of protecting groundwater. At new tailings piles, this can be accomplished by a three-step program:

1. Install a liner to prevent seepage of leachate into the groundwater or, alternatively, select a site with characteristics that have a high probability of protecting groundwater, and

2. Conduct monitoring on a schedule that will assure early identification of any hazardous constituents from the tailings in the groundwater and perform corrective actions, as needed..

3. Install a cap to prevent infiltration of precipitation into the hazardous materials after closure of the impoundment.

The cost of liners ranges from \$8 to \$12 million to achieve this benefit. The additional cost of selecting a "good" site are anticipated to be small compared with the cost of a liner. The cost of a monitoring program is negligible when compared to liner costs.

At existing tailings piles the benefits of groundwater protection are the same, i.e., preserving the groundwater quality for future uses. Costs, however, can range from small, where groundwater is currently adequately protected due to site characteristics, up to large, when transfer of tailings to a new, lined tailings pond is required to protect groundwater.

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Chapter 8: OBJECTIVES AND METHODS FOR TAILINGS DISPOSAL

8.1 Health and Environmental Protection Objectives

Based on the results in the preceding chapters, we have identified the following objectives for these standards.

1. To discourage future use of tailings in or near buildings. The widespread past use of tailings around foundations or in construction materials has caused an increase of radon decay products in buildings, leading to increased risk of radiation-induced lung cancer.

2. To protect people from radon emanating from tailings piles. Radon exposure of people living in the vicinity of tailings piles leads to increased risk of lung cancer. Also, since radon is a chemically inert gas with a radioactive half-life of 3.8 days, radon released from tailings can travel long distances before it decays. As the radon decays, it exposes large numbers of people to low levels of radiation.

3. To prevent the surface spread of tailings. Tailings may be spread by wind and water. This can cause radiation exposure of local residents from both radon decay products and gamma radiation. In addition, the spread of tailings may contaminate surface water.

4. To protect groundwater. Contamination of groundwater occurs when water comes in contact with tailings or leaches radioactive and toxic materials from the tailings and then moves into a groundwater aquifer through fissures, percolation, or by other means. The degree of risk to man and livestock depends on the concentrations of contaminants in the water and the uses of the water (human consumption, livestock watering, irrigation, etc.).

Because of the long lifetimes of the radioactive contaminants in tailings and the presence of toxic materials (which do not decay), the potential for harming people by any of the above pathways will persist essentially indefinitely. It is therefore necessary to satisfy the above objectives for as long a period as practical. Many factors affect the long-term effectiveness of tailings disposal methods. They include external phenomena, such as erosion by wind and rain, earthquakes, floods, and glaciers; internal chemical and mechanical processes in the piles; and human activities. Predictions of the stability of disposed tailings become less certain as the time period increases. Beyond several thousand years, long-term geological processes and climatic change will govern the effectiveness of most control methods.

These objectives are interrelated. For instance, radon control may be achieved by placing a thick earth cover over the tailings. This method also controls the spreading of tailings, attenuates external gamma radiation, prevents groundwater contamination, and isolates the tailings so as to discourage misuse.

Methods to prevent radon emissions into the atmosphere range from the use of simple barriers to delay the release of radon until it has decayed, to more complex means, such as incorporating tailings into asphalt or concrete, or chemical processing to remove the radium and thorium.

Various methods can be used for isolating tailings, ranging from temporary measures, such as fencing, to more permanent measures, such as using a simple earthen cover or deep disposal. Greater amounts of material, such as earth, placed between the tailings and the accessible environment increase the isolation of the tailings. Isolation is here taken to mean the degree to which man is discouraged from intruding into the tailings.

Protection from external gamma radiation is achieved by placing materials of sufficient mass over the source of the penetrating (gamma) radiation. Thus, a plastic sheet will have essentially no effect on gamma levels, whereas a layer of earth is quite effective.

Methods for control of windblown and precipitation-carried tailings include soil and plastic coverings, chemical and asphalt binders sprayed on the tailings, grading and contouring to eliminate steep slopes, rock covers, and revegetation. Some methods, such as chemical and asphalt sprays, do not last long on tailings and are more suitable for use during the operating phase of a mill.

Methods for preventing contamination of groundwater fall into four groups:

1. Placing a barrier between the tailings and the aquifer which will either prevent the movement of water from the tailings to the aquifer (or vice versa) or will remove hazardous materials by adsorption.

2. Fixing the tailings into a solid mass that prevents the leaching of hazardous materials from tailings by water.

3. Contouring and covering to minimize the movement of precipitation into tailings.

4. Selecting a site that is far removed from aquifers, with characteristics that minimize the movement of water into or out of tailings, and/or that provide natural adsorption of hazardous materials.

Not all these methods are feasible for every tailings pile. Some are only appropriate for new tailings. A significant factor is that most existing uranium mills are located in arid areas of the western United States where natural evapotranspiration generally exceeds precipitation. The selection of a site can eliminate the need for a liner, if the soil has the needed permeability and adsorption characteristics. Disposal methods could also be different for mill sites where abandoned surface mines or natural land depressions are nearby.

8.2 Longevity of Control

Mill tailings will be hazardous for hundreds of thousands of years. Although economically feasible methods which assure control for such long-term periods are beyond present knowledge and experience, enough is known to provide protection at reasonable cost for periods of hundreds to thousands of years.

Control failures can occur through natural phenomena or through human intrusion. Natural phenomena, such as erosion and deposition, flooding, climatic change, earthquakes, vulcanism, and glaciation can change the landscape. Human disturbance can also take a number of forms, ranging from constructing buildings to drilling, mining, and dam building. Not all of these activities would cause control failures, however; at some sites, human intrusions and natural phenomena may actually increase isolation of the tailings by depositing additional materials or soil on the tailings. The longevity of protection achievable will vary considerably from site to site at existing sites.

In the following discussion controls are grouped into two broad classes: those that depend on active institutional maintenance, and those that do not. "Active" measures include fences, guards, repair of drainage channels, replacement of eroded cover, and maintenance of vegetative cover. Unfortunately, there is no general consensus on the length of time human institutions will remain effective or reliable to continue such active measures. In this regard, failure of institutional controls does not necessarily imply a complete breakdown of societal structure. The more likely situation would be failure of institutional controls through program reductions, reorganization, changes in priorities, or through the failure of special funding mechanisms.

8.2.1 Human Intrusion

The effectiveness of controls in discouraging intrusion over long time periods is difficult to evaluate. Probably the worst scenario is the use of tailings as a resource for construction material by residents of a nearby population center. This can (and has) led to widespread use of tailings around, under, and in residences, schools, and other inhabited structures. Easily removable or attractive control materials may have a potential for promoting misuse. Examples are fences and easily removed rock covers.

Inhibiting of intrusion for long periods is more likely to be successful by using passive methods. Thick earth covers, for example, provide significant long-term passive protection against intrusion. Other effective "passive" methods include heavy rock cover, deep-mine disposal, below-grade disposal, solidification in a cement or asphalt mixture, or coverings of a tailings-cement mix.

8.2.2 Erosion and Gully Intrusion

All surface disposal methods are subject to erosion. Erosion of stabilized tailings piles can occur as or be caused by sheet erosion, gully intrusion or erosion, wind erosion, and differential settlement. Nelson et al. (Ne83) describe these various modes and discuss long-term mitigating measures in some detail.

Sheet erosion is caused by unconcentrated water flowing directly over the surface of the tailings impoundment and the cover (the engineering design methods necessary to control such erosive forces). Sheet erosion is defined as that erosion which occurs as a result of the impact of raindrops striking the ground surface or water flowing in small ephermal rills. The amount of sheet erosion that can occur at a given location depends on the slope of the land, nature of the cover material, type and density of the cover material, and rainfall duration and intensity.

Control of sheet erosion can be accomplished by grading the cover to gentle, flat slopes and placing gravel, cobbles, or rock layers over the cover, or coarse gravel mixed with finer soil. Such controls can be considered to duplicate desert landforms that have been stable for thousands of years and are described as desert pavements or gravel armor. The design of such controls is quite site specific, however, as emphasized by Nelson, et al. (Ne83).

Gully erosion is caused by concentrated water flowing over the tailings that can cut deep channels through embankments or cover materials and disperse tailings downstream. Gullies can also be initiated off the tailings area and migrate upstream into the tailings. The formation of gullies depends on topographical features, such as slope angle and slope length, the existence of stable base levels on or near the site, erodibility of the soil, and the flood flow velocity.

The best method of controlling gully erosion is by preventing gully initiation (Ne83). Topographical features can be altered by providing gentle and shorter slopes, gradual changes in grade, and establishing base levels around the site (rock trenches, wing walls, etc.). Soil erodibility can be reduced by providing larger grained soils (gravel) and/or natural vegetation. Flood flow velocity can be reduced or eliminated by providing diversion ditches. Gentle and short slopes can also reduce this velocity. Depending on a given site's features, it is likely a combination of these controls will be required.

Wind erosion is caused by suspension of small particles in the air and by creep of particles moving along the ground surface. Materials most highly susceptible to wind erosion are fine-grained noncohesive sands and silts with diameters in the range of 0.02 to 0.10 mm. Particles less than 0.002 mm, which are classified as clays, are highly resistant to wind erosion due to cohesion (Ne83).

Wind erosion may be controlled by increasing surface roughness through vegetation and using different rock sizes. Measures taken to control water sheet erosion generally should minimize losses by wind erosion.

Differential settlement is not erosion itself but can initiate erosion by channelizing runoff. It can also cause failures by cracking of cover material and by impounding water in depressions. Factors which cause differential settlement include differences in compressibility between different grain sizes of tailings, nonuniformity of tailings in the impoundment, and variation in compressibility of underlying materials.

Controls for differential settlement are surcharging and grading. In surcharging, more cover material than necessary is placed over compressible materials to cause a known amount of settlement within the material. Grading also places additional cover over compressible materials, where differential settlement is not expected to be great.

8.2.3 Floods and Other Natural Processes

Natural processes that can destroy the integrity of disposed tailings piles include floods, winds, and earthquakes. Floods are probably the greatest hazard to integrity. Methods are available to protect piles against floods. New piles can be located so as to minimize disruptions from floods and winds. For existing and new piles, diversion ditches and embankments can be constructed, rocks can be placed on the slopes of piles (and on top, if needed), and the tailings can be graded to gradual slopes. Existing piles can also be moved, if sufficient protection is not afforded by these methods. These are all passive controls.

The time over which controls should be effective is an important factor in standards for long-term protection. Specifying this time directs the design of disposal methods that have reasonable assurance of providing such effectiveness over this period. The design of a tailings disposal method is similar to the design of other major projects, such as dams, bridges, causeways, etc., that are subjected to natural disruptive processes (Ju83, Ne83, Cob78).

The first design step is to determine the size of the flood that will be used in the design of the disposal method. This is accomplished by a probabilistic analysis. For example, a flood of a certain magnitude will occur periodically, i.e., a 100-year flood is defined as a flood that has a recurrence rate of 1/100 each year, or 0.01 in any one year.

The probability (or likelihood) that a flood equal to or greater than this 100-year flood will occur in a specified number of years is given by the formula:

$$P_t = 1 - (1-t)^n$$

where

P_t = Probability that an event with recurrence rate of t will occur in n years.

t = Recurrence rate of an event (1/T)

T = Recurrence time of event in years

n = Period of concern in years.

The probability that a 100-year event (flood) will occur sometime during a 100-year period is thus 0.63, as is the probability that a 1,000-year event (flood) will occur sometime during a 1,000 year period. Thus, it is more likely than not that an event with a recurrence time equal to the period of concern will occur within the period of concern.

For any period of concern, it is useful to determine a series of probabilities that events with various recurrence times will occur within that period of concern. For example, probabilities and corresponding recurrence times are plotted in Figure 8-1 for three periods of concern; 100 years, 400 years, and 1,000 years. This plot

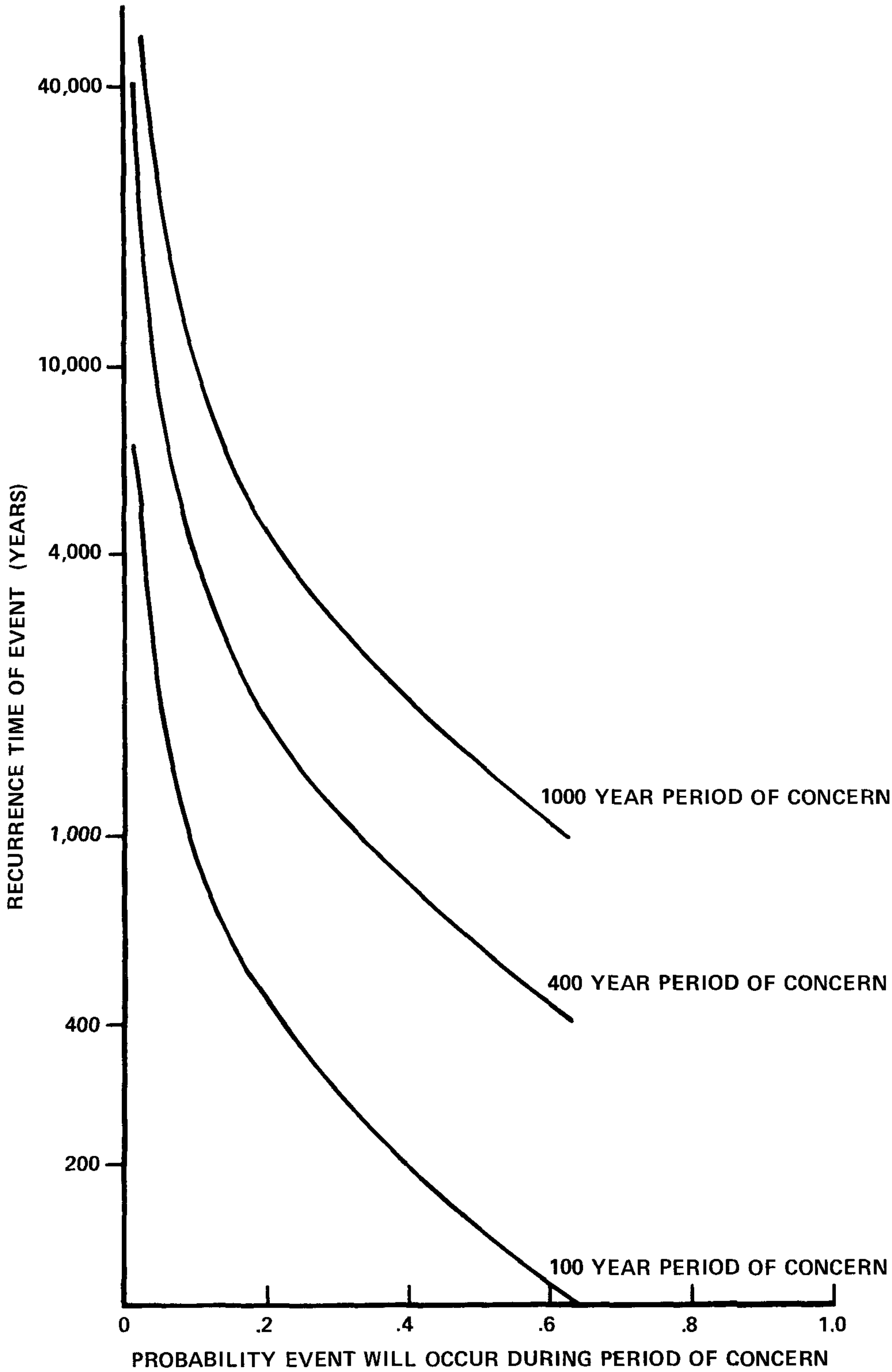

Figure 8-1. Recurrence Times Versus Probabilities for Various Periods of Concern.

clearly illustrates that the probability is high that an event with a recurrence time equal to the period of concern will occur during the period of concern, as noted above.

The most important point shown in Figure 8-1, however, is that the recurrence time becomes very long for low probabilities, regardless of the period of concern. (The recurrence time defines the size, or design, of the event (flood), i.e., a recurrence time of a 10,000-year flood). For example, for a probability of 5 percent the design event is 2000 years for a 100-year period of concern, is almost 10,000 years for a 400-year period of concern, and is 20,000 years for a 1,000-year period of concern. Thus, specifying the period of concern (or the period over which protection must be provided) determines the size of the event (flood) for design purposes, given some reasonably low probability that the event will occur within the period of concern.

The long recurrence times of these design floods preclude the use of historical data, which are of too short a duration. Rather the design is based on the probable maximum flood (PMF) which in turn is determined from the probable maximum precipitation (PMP) over the area that could affect the disposed tailings. The PMP can be obtained from depth-area-duration relationships developed for the entire United States by the National Oceanographic and Atmospheric Administration (NOAA60, NOAA77-78). It is important to recognize that the size of flood, is not proportioned, in general, to the length of the period of concern. That is, in most cases the PMF is not significantly larger than projections of floods for only moderately long periods of concern (e.g., 1,000-year floods). Nelson, et al. (Ne83) discuss this in detail, especially in regard to size of the drainage basin contributing to the PMF at specific sites. They conclude, "To provide for a level of risk consistent with normal engineering practice for 200-, 500-, or 1,000-year stability periods requires a design storm having a recurrence interval of several thousand years. Because the PMP is based on site specific physical meteorological limitations which avoid the inaccuracies associated with extending limited data bases for long time periods, it is reasonable and prudent to use a PMF based on the PMP as the design flood."

8.2.4 Longevity of Control

We have chosen two time periods for evaluating the longevity of effective control. A short time period of 100 years was chosen for one case, since this has been proposed as the limit for reliance on institutional controls (EPA78). A period of about 1,000 years was selected for the second case. This case displays the difference between active and passive controls, as well as the expected variation of effectiveness of controls over longer time periods.

In general, the effectiveness of controls over time can be rated as follows:

Highest	-	Deep geological disposal.
	-	Below-grade surface disposal.
	-	Above-grade surface disposal, entire area covered with thick earth and rock cover.
	-	Above-grade surface dispoal, entire area covered with thick earth, slopes covered with rock.
	-	Above-grade surface disposal, entire area covered with thick earth.
Lowest	-	Above-grade surface disposal, entire area covered with thin earth and maintained.

This ranking assumes the tailings pile is located where erosion occurs. If tailings are located where soil deposition is taking place, the ranking will be equal for all cases as long as deposition continues.

8.3 Disposal Methods and Effectiveness

8.3.1 Earth Covers

Earth placed over tailings slows the movement of radon into the atmosphere by various attenuation processes. When the earth is moist, attenuation increases. Different soils have different attenuation properties; these can be approximately quantified in terms of a quantity called the "half-value layer" (HVL). The HVL is that thickness of cover material (soil) that reduces radon emission to one-half its value. Figure 8-2 shows the percentage of radon that would be predicted to penetrate various thicknesses of materials with different HVLs. These values are nominal; the actual HVL may vary significantly. From Figure 8-2 it can be seen that 3 meters of sandy soil (HVL = 1.0 meters) is projected to reduce the radon released from tailings by about 90 percent. Soils with better attenuation properties would require less thickness to achieve the same reduction. For example, 1 meter of compacted moist soil (HVL = 0.3 meters) would be predicted to reduce the radon release by about 90 percent.

A more complete treatment of radon attenuation based on the work of Rogers (Ro81), is given in Appendix P of the NRC Generic EIS for mill tailings. That analysis concludes that the effectiveness of an earthen cover as a barrier to radon depends most strongly on its moisture content. Typical clay soils in the uranium milling regions of western United States exhibit ambient moisture contents of 9 percent to 12 percent. For nonclay soils, ambient moisture contents range from 6 percent to 10 percent. The following table provides, as an example, the cover thicknesses needed to reduce the radon emission to 20 pCi/m^2s for the above ranges of soil moisture. Four examples of tailings are

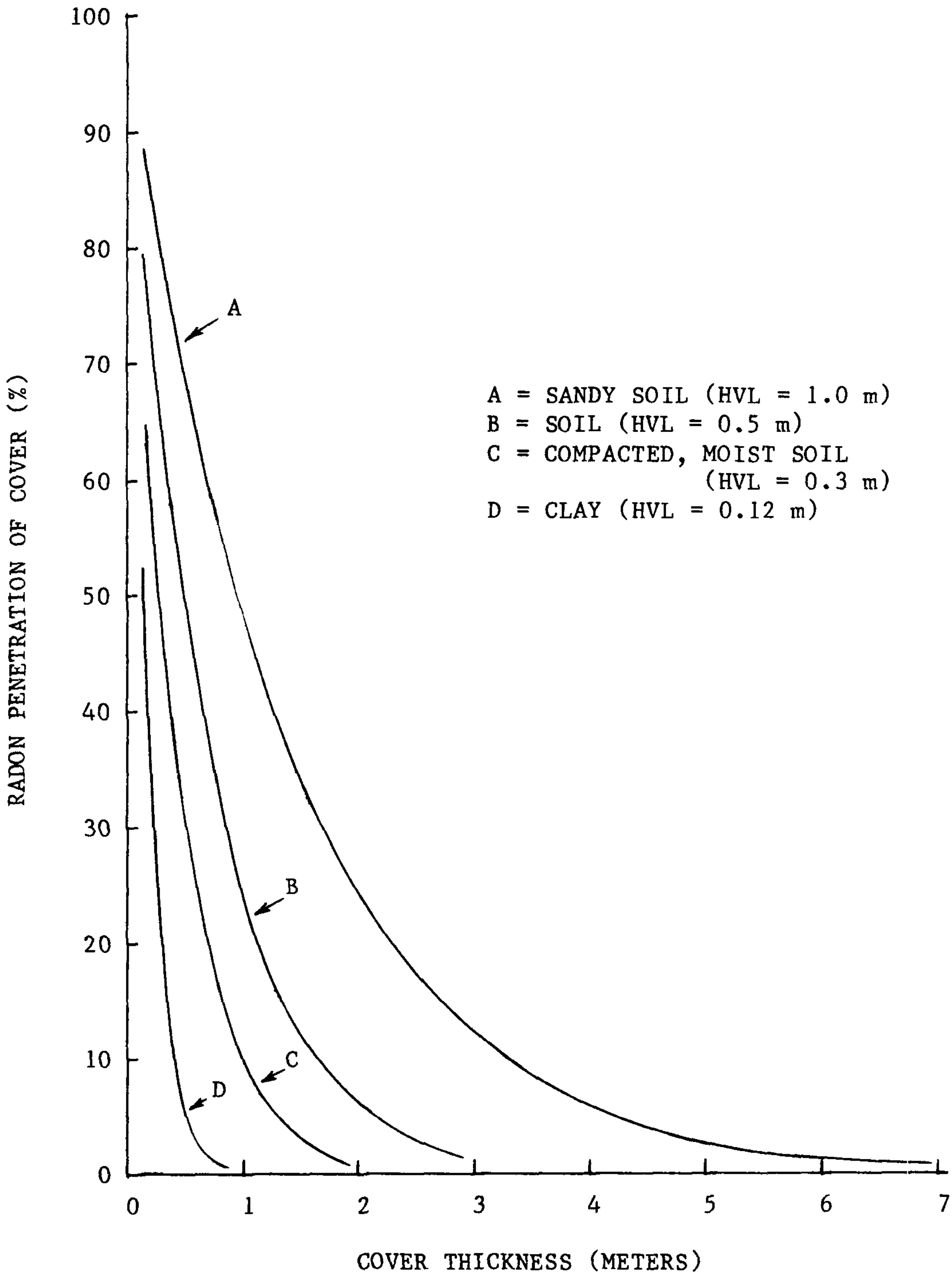

Figure 8-2. Percentage of Radon Penetration of Various Covers by Thickness.

shown that cover the probable extreme values of radon emissions from bare tailings at existing sites (100 to 1000 pCi/m^2s); the most common values lie between 300 pCi/m^2s and 500 pCi/m^2s.

Table 8-1. Estimated Earthen Cover Thickness (in meters) to Reduce Radon Emissions to 20 pCi/m^2s

Radon Emission from Tailings (pCi/m^2s)	Percent Moisture Content of Cover			
	6	8	10	12
100	1.7	1.3	1.0	0.7
300	2.8	2.1	1.5	1.1
500	3.4	2.6	2.0	1.5
1000	4.1	3.2	2.4	1.8

In practice, design techniques must take account of uncertainties in the measured values of the specific materials used, the tailings to be covered, and predicted long-term values of equilibrium moisture content for the specific location, in order to assure meeting any given radon emission limit over the long term. The uncertainty in predicting reductions in radon flux increases rapidly as the required radon emission limit approaches background. Even at 20 pCi/m^2s the uncertainty may approach a factor of three (Ro83). For example, the calculated emission rates using Roger's method (Ro81) for four earthen test plots at Grand Junction, Colorado, are compared to actual performance in Table 8-2 (Ge81, Ba82, Ha83).

Table 8-2. Summary of Radon Flux Measurements Mode at Grand Junction Over a Two-Year Period (Ba82)

Radon Barrier	Average Tailings Source Flux (pCi/m^2s)	Average Flux (pCi/m^2s)	Moisture Content (%)	Calculated Flux (pCi/m^2s)
1.2m Mancos Shale/ 1.8m Adobe	619 ± 221	1.0 ± 1.1	15.8	2.32
1.2m Bentonite/ 1.8m Adobe	589 ± 285	8.6 ± 8.5	20.2	0.07
1.2m Compacted Adobe/ 1.8m Adobe	316 ± 1	6.6 ± 10.2	11.9	6.92
3m Uncompacted Adobe	195 ± 132	18.3 ± 25.2	6.5	14.9

Two tests produced results close to the predicted values (the compacted and uncompacted adobe cases). The test of the Mancos shale and adobe was more than a factor of 2 less than the predictable value and the test of the bentonite and adobe was more than a factor of 100 higher than the predicted value. It should be noted that these test plots are still far from reaching equilibrium moisture content (representative values in the area range from 3.3 percent for Mancos shale to 11.0 percent for bentonite clay).

The thickness of earthen cover needed to provide isolation is not directly calculable. Perhaps the best approach is to review the depths to which excavations for common activities are routinely made. Excavations are routinely made to 6 to 8 feet for public utilities (water and sewer pipes, power lines, telephone lines). Footings for house foundations are often placed at an 8-foot depth. In colder climates it is important that water lines and foundations be placed below the frost depth to avoid freezing problems. Graves are also dug to a depth of 6 feet or more.

The amount or thickness of earth that will attenuate gamma radiation to one-half its initial value is also called a half-value layer (HVL). As with radon adsorption, the HVL for gamma attenuation depends on soil composition, compaction, moisture content, and other factors. The average HVL of compacted soil for gamma radiation from tailings is about 0.1 meter. Therefore, a soil thickness of 0.5 meter will reduce the gamma radiation to about 3 percent of its initial value from the uncovered tailings, and 1 meter of soil would reduce it to about 0.1 percent of its initial value.

The model tailings pile is assumed to have a radium-226 concentration of 280 pCi/g. This produces a gamma-absorbed dose rate in air of about 4,000 mrad/year on top of the uncovered tailings, assuming a homogeneous distribution of radium-226 in the tailings. An earth covering of 1 meter would reduce this absorbed dose rate in air to about 7 mrad/year. This is slightly less than the total gamma dose from the uranium-238 series under average background conditions.

Earthen covers can also prevent the movement of tailings by wind and water. A combination of grading and contouring slopes, covering with 0.5 meter of earth, landscaping, and continuing maintenance is considered the minimum control for these pathways, as long as maintenance is continued. Longer term protection that does not rely on maintenance can be provided by use of thicker earth covers, and rock or other forms of surface stabilization.

8.3.2 Basin and Pond Liners

Liners are materials placed on the botton of a tailings retention basin or pond to prevent or reduce the seepage of water into the underlying soil. Liners can be made of clays, asphalts, concretes, and polymers (plastics), or various combinations of these (Ba81, Bu81, NRC80).

Agency policy on the use of liners for groundwater protection was delineated in recently promulgated regulations under the Solid Waste Disposal Act (EPA82). A liner placed beneath the waste in a land disposal unit is often a key element of a general liquids management strategy. However, liners are just one component of an overall liquid management system. A liner is a barrier that prevents or greatly restricts migration of liquids into the ground. No liner, however, can keep all liquids out of the ground for all time. Eventually, liners will either degrade, tear, or crack and will allow liquids to migrate out of the unit. *It is, therefore, important that liquids be removed during the* time that the liner is most effective. Leachate collection and removal systems at landfills and measures to remove free liquids from surface impoundments at closure are the principal techniques used to remove liquids.

The Agency view of the function of a liner contrasts with that of some members of the public and the regulated community. Some view liners as devices that provide a perpetual seal against any migration from a waste management unit. The more reasonable assumption, based on what is known about the pressures placed on liners over time, is that any liner will begin to leak eventually. Others have argued that liners should be viewed as a means of retarding the movement of liquids from a unit for some period of time. While this view accords with how liners do in fact operate, this represents an incomplete regulatory strategy for ground water protection because it achieves only a delay of the appearance of groundwater contamination rather than a permanent solution. Accordingly, liners should be viewed as a barrier best used to maintain control of liquids prior to their removal from the waste management unit during its active life. Assurance of long-term protection is best achieved by a combination of removal of excess liquids and prevention of influx of new liquids after disposal.

Thus, while liners may remain effective for preventing migration from the unit until well after disposal, their principal role occurs earlier. In final disposal, the Agency believes that a protective cap becomes the prime element of the liquids management strategy. A well-designed and carefully maintained cap can be quite effective at reducing the volume of liquids entering a unit and therefore can substantially reduce the potential for leachate generation at the unit for long periods.

The Battelle Pacific Northwest Laboratory group has performed a comprehensive review of liners for uranium tailings (Bu81). They selected seven materials for laboratory testing (Ba81) on the basis of their potential usefulness as liners for uranium mill tailings ponds. These materials were asphalt concrete, asphalt rubber, catalytic airblown asphalt, Hypalon (a chlorosulphonated polyethylene), sodium-bentonite, saline seal-100 bentonite, and GSR-60 bentonite. They also tested a native soil at one of the alternative disposal sites for the Durango, Colorado, inactive tailings pile. The materials were tested for permeability (increased permeability is caused by failures through chemical attack of the asphalts and synthetics or through reduction of the ion exchange capacity of the clays), physical stresses, and radiation damage. Based on laboratory tests, expected field effectiveness, and a cost analysis, the liners selected for field studies were a catalytic airblown asphalt-and-soil amended with sodium-bentonite.

For this analysis, to protect groundwater before the final disposal of the tailings, we assume a plastic liner is installed on the bottom and sides of a disposal pit. Earthen cover is assumed to provide an adequate cap, after disposal, to control influx of water in the arid western regions typical of U.S. uranium mills. At wet sites typical of the eastern U.S., however, it would be necessary to prevent infiltration of precipitation through the cover into the tailings. Thus, a cover that is less permeable than the liner would be required.

8.3.3 Thermal Stabilization

Thermal stabilization is a process in which the tailings are sintered at high temperatures. The Los Alamos National Laboratory has conducted a series of tests on tailings from four different inactive mill sites (Dr81). Tailings were sintered at temperatures ranging from 500° to 1200°C. Tests were then run on the various properties of these tailings. The results are presented in Table 8-3.

Table 8-3. Percent Reduction in Emanating Ra-226 at Temperatures from 500° to 1200°C[a]

Sintering Temperature (°C)	Shiprock, N.M., Pile[b] Sands (%)	Shiprock, N.M., Pile[b] Fines (%)	Durango, Colo., Pile[b] Sands (%)	Durango, Colo., Pile[b] Fines (%)
500	15	16	48	61
600	29	27	64	68
700	44	37	76	80
800	63	58	87	88
900	83	84	92	91
1000	92	96.1	95.5	92
1100	96.4	98.8	99.0	99.8
1200	97.7	99.2	99.5	99.8

(a) $\left[1 - \frac{\text{treated tailings}}{\text{untreated tailings}}\right]100\%$

(b) Original emanating Ra-226:

Shiprock sands = 39 pCi/g.
Shiprock fines = 214 pCi/g.
Durango sands = 140 pCi/g.
Durango fines = 473 pCi/g.

Source: Dr81.

These results indicate that thermal stabilization can be quite effective in preventing the release (emanation) of radon from tailings. The authors note that before thermal stabilization can be considered as a practical disposal method, information is needed on the following:

1. The long-term stability of the sintered material exposed to physical degradation and chemical attack (e.g., solubility of new minerals and amorphous material found in thermally stabilized tailings).

2. The interactions of the tailings and the refractory materials lining a kiln.

3. The gaseous and particulate emissions produced during sintering of tailings.

4. Revised engineering and economic analysis as more information is developed.

Since gamma radiation is still present, protection against the misuse of sintered tailings is still required. While the potential health risk from external gamma radiation is not as great as that from the radon decay products, it can produce unacceptably high exposure levels in and around occupied buildings. Also, the potential for groundwater contamination may require the use of liners.

8.3.4 Chemical Processing

The Los Alamos National Laboratory has also studied various chemical processes to remove thorium-230 and radium-226 from the tailings, along with other minerals (Wm81). After removal from the tailings, the thorium and radium can be concentrated and fixed in a matrix such as asphalt or concrete. This greatly reduces the volume of these hazardous materials and allows disposal with a higher degree of isolation than economically achievable with tailings.

The NRC has considered the processing of uranium ore in a nitric acid mill (NRC80). This chemical process would strip a large fraction of the thorium and radium from the ore, along with uranium and other minerals. The thorium and radium would then be concentrated, fixed in a matrix, and disposed of in a manner similar to the process just described for sulfuric acid treatment of the tailings.

The major question regarding both these processes is whether they reduce the thorium and radium values in the stripped tailings to safe levels. If processing efficiencies of 80 percent to 90 percent were attained, radium concentrations in tailings would still be in the 30 to 60 pCi/g range. This concentration can cause excessive levels of radon decay products in occupied structures if these treated tailings were placed under or around the structures. Thus, careful disposal of the stripped tailings would still be required to prevent misuse. Another disadvantage of chemical processing is the cost, although some of the costs might be recovered from the sale of other minerals recovered in the processing (Th81). The value of other minerals can be expected to vary greatly (Th81) from ore to ore.

8.3.5 Soil Cement Covers

A mixture of soil and Portland cement, called soil cement, is widely used for stabilizing and conditioning soils (PC79). It is used to condition subsoils under highway pavements, to serve as a base for large parking lots where it is covered with asphalt, and to stabilize slopes by preventing erosion, among other uses.

The aggregate sizes of tailings appear suitable to make a good quality soil cement, which is relatively tough, withstands freeze/thaw cycles, and has a compressive strength of 300 to 800 psi. When combined in a disposal system with a 1-meter earth cover over it, soil (tailings) cement would be likely to provide reasonable resistance to erosion and intrusion, to substantially reduce radon releases, and to shield against penetrating radiation. Its costs are expected to be comparable to those of thick earth covers.

The long-term performance of soil cement is unknown, especially as tailings piles shift or subside with age. Also, soil cement cracks at intervals when placed over large surface areas. The importance of this cracking on the effectiveness of soil cement has not been evaluated, but is expected to be small.

8.3.6 Deep-Mine Disposal

Disposal of tailings in worked-out deep mines offers several advantages and disadvantages compared to surface disposal options. The probability of intrusion into and misuse of tailings in a deep mine is much less than that achievable with surface disposal. Radon releases to the atmosphere would be eliminated, for practical purposes, as would erosion and external radiation.

The greatest problem with deep mine disposal is the potential contamination of groundwater. This problem is most difficult to evaluate, especially over the long term. Also, this method would be cost-effective for only those mills near deep mines because of the high cost of transporting tailings.

8.3.7 Solidification in Concrete or Asphalt

This disposal method separates the sands fraction of the tailings from the slimes fraction. The sands make up the greatest part of the tailings weight, while most of the radioactive material is in the slimes. After separation, the sands are washed and discharged into a surface pit. The slimes are separated from the water, dried and then solidified in concrete or asphalt. The solidified slimes can then be disposed of in the pit with the sands or by other methods offering more isolation. The NRC analyzed this method in some detail, including a cost evalution (NRC80).

Since about 15 percent of the radioactivity is in the sands, this fraction will contain about 60 pCi/g of radium-226. This concentration can lead to an excessive buildup of radon in structures if these sands are misused under and around structures. Thus, the sands fraction will require a barrier, such as an earth cover, to isolate them and to prevent misuse . Also, since toxic metals will be present in both fractions (Coa81), a liner may be needed to protect groundwater from the sands fraction.

Overall, this method is costly, provides a relatively high level of protection from 85 percent of the radioactivity in the tailings, but provides little protection from the remaining radioactivity and toxic materials unless additional controls are used.

8.4 Selection of Disposal Method For This Analysis

Earthen covers were selected for analysis for the following reasons:

1. Thick earthen covers are effective in discouraging misuse of tailings, in reducing radon emissions, in essentially eliminating gamma radiation, in protecting groundwater for long-term periods, and in resisting erosion.

2. Thick earthen covers can be made long lasting by stabilizing the surface with vegetation and/or rock.

3. Costs are relatively low and can be estimated with some degree of certainty.

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Chapter 9: ALTERNATIVE STANDARDS FOR TAILINGS DISPOSAL

In this chapter we first consider the various quantities which can be used to express limitations on environmental releases. We then formulate alternative standards that accomplish, in varying degrees, the objectives set forth in Chapter 8. Finally, we determine the cost of controls required to implement each of these alternatives.

9.1 Form of the Standards

9.1.1 Dose or Exposure Rate Limits

Health protection standards based on radiation dose or exposure have two major advantages. First, the health risk to an individual can be limited directly. Second, the cumulative risk from all pathways to humans from the source is included. Partly because of these advantages, the Federal Radiation Council Radiation Protection Guidance for Federal Agencies (FRC60) and the Environmental Radiation Protection Standards for Uranium Fuel Cycle Operations (40 CFR 190) (EPA77), with the exception of the standards for certain long-lived radionuclides, are in this form.

However, dose or exposure rate limits are not useful in establishing health protection standards in connection with the disposal of uranium mill tailings because they have an inadequate relationship with some of the principal objectives of disposal, such as preventing misuse of the tailings and controlling radon emissions from tailings for a long period of time. Establishing an environmental dose rate limit (or Working-Level Limit) near a tailings pile gives no assurance of providing a long-lasting barrier controlling radon or of inhibiting the use of tailings. In addition, limits on dose imply a need to know the locations of individuals for long periods of time into the future. Unless an exclusion area can be maintained indefinitely, conformance to a dose limit could not be assured.

9.1.2 Concentration Limits in Air and Water

The primary advantage of standards specifying concentration limits of hazardous or toxic materials in air or water is ease of compliance. Most monitoring involves measurements of concentrations in environmental media. Thus, monitoring results can be compared to concentration limits to determine compliance. This is a useful approach in evaluating the performance of emissions and effluent controls at operating facilities.

Concentration limits of radon in air can assure a given level of performance of control measures. The relationship between radon emissions from a pile and offsite concentrations of radon in air is presented in Chapter 5.

Concentration limits are appropriate for the water pathway during operation and closure, for which the period of concern is, at most, decades, and which are used to assess the need for corrective actions. EPA groundwater protection policy, which dictates the form of groundwater standards, specifies concentration limits. However, they are not appropriate for other pathways since they could be satisfied largely by institutional methods, such as acquiring and maintaining control over land, that are not appropriate in view of the long-term hazard.

9.1.3 Release Rate Limits

This form of standard is useful for controlling emissions when either total quantities discharged or ambient levels of a pollutant are of concern. It is also useful for controlling emissions and effluents when it is desirable to force a specific level of control.

Because of these advantages a release rate limit approach appears to offer the best choice of accomplishing the primary objectives of these standards. A release rate limit can assure that an effective and durable barrier controls radon emissions and isolates the tailings from the environment. This barrier can also provide significant assurance that the tailings would not be removed from the site and used in and around occupiable structures.

9.1.4 Engineering/Design Standards

Engineering or design standards specify methods or procedures and the critical dimensions or characteristics of the method. Such standards have the advantage of directly assuring a solution of the problem. For tailings disposal, a design standard could require that tailings be covered with a certain type of soil to a minimum thickness and with a maximum slope. Soil stabilization methods could also be spelled out, such as rock cover on the slopes and vegetation over the remainder of the disposal site.

Several disadvantages are inherent in design standards. They tend to squelch ingenuity and initiative to develop improved and less costly methods. They do not reflect the variations in local conditions that may lead to greater health protection if properly utilized or exploited. They are difficult to change or modify. The disadvantages of design standards appear to outweigh the advantages for use in the disposal of uranium mill tailings. In addition, the legislative history of the Act does not support the use of such standards.

A second approach in engineering/design standards can be based on probabilities considerations. In this form, the primary objective of the standard is stated clearly. Then probabilities (in quantified terms) are assigned for achieving the primary objective during various future periods. For example, in the near term, the numerical probability assigned to meeting the primary objective could be high. For longer periods, the probability could be reduced, reflecting inability to predict the effectiveness of controls over longer times.

Compliance with a probability-based standard uses models, which project the future performance of control methods, and expert views. The advantage of this approach is that it forces an appraisal of the long-term hazards associated with the tailings. However, the present state of the art for tailings disposal limits the usefulness of numerical probability-based design standards.

9.2 Alternative Disposal Standards

We have evaluated a range of alternatives for disposal standards based on the objectives described in Section 8.1, the most likely disposal method chosen in Chapter 8, and the form of the standard considered in Section 9.1. These alternatives are presented in Table 9-1. The requirements selected to meet the objectives are shown for each alternative. Most of the requirements are expressed quantitatively, and in combination they achieve the overall objective of reducing risks to people from tailings. The ranges of the controls vary widely, from no control (Alternative A) to high levels of control (Alternatives C-5 and D-5).

Uranium mill tailings will remain hazardous for hundreds of thousands years due to the 75,000-year half-life of thorium-230. Protecting public health for such periods of time is difficult to conceptualize, much less assure. On a practical basis, controls reasonably can be relied on for periods defined as:

- Active control—a maximum period of about 100 years.
- Available and practical engineering controls--a period extending from a few hundred years to a few thousand years.
- Controls featuring great isolation--a period of many thousands of years limited by major geological activity.

These periods will be used in the ensuing discussions of alternative standards.

In preparing alternatives, it is important to separate active (institutional) and passive (engineered) controls so that the differences in benefits and costs are apparent. It is also important to delineate the differences in benefits and costs for disposal methods that can be used at new tailings impoundments. Thus, alternatives were developed as follows:

Alternative	Type of Control
Group A	Base case. No controls.
Group B	Institutional (active) controls.
Group C	Passive (engineered) controls.
Group D	Passive (engineered) controls for new tailings impoundments.

Within each group the radon emission level was varied (as indicated by the number following the group letter, i.e., B-1, B-2, etc.) to depict the cost effectiveness of different levels of radon control.

Alternative A. This alternative is the "no standards" case and represents conditions if nothing is done. The piles will remain hazardous for a long time, taking about 265,000 years for the radioactivity to decay to 10 percent of current levels. The radon emission rate from a model pile is estimated to be 400 pCi/m^2s, compared to a background rate for typical soils of about 1 pCi/m^2s. We also know that the concentration of some toxic chemicals in the tailings is hundreds of times background levels in ordinary soils, so that the potential for contaminating groundwater is present and continues indefinitely.

Alternative B-1. This alternative specifies that control measures include a durable cover that is subject to inspection and maintenance requirements for 100 years. Institutional controls (inspection and maintenance) would also be required to prevent significant contamination of groundwater, or groundwater would be treated before use. No radon emission rate is specified.

Alternative B-2. Control measures require a durable cover that is subject to inspection and maintenance for 100 years. The radon emission limit is 60 pCi/m^2s. Institutional controls would also be required to protect groundwater.

Alternative B-3. Control measures require a durable cover that is subject to inspection and maintenance for 100 years. The radon emission limit is 20 pCi/m^2s. Groundwater would be protected through the use of institutional controls, such as monitoring and corrective actions.

Alternative C-1. Control measures are designed so there is readonable assurance they will be effective for 1,000 years. No requirement is specified for radon emissions. Water quality is expected to be protected for about 100 years.

Alternative C-2. Control measures are designed so there is readonable assurance they will be effective for a few 1,000 years.

Table 9-1. Alternative Standards for Disposal of Uranium Mill Tailings

Alternative Standard	Minimum Time Controls Should Prevent Erosion and Misuse (years)	Radon Emissions Permitted from Top of Pile (pCi/m^2-sec)	Expected Time Controls Should Protect Groundwater (years)
A	None	No limit	None
B-1	100	No requirement	100
B-2	100's	60	100
B-3	100's	20	100
C-1	1,000	No requirement	100
C-2	1,000	60	100's
C-3	Many 1,000	20	1,000
C-4	Many 1,000	6	1,000
C-5	Many 1,000	2	1,000
D-2	1,000	60	1,000
D-3	Many 1,000	20	1,000
D-4	Many 1,000	6	1,000
D-5	Many 1,000	2	1,000

The radon emission limit is 60 pCi/m^2s. Groundwater is expected to be protected for a few hundred years.

Alternative C-3. In this alternative control measures are designed to be effective for 1,000 years. The radon emission limit is 20 pCi/m^2s. Water quality is expected to be protected for about 1,000 years.

Alternative C-4. Control measures are designed to be effective for at least 1,000 years. The radon emission limit is 6 pCi/m^2s. Water quality is expected to be protected for at least 1,000 years.

Alternative C-5. Control measures are designed to be effective for at least 1,000 years. The radon emission limit is 2 pCi/m^2s. Water quality is expected to be protected for at least 1,000 years.

Alternative D-2. Disposal below grade by a staged disposal method is required. This will provide a significant reduction in radon emissions during mill operations. Control measures are designed to be effective for 1,000 years. The radon emission limit is 60 pCi/m^2s. Water quality is expected to be protected for about 1,000 years.

Alternative D-3. Disposal below grade by staged methods is required, thus providing reduction of radon emissions during mill operations. Control measures are designed to be effective for 1,000 years. The radon emission limit is 20 pCi/m^2s. Water quality is expected to be protected for more than 1,000 years.

Alternative D-4. Disposal below grade by staged methods is required, thus providing reduction of radon emissions during mill operations. Control measures are designed to be effective for at least 1,000 years. The radon emission limit is 6 pCi/m^2s. Water quality is expected to be protected for more than 1,000 years.

Alternative D-5. Disposal below grade by staged methods is required, thus providing reduction of radon emissions during mill operations. Control measures are designed to be effective for at least 1,000 years. The radon emission limit is 2 pCi/m^2s. Water quality is expected to be protected for more than 1,000 years.

9.3 Estimated Costs of Methods for Alternative Standards

Costs are estimated for the levels of control which will satisfy the levels of health protection shown in Table 9-1. A range of thicknesses of earth covers provides the various radon emission levels. Various protective materials are used to increase the long-term effectiveness of the cover.

Because the large differences in the sizes of existing tailings piles at licensed sites can lead to large cost differences, these piles have been separated into three groups: 2 million tons (MT), 7 million tons, and 22 million tons. Their characteristics are given in Appendix B. This grouping is for costing purposes only. While the divergence in estimated costs for existing piles is great, the range in potential health risks is small. Estimates of potential health risks are largely dependent on the area covered by the tailings. The area of the model pile (Chapter 4) and a listing of existing piles (Chapter 3) indicate the areas vary by a factor of only plus or minus 40 percent.

	Area (hectares)	Ratio of Area of Existing Piles to Area of the Model Pile
Model pile	80	1.0
Existing 2 million tons	49	0.61
Existing 7 million tons	73	0.91
Existing 22 million tons	113	1.4

Thus, potential health risk estimates can be treated uniformly, regardless of the pile size.

9.3.1 Disposal Methods for Existing Tailings Piles

Method B1-E

The edges of the square tailings pile are graded and contoured to a 3:1 (H:V) slope. The entire area is then covered with 0.5 meter of earth obtained nearby. A 6-feet high, 6-gage aluminum chain link fence is placed around the exclusionary zone, which is assumed to be 0.5 kilometer from all sides of the pile. The covered pile is landscaped,assuming that suitable loam or topsoil is available onsite. The borrow-pit is reclaimed. Maintenance and inspection are added for a 100-year period. The costs for this method are summarized in Table 9-2.

Method B2-E

The sides of the tailings piles are graded to 3:1 (H:V) slope. The tailings are covered with 1.5 meters of earth obtained nearby and the entire surface is landscaped. A fence is installed to form an exclusion area 0.5 kilometer wide all around the disposed tailings. The borrow pit is reclaimed. The costs for this method are shown in Table 9-2.

Method B3-E

For this method the edges of the square tailings pile are graded to a 3:1 (H:V) slope. The entire tailings area is covered with 2.4 meters of earth obtained nearby or locally. The entire area (slopes and top) are landscaped after covering. A fence is installed to form an exclusion area 0.5 km wide around the edge of the tailings. The borrow pit is reclaimed. The costs for this option are listed in Table 9-2.

Method C1-E

The sides of the tailings piles are graded to a 5:1 (H:V) slope, after which the entire area is covered with 0.5 m of gravelly earth obtained nearby or locally. The slopes are covered with 0.5-meter rock cover. No fence is needed. The borrow pit is reclaimed. The costs for this option are presented in Table 9-2.

Method C2-E

The edges of the tailings piles are contoured to a slope of 5:1 (H:V). The entire area is then covered with 1.5 meters of earth obtained nearby except the top 0.5-meter of the cover is gravelly earth. The slopes are covered with a 0.5-meter thick rock cover. No fence is necessary. The borrow pit is reclaimed. The costs for this option are presented in Table 9-2.

Method C3-E

The sides of the tailings piles are graded to a 5:1 (H:V) slope. The entire area is then covered with 2.4 meters of earth obtained nearby of which the top 0.5-meter layer is gravelly earth. A 0.5-meter rock cover is added to the slopes. The borrow pit is reclaimed. The costs for this method are listed in Table 9-2.

Method C4-E

The sides of the pile are graded to a 5:1 (H:V) slope. The entire area is covered with 3.4 meters of earth obtained nearby of which the top 0.5-meter layer is gravelly earth. A 0.5-meter rock cover is placed on the slopes. No fence is needed. The borrow pit is reclaimed. The costs for this method are listed in Table 9-2.

Method C5-E

The sides of the pile are graded to a 5:1 (H:V) slope. The entire area is covered with 4.3 meters of earth obtained locally of which the top 0.5-meter layer is gravelly earth. A 0.5-meter rock cover is placed on the slopes. No fence is needed. The borrow pit is reclaimed. The costs for this method are shown in Table 9-2.

9.3.2 Disposal Methods for New Tailings Piles

Method A

This method is the same as the base case in the NRC analysis (NRC80). An initial square basin would be formed by building low earthen embankments along each side of 947 meters length at the centerline. The mill tailings would be slurried into the basin, and as the basin filled, the coarse fraction of the tailings (sands) would be used to raise and broaden the embankments. The final dimensions of the embankments would be 10 meters high and 13 meters wide at the top. When the mill ceases operations, no specific control measures for disposal would be used. The cost for this option is listed in Table 9-2 and consists only of preparation of the initial basin.

Methods B1-N, B2-N, and B3-N

These methods use earth covers on the tailings and rely on institutional controls to prevent misuse and to maintain the covered pile. A pit is excavated close to the mill and measures 930 meters square by 2 meters deep. Embankments are constructed along each side, 947 meters long, 10 meters high, and 13 meters wide at the top. The pit is lined with 1 meter of clay obtained locally. Tailings are pumped directly into the pit during operation of the mill. It is assumed that water from the pond will be recycled to the mill, thereby negating the need for an evaporation pond.

At the end of mill life, the embankments are excavated and placed on top of the tailings. The slopes of the covered tailings are graded to 3:1 (H:V). The cover thickness is 0.5 meters for B1-N, 1.5 meters for B2-N, and 2.4 meters for B3-N. The entire area is landscaped. A fence is placed around the disposal area and provides a 0.5-kilometer exclusion zone. Borrow pits are reclaimed. The site is maintained for 100 years by irrigation of the vegetative cover and inspection and repair of the earth cover and fence. Costs are shown in Table 9-2.

Methods C1-N, C2-N, C3-N, C4-N and C5-N

Passive controls are used in these methods. These methods use earth covers, 0.5-meter rock covers on the slopes and 0.5-meter gravel layers on the top. A pit is prepared and used in the same manner to that described for methods B1-N, B2-N, and B3-N, including the liner.

At the end of mill life, the embankments are excavated and placed on top of the tailings. The cover thickness is 0.5 meters for C1-N, 1.5 meters for C2-N, 2.4 meters for C3-N, 3.4 meters for C4-N, and 4.3 meters for C5-N. The slopes of the disposed tailings are graded to 5:1 (H:V) and then covered with rock to a depth of 0.5 meter. The top of the disposed tailings area (that part not covered with rock) is covered with a 0.5-meter layer of gravelly soil which replaces the top 0.5-meter of earth. No fence is needed. The costs are listed in Table 9-2.

Methods D2-N, D3-N, D4-N, and D5-N

These methods are somewhat similar to the staged or phased disposal method described by the NRC's GEIS (NRC80). This method uses 6 pits, each 280 meters square at the bottom and with 2:1 (H:V) slopes. Two pits are constructed initially and lined with 1 meter of clay. Tailings are pumped to the first pit until it is full and then pumped to the second pit. When the first pit is sufficiently dry, the third or fourth pit is excavated, and the excavated earth is used to cover the first pit to the original ground contour. The earth cover thickness is 1.5 meters for D2-N, 2.4 meters for D3-N, 3.4 meters for D4-N, and 4.3 meters for D5-N. This process continues sequentially until the end of mill life. An evaporation pond is needed in this method. Costs for this pond are taken from the NRC GEIS and corrected for inflation.

At the end of mill life there will likely be four completed pits, which are covered with earth to the original ground contour and 2 uncovered pits. When sufficiently dry, these last two pits are covered with excavated earth to the original ground contour. The disposed tailings area is landscaped. The areas covered by the evaporation pond and excess excavated earth are restored. The costs for this method are presented in Table 9-2.

Cost Estimates

Cost estimates for the disposal of tailings at active uranium milling sites are presented in Table 9-2 along with a summary of critical design features. The cost estimate details are developed in Appendix B, which also includes characteristics of tailings piles, unit costs, and descriptions of disposal methods.

All cost estimates in Table 9-2 include an increase of 25 percent for overhead and profit, but do not include the cost of a liner for the tailings pond. The disposal costs for the model pile are greater than for the existing 7-MT pile. The difference is due to the larger size of the model and the costs of preparing the initial tailings impoundment. The model pile, taken directly from the NRC Generic EIS (NRC80), appears oversize when compared with industry practice. This leads to the considerably greater costs for the model pile when compared to an existing pile containing about the same quantity of tailings. These cost estimates for the NT methods can be considered maximum costs.

9.4 Accidental and Radiation-Induced Deaths from Disposal

One of the costs of control is the possibility of accidental deaths during the disposal of tailings and when moving tailings. Table 9-3 shows our estimate of the number of accidental deaths that could be associated with each alternative disposal standard. These estimates include accidental deaths of workers and premature, radiation-induced deaths of construction workers at the tailings sites.

In our review of the existing tailings sites, we identified only two sites that may be vulnerable to flooding. Even for these two sites, it is not clear that the tailings would have to be moved to provide protection against flooding. Thus, we have made no estimate of the number of deaths that might occur, primarily to workers and the public, from transportation accidents if the tailings piles are moved.

The most important parameter in this simplified analysis of accidental deaths is the number of person-hours of labor required to do the job. This is used to estimate the number of construction-related deaths, as well as the number of premature deaths from radiation exposure.

The labor required for piles that are to be controlled onsite is proportional to the amount of earthmoving to be done; a gradual slope requires more earthmoving than a steep slope, roughly in proportion to the ratio of the slopes, and a thick cover requires more earthmoving than a thinner one. Based on figures from a DOE contractor (DeW81), we estimate that Alternative B1-N would require about 110 person-years of labor for the model pile. The labor requirements for C3-N and D3-N would be 280 person-years. The labor requirements for each alternative are estimated by scaling directly by the area covered by the tailings

Table 9-2. Summary of Cost Estimates for Disposal of Active Uranium Mill Tailings

Method	Cost[a] (In millions of 1983 dollars)			Maximum slope	Cover thickness (m)	Rock cover (0.5 m)	Pebbly soil cover	Vegetation cover
				NEW TAILINGS PILE				
A[b]	1.26			-	-	-	-	-
B1[c]	11.4			3:1	0.5	-	-	Yes
B2[c]	15.0			3:1	1.5	-	-	Yes
B3[c]	19.0			3:1	2.4	-	-	Yes
C1	11.4			5:1	0.5	Yes	Yes	-
C2	16.0			5:1	1.5	Yes	Yes	-
C3	20.0			5:1	2.4	Yes	Yes	-
C4	24.3			5:1	3.4	Yes	Yes	-
C5	28.4			5:1	4.3	Yes	Yes	-
D2[d]	32.1			-	1.5	-	-	Yes
D3[d]	35.5			-	2.4	-	-	Yes
D4[d]	39.5			-	3.4	-	-	Yes
D5[d]	43.1			-	4.3	-	-	Yes
				EXISTING TAILINGS PILE				
	By pile size (MT)							
	2	7	22					
B1[c]	4.2	6.4	10.8	3:1	0.5	-	-	Yes
B2[c]	6.9	10.4	17.3	3:1	1.5	-	-	Yes
B3[c]	9.2	14.0	23.0	3:1	2.4	-	-	Yes
C1	3.2	6.3	13.6	5:1	0.5	Yes	Yes	-
C2	5.9	10.5	20.6	5:1	1.5	Yes	Yes	-
C3	8.3	14.3	26.8	5:1	2.4	Yes	Yes	-
C4	10.9	18.5	33.8	5:1	3.4	Yes	Yes	-
C5	13.3	22.2	40.0	5:1	4.3	Yes	Yes	-

[a] Costs include a 25 percent increase for overhead and profit, but do not include the costs of an impoundment liner.
[b] Base case; no disposal.
[c] Fenced; inspected and maintained for 100 years.
[d] Staged below grade disposal.

Table 9-3. Accidental and Radiation-Induced Deaths Associated with Alternative Levels of Tailings Control

Method	Accidental Deaths	Radiation-Induced Deaths
	NEW TAILINGS	
For a Model Pile		
B1-N	0.07	0.04
B2-N	0.13	0.09
B3-N	0.16	0.10
C1-N	0.14	0.08
C2-N and D2-N	0.16	0.10
C3-N and D3-N	0.17	0.11
C4-N and D4-N	0.18	0.12
C5-N and D5-N	0.19	0.13
	EXISTING TAILINGS (As of January 1983)	
For 2-million-ton piles: (11 piles)		
B1-E	0.4	0.3
B2-E	0.5	0.4
E3-E and C1-E	0.7	0.5
C2-E	0.8	0.6
C3-E	1.0	0.7
C4-E	1.1	0.8
C5-E	1.2	0.8
For 7-million-ton piles: (12 piles)		
B1-E	0.5	0.3
B2-E	0.7	0.4
B3-E and C1-E	0.9	0.5
C2-E	1.0	0.6
C3-E	1.2	0.8
C4-E	1.3	0.9
C5-E	1.4	0.9

Table 9-3. Accidental and Radiation-Induced Deaths Associated with Alternative Levels of Tailings Control (Continued)

Method	Accidental Deaths	Radiation-Induced Deaths
	EXISTING TAILINGS (As of January 1983)	
For 22-million-ton piles: (3 piles)		
B1-E	0.2	0.2
B2-E	0.3	0.2
B3-E and C1-E	0.4	0.3
C2-E	0.5	0.3
C3-E	0.6	0.4
C4-E	0.7	0.5
C5-E	0.7	0.5
TOTAL:		
B1-E	1.1	0.8
B2-E	1.5	1.0
B3-E and C1-E	2.0	1.3
C2-E	2.3	1.5
C3-E	2.8	1.9
C4-E	3.1	2.2
C5-E	3.3	2.2

(see Section 9.3), using an effective area of the model pile of 80 hectares.

The occupational deaths resulting from this are estimated from mortality statistics for the construction industry: 60 deaths per 100,000 worker-years (NS78). This corresponds to 6×10^{-4} accidental deaths per person-year.

Radiation-induced deaths are difficult to estimate since it is impossible to anticipate measures that might be used to protect workers. However, in the worst case, the gamma radiation exposure rate over a bare tailings pile (typically 1 mrem/h) for a working year would lead to exposures of about 2 rem/y. Inhalation of radon decay products would, at most, lead to a comparable risk. In Table 9-3, we have assumed that the maximum risk of premature, radiation-induced death is equivalent to the risk from an exposure of 4 rems (whole-body equivalent) of gamma radiation per person-year of labor. Radiation-induced deaths are estimated at the rate of 2 x 10^{-6} per person-rem. Since radiation exposures will be significantly reduced as the earth cover is added, the radiation-induced death estimate was taken as one-half the value obtained without credit for shielding by the cover.

9.5 Alternative Cleanup Standards for On-site Contaminated Land

We have analyzed four alternative cleanup standards for on-site contaminated lands. All have requirements that limit the amount of radium contamination because the presence of radium is a reasonable index of the health hazard, including that due to toxic chemicals as well as other radionuclides.

Alternative L1 approaches a high-cost nondegradation alternative; below this proposed radium limit it is usually not possible, using conventional survey equipment, to accurately distinguish between contaminated land and land with high naturally-occuring levels of radium. Alternatives L2 and L3 approximate optimized cost-benefit standards, but L2 demands a more rigorous cleanup of the soil surface. Alternative L4 is a least-cost alternative that allows high radiation levels that are close to Federal Guidance recommendations for exposure of individuals to all sources of radiation excepting natural background and medical uses.

The four alternative standards are:

Alternative L1. Land is cleaned up to levels not exceeding an average 5 pCi/g of radium-226 in any 5-cm layer within 30 cm of the surface and in any 15-cm layer below 30 cm of the surface.

Alternative L2. Land is cleaned up to levels not exceeding an average of 5 pCi/g in the 15-cm surface layer of soil, and an average of 15 pCi/g over any 15-cm depth for buried contaminated materials.

Alternative L3. Land is cleaned up to levels not exceeding an average of 15 pCi/g in any 15-cm depth of soil.

Alternative L4. Land is cleaned up to levels not exceeding an average of 30 pCi/g in any 15-cm depth of soil.

In Table 9-4 we list the estimates of the costs and benefits of each alternative standard for on-site contaminated land at the 26 existing mill sites. In each standard, the only remedial method for which we estimated cost was the removal and disposal of contaminated soil, since this is generally less costly than placing earth cover and vegetation over contaminated areas and excluding access by fencing. The benefits are expressed by (1) the number of acres of land that are cleaned up and returned to productive use, and (2) the typical maximum residual risk to individuals living in houses that might then be built on this land.

The number of acres requiring cleanup under each option was estimated based on NRC's analysis of land decontamination (NRC80). By assuming a typical depth profile of the radium contamination, it is possible to relate the gamma radiation levels measured by the survey to the areas of land contaminated above a specific concentration level of radium. If the top 15-cm layer of earth is uniformly contaminated with 30 pCi/g of radium, the gamma field at the surface would be 63 percent of the gamma flux from an infinitely thick layer, or 34 microroentgens/hr (He78). However, if the 30-pCi/g average in the top 15 cm of earth is due to a thin surface layer of nearly pure tailings of a few hundred pCi/g, the resulting gamma radiation at the surface would be about 54 microroentgens/hr. Since we expect windblown contamination profiles to be somewhere in between these extremes, we estimate that, on the average, 44 microroentgens/hr above background (385 mrem/y) implies 30 pCi/g radium contamination in the top 15 cm of soil (Standard L4). Similar analyses for Alternative Standards L1, L2, and L3 result in 3, 7, and 22 microroentgens/hr, respectively (or 26, 61, and 193 mrem/y, respectively). Additional deeper contamination would yield only slightly higher gamma values because of shielding by the surface layer.

Using these correlations between radium contamination levels and gamma radiation levels, the areas requiring cleanup under each standard were estimated based on the NRC analysis. The total costs of cleanup were then calculated assuming a cleanup cost of $15,300 (1983 dollars) per acre for heavily contaminated land (ore storage areas) and $2600 (1983 dollars) per acre for land contaminated with windblown tailings.

The highest risk to people living in houses built upon contaminated land is due to the inhalation of radon decay products from radon that seeps into the house. In the worst case, Alternatives L1 and L2 would allow thick-surface earth layers with 5 pCi/g contamination, while Alternatives L3 and L4 would allow thick layers of contaminated soil at 15 pCi/g and 30 pCi/g, respectively. On the average, houses built on such 5 pCi/g earth would be expected to have indoor radon decay product levels of about 0.02 WL. Houses with poorer-than-average ventilation would have higher levels, while well-ventilated houses would have lower levels. Houses built on land more heavily contaminated than 5 pCi/g would have higher average indoor decay product levels in proportion to the contamination. The estimated risks due to lifetime exposure from these levels are listed in Table 9-4. These are maximum estimates since most contaminated land away from the immediate mill sites (where houses might be built) has only thin layers (a few tens of centimeters) of contaminated material.

The gamma radiation levels to individuals permitted under the four alternative standards are 80 mrem/yr for L1 and L2, 240 mrem/yr for L3, and 470 mrem/yr for L4. This assumes a thick layer of contaminated material over a large area at the maximum permitted levels of radium concentrations. These doses would lead to increased risk of many kinds of cancer, but this increase would be small compared to the lung cancer risks due to radon decay products.

Table 9-4. Costs and Benefits of Alternative Cleanup Standards for Land (in 1983 dollars)

Alternative	Radium-226 Soil Concentration Limit (pCi/g)	Number of Acres Requiring Cleanup[a]	Total Cost (millions of dollars)	Estimated Residual risk of Lung Cancer[b]
L1	5	8300	27.9	2 in 100
L2	5 to 15	5700	21.3	2 in 100
L3	15	3100	14.6	6 in 100
L4	30	520	7.8	10 in 100

(a)Areas of land on uranium milling sites that have radium contamination in excess of the soil concentration limit. It is assumed that about 20 acres (the ore storage pad) at each site is heavily contaminated and must be excavated to 3 feet. The remaining area is contaminated by windblown tailings and is excavated to 6 inches (NRC80). These totals are for the 26 existing sites.

(b)The lifetime risk of lung cancer to the individual living in a house built on land contaminated to the limits allowed by the alternative standards. This is based on the relative-risk model; use of the absolute-risk model gives risks which are about a factor of two lower.

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NS78 National Safety Council, "Accident Facts," 444 N. Michigan Ave, Chicago, Illinois.

Chapter 10: ANALYSIS OF COSTS AND BENEFITS FOR TAILINGS DISPOSAL ALTERNATIVES AND SELECTION OF THE STANDARD

10.1 Benefits Achievable Through Disposal of Tailings

The estimated benefits of disposal of tailings include:

1. Reducing the likelihood of misuse of tailings, and the resulting risk of lung cancer deaths from inhaling radon decay products.

2. Reducing the risk of lung cancer deaths caused by emissions of radon and its decay products.

3. Reducing the contamination of water with radioactive and other hazardous or toxic materials.

4. Reducing the spread of radioactive and other hazardous or toxic materials.

5. Eliminating, for practical purposes, exposure to gamma radiation from tailings.

All of these benefits are achieved by stabilizing the tailings by adding earthen cover material and instituting protective measures for groundwater, where needed.

The benefit we are best able to quantify is the number of lung cancer deaths averted by controlling radon emissions. We can estimate the reduction in radon emissions resulting from the placement of a given thickness of earthen cover, and translate this reduction into lung cancer risk averted (see Chapter 6). The benefits of radon control are quantified for both the total risk to populations of lung cancer death that is averted and for the reduction in risk to individuals living near the piles. These benefits are proportional to the length of time the control remains effective.

Most of the other benefits of controlling the tailings piles are not quantifiable, although the goals are well defined: the reduction of health risks from exposure to the hazardous materials contained in the tailings. For example, we are unable to translate flood protection measures into the number of health effects averted. The missing linkages are: 1. The translation from specific flood protection measures to flood damage averted; 2. The translation from flood damage to the pile to distribution of tailings spread along the downstream river valley; and 3. The translation from the tailings spread along the river valley to the number, length, and level of exposures. There are similar problems with quantifying the chance of misuse. The permanence of erosion control, i.e., the years of erosional spreading avoided and the years of water quality protection can be evaluated, but, the consequences avoided are not readily quantified.

The benefits for each alternative standard are displayed in Tables 10-1 and 10-2 and are quantified when possible.

The benefits of controlling tailings at existing sites are summarized in Table 10-1. There were about 175 million tons of tailings at 26 active mill sites January 1983. Table 10-1 is presented primarily to show the cost effectiveness of controlling existing tailings, which may be different than the cost effectiveness of controlling future tailings.

The benefits of controlling tailings at all sites, both existing and new, are summarized in Table 10-2. Based on current DOE projections, it is estimated that another 175 million tons of tailings will be generated by 2000.

10.1.1 Benefits of Stabilization

The benefits of stabilizing the tailings are expressed in terms of the reduced chance of misuse and the years of erosional spreading avoided. The number of health effects averted cannot be estimated.

The major benefit of stabilizing a pile is the inhibition of the hazards associated with human intrusion and misuse of the tailings piles; this can be expressed only in qualitative terms. We have assigned relative values to the probability of misuse, based on the assumption that thicker covers provide greater inhibition of misuse. Also, the below-grade disposal method, with a 2.4-meter earth cover up to the original ground contour, is expected to provide greater inhibition of misuse than above-grade disposal with the same cover thickness.

The likelihood of misuse during the period of effectiveness of these alternatives ranges from most likely for the no-requirements alternative to unlikely for alternatives with 2.4 meters of earth cover and very unlikely for the method with 4.3 meters of earth cover.

Table 10-1. Benefits of Controlling Uranium Mill Tailings at Existing Active Sites[a]

Alternative Standards	Stabilization		Radon Control			Water Protection
	Chance of Misuse	Minimum time erosion avoided (y)	Residual Risk[b] of Lung Cancer (% reduction)	Deaths Avoided: In first 100 years	Deaths Avoided: Total	Groundwater Protected (y)
A	Very likely	0	2 in 10^2 (0)	0	0	0
B-1	Likely	Hundred	1 in 10^2 (50)	250	1,000	100
B-2	Less likely	Hundreds	4 in 10^3 (80)	400	1,500	100
B-3	Less likely	Hundreds	1 in 10^3 (95)	475	2,000	100
C-1	Likely	Thousands	1 in 10^2 (50)	250	Thousands	100
C-2	Less likely	Thousands	4 in 10^3 (80)	400	Many thousands	Hundreds
C-3	Unlikely	Thousands	1 in 10^3 (95)	475	Tens of thousands	1,000
C-4	Very unlikely	Many thousands	3 in 10^4 (98.5)	490	Tens of thousands	>1,000
C-5	Very unlikely	Many thousands	1 in 10^4 (99.5)	497	Tens of thousands	>1,000

(a)For tailings at 26 licensed sites as of January 1983.
(b)Lifetime risk of fatal cancer to an individual assumed to be living 600 meters from center of a tailings pile.

Table 10-2. Benefits of Controlling Uranium Mill Tailings at Active Mill Sites through the Year 2000[a]

Alternative Standards	Stabilization: Chance of Misuse	Stabilization: Minimum time erosion avoided (y)	Radon Control: Residual Risk[b] of Lung Cancer (% reduction)	Radon Control: Deaths Avoided, In first 100 years	Radon Control: Deaths Avoided, Total	Water Protection: Groundwater Protected (y)
A	Very likely	0	2 in 10^2 (0)	0	0	0
B-1	Likely	Hundred	1 in 10^2 (50)	300	1,200	100
B-2	Less likely	Hundreds	4 in 10^3 (80)	480	1,800	100
B-3	Less likely	Hundreds	1 in 10^3 (95)	570	2,100	100
C-1	Likely	Thousands	1 in 10^2 (50)	300	Thousands	100
C-2	Less likely	Thousands	4 in 10^3 (80)	480	Many thousands	Hundreds
C-3	Unlikely	Thousands	1 in 10^3 (95)	570	Tens of thousands	1,000
C-4	Very unlikely	Many thousands	3 in 10^4 (98.5)	590	Tens of thousands	>1,000
C-5	Very unlikely	Many thousands	1 in 10^4 (99.5)	597	Tens of thousands	>1,000
D-2	Unlikely	Thousands	4 in 10^3 (80)	480	Several thousand	1,000
D-3	Unlikely	Many thousands	1 in 10^3 (95)	570	Tens of thousands	>1,000

See footnotes at end of table.

Table 10-2. Benefits of Controlling Uranium Mill Tailings at Active Mill Sites through the Year 2000[a] (Continued)

Alternative Standards	Stabilization		Radon Control			Water Protection
	Chance of Misuse	Minimum time erosion avoided (y)	Residual Risk[b] of Lung Cancer (% reduction)	Deaths Avoided: In first 100 years	Deaths Avoided: Total	Groundwater Protected (y)
D-4	Very unlikely	Many thousands	3 in 10^4 (98.5)	590	Tens of thousands	> 1,000
D-5	Very unlikely	Many thousands	1 in 10^4 (99.5)	597	Tens of thousands	> 1,000

(a) These estimates include the benefits resulting from control of 26 existing piles and 9 projected new piles.

(b) Lifetime risk of fatal cancer to an individual assumed to be living 600 meters from center of a tailings pile.

The Grand Junction cleanup program is an example of the kind of expensive remedial actions that stabilization should prevent. The tailings in Grand Junction buildings are now being cleaned up at a cost of about $23 million, to avoid an estimated 75 to 150 lung cancer deaths. The additional cost of cleaning up contaminated offsite land is estimated at $22 million to $31 million.

A second benefit of stabilization is the prevention of erosion. The benefit of preventing tailings erosion can be expressed in a semiquantitative way by estimating the number of years that erosional spreading is prevented. Protection from erosion is estimated to range from a few hundred years to many thousands of years for the various alternatives. Since erosion may now be taking place at some sites, benefits can be derived from any remedial measure that reduces erosion. For example, EPA estimated the cost for cleanup of contaminated land around inactive tailings piles at $8,000 (1983 dollars) per acre. The total cost for cleanup of such lands depends on the area contaminated and the level to which it must be cleaned up.

A third benefit of stabilization is protection against floods which could wash tailings downstream to flood plains, where land use is residential and agricultrual. Should this happen, expensive remedial measures would probably be needed. A recent tailings "spill" (failure of a dam containing a tailings pile at an active mill) in the Southwest contaminated hundreds of acres of land (of limited value) over a distance of about 20 miles. We estimate the cost of cleanup of that spill to be $1 million to $5 million, depending on the cleanup criteria used. The total radioactivity spilled was less than 5 percent of that in an average active pile.

10.1.2 Benefits of Radon Control

The estimated benefits of radon control can be quantified. For individuals living near a tailings pile, the benefit is a reduction in health risk. The maximum risk of death to nearby individuals during their lifetime is estimated to be about 2 chances in 100 for the no-requirements of Alternative (A). This risk drops to less than 1 chance in 1,000 for Alternatives B-3, C-3, and D-3. The greatest risk reduction is achieved by Alternatives C-5 and D-5, which have a 2 pCi/m^2s radon emission limit and reduce the risk to less than 1 chance in 10,000.

The total national lung cancer death rate from radon emissions from existing active piles is estimated at 500 per century if no controls are used. This estimate will increase as additional tailings are produced if controls are not used. Alternatives with a 20 pCi/m^2s radon emission rate would reduce this rate to about 25 per century for hundreds to thousands of years. The benefit from a more restrictive radon emission rate would be the virtual elimination of the radon risk. Alternatives C-5 and D-5 are estimated to provide greater than 99 percent control of radon for at least 1,000 years.

10.1.3 Benefits of Protecting Water

Protection of water quality is a benefit that cannot be quantified, because future uses of the water cannot be estimated. Unlike air, which must be breathed, water may or may not be used in ways that might cause an increase in health risks. Also, water may be tested for contaminants and, if polluted, it may be cleaned to levels suitable for its projected use, or may be rejected, if an alternative is available. However, after disposal the protective cover, or cap, over the tailings can be quite effective at reducing the volume of liquids entering the tailings and therefore can substantially reduce the potential for contamination of groundwater for long periods.

The benefit of protecting groundwater is the preservation of its existing quality for future uses. These uses are drinking, lifestock watering, and limited irrigation. A specific benefit of groundwater protection would be the reduction, or elimination, of molybdenosis in cattle, which has occurred at a site in Colorado where molybdenum from a tailings pond contaminated groundwater.

Existing uranium tailings are located in areas with low precipitation. This means there is little need to discharge waste water to surface waters. Waste water can be held in ponds, where it evaporates or can be recycled back to the process. Only one uranium mill currently has a National Pollution Discharge Elimination System (NPDES) permit, under the Clean Water Act, for example. However, uranium mining and milling may occur in wetter areas in the future where discharges to surface waters may be unavoidable. In these cases, the operator would be required to obtain a NPDES permit, which would assure protection of surface water quality.

10.2 Benefits and Costs for a Model Tailings Pile

The benefits derived from disposal of tailings have been estimated as shown in Tables 10-1 and 10-2 for the various alternative standards. The total costs of these methods have been estimated as listed in Table 10-3. In this section these benefits and costs are evaluated for each alternative standard.

10.2.1 Baseline Case A

This case is used as a baseline to which the benefits of other methods can be compared. While this alternative would not achieve the goals or objectives of the disposal standards, it has the significant benefit of preventing the flagrant discharge of all tailings into surface waters. This control has been practiced by the industry for some time, however, and is considered appropriate as a baseline. Cancer deaths from radon emissions from uncontrolled piles are estimated to be 5 per year for existing tailings piles. These deaths are expected to increase to 6 per year for all the tailings that are projected to exist by the year 2000, if no controls are implemented.

Table 10-3. Total Costs of Controlling Uranium Tailings at Active Sites (1983 dollars in millions discounted at 10%)

Alternative Standard	Present Worth Costs (10% discount rate)[a] Existing Tailings	Future Tailings	Total Cost
A	0	1	1
B-1	117	83	200
B-2	192	95	287
B-3	256	111	367
C-1	115	95	210
C-2	192	112	304
C-3	260	128	388
C-4	336	146	482
C-5	403	165	568
D-2	192	156	348
D-3	260	160	430
D-4	336	186	522
D-5	403	204	607

[a]These cost estimates assume that two-thirds of the future tailings generated at existing mills will be placed in existing impoundments and the other one-third will be placed in new, lined impoundments. We assume that the average radium contents of existing and future tailings is 400 pCi/m^2s.

10.2.2 Alternative Standards B-1, B-2, and B-3

The concept underlying these alternatives is active control and maintenance. The earth cover, loam, and vegetation would reduce radon emanation and associated health effects for the 100-year period maintenance is performed. The total radon deaths avoided would be 1,000 for Alternative B-1, 1,500 for Alternative B-2 and 2,000 for Alternative B-3. The chance of misuse is small for 100 years because of a fence and continuing human activities such as maintence and inspection. Annual inspection and repair actions would provide protection against windblown and surface water contamination and external radiation for as long as such actions continue.

Most of the benefits for these alternative are considered to end when maintenance activities cease. Once the sprinkling (irrigation) of the vegetation stops, chemicals from the tailings will probably kill the vegetation, and the cover will be denuded and rapidly eroded. However, this scenario could be modified by selection of a site where the deposition of material exceeds the erosion of material. Even in this case the deposition rate is likely to be low, thus allowing continued radon releases and significant chances of misuse for a long period.

The estimated total costs for Alternatives B-1 through B-3 are $200 to $370 million as listed in Table 10-3.

The estimated number of accidental and radiation induced deaths for Alternative B-1 is 3, for Alternative B-2 is 4, and for Alternative B-3 is 6.

10.2.3 Alternative Standards C-1 through C-5

The concept underlying these alternatives is passive, engineered controls that will provide long-term protection without monitoring, inspection, and repair. Different thicknesses of earthen covers control radon emissions by 50 percent (for Alternative C-1) to greater than 99 percent (for Alternative C-5). The total radon deaths avoided would range from thousands to tens of thousands for the time periods that the rock and pebbly soil protected covers would last. The chance of misuse would be low during an initial period, especially if large size rock is used on the slopes. However, with the passage of time the chance of misuse would increase as reasons to avoid the pile (disposed tailings) were forgotten or became obscure, and the pile became known as a resource area for rock and sand. It is estimated that this initial period would be about 100 years, after which the likelihood of misuse would increase somewhat. The benefits of preventing windblown and surface water contamination and protecting against external gamma radiation are estimated to last thousands of years.

The estimated total cost for C Alternatives range from $210 to $570 million (Table 10-3).

The estimated number of accidental and radiation induced deaths for Alternative C-1 is 5, for C-2 is 6, for C-3 is 7, C-4 is 8, and for C-5 is 8. These include control of existing tailings plus all tailings generated to the year 2000.

10.2.4 Alternative Standards D-2 through D-5

These alternatives would require staged disposal of the tailings, whereby several tailings storage ponds are used during the lifetime of a mill. After each pond is filled, it is allowed to dry and is then covered with earth to the original ground level. This has the additional benefits of reducing the total quantity of tailings requiring disposal at the end of mill life and of controlling part of the radon emissions during operations. This latter benefit is discusssed in Chapter 7. Staged disposal is considered feasible for new impoundments only. Existing tailings piles, which may contain future tailings, are controlled to levels described in Alternatives C-1 through C-5.

The benefits of this alternative include reductions in radon deaths, a greatly reduced chance of misuse for thousands of years, and virtual elimination of surface water and land contamination and external radiation exposure. The chance of misuse is likely to be less for these alternatives because the tailings disposal site should be indistinguishable from the surrounding terrain. By placing the tailings below grade and covering them to the initial land contour, there would be no easily identifiable pile with rock covered slopes, clearly an indication of human activity.

The estimated total costs for these alternatives range from $350 to $600 million for both new and existing tailings sites. Alternatives C-2 through C-5 for existing tailings were used in conjunction with D-2 through D-5 to estimate total costs.

The estimated number of accidental and radiation-induced deaths for Alternative D-2 is 6, D-3 is 7, D-4 is 8, and D-5 is 8.

10.3 The Standard Selected

Selecting a limit for radon emissions from tailings involves four public health objectives, in addition to reducing health effects from radon released directly from the pile. These may all be achieved by using a thick earthen cover, which serves to inhibit misuse of tailings, to stabilize tailings against erosion and contamination of land and water, to minimize gamma exposure, and to avoid contamination of groundwater from tailings. A radon emission limit of 20 pCi/m^2s or less would require use of a sufficiently thick earthen cover to achieve all of these objectives. Our analysis shows that a limit of 20 pCi/m^2s is also cost-effective for eliminating most health effects in regional and national populations from radon released directly from the pile. Such a limit would also reduce maximum individual risks to residents near tailings piles to less than one in 1,000. We concluded that levels higher than 20 pCi/m^2s are not justified, based on the cost-effectiveness of risk reduction to 20 pCi/m^2s, and the unacceptably high maximum individual risks involved at higher levels.

The risk to people who live permanently very close to tailings piles can still be relatively high, up to 1 in 1,000 for lifetime residency, for a limit of 20 pCi/m^2s. However, the practicability and cost-effectiveness of providing more radon control by requiring design for lower levels of emission falls rapidly below 20 pCi/m^2s.

We note that no pile has ever been protected by such a cover; that is, covers with defined levels of control and longevity are undemonstrated technology. The design of covers to meet a specific radon emission limit and period of longevity must be based on measurements of properties of local covering materials and prediction of local parameters, such as soil and tailings moisture, over the long term. Because of uncertainties in measuring and predicting these parameters, the uncertainty of performance of soil covers increases rapidly as the stringency of the control required increases. Thus, in the case of lower levels, the primary issue becomes whether conformance to a design standard for such levels is practicably achievable.

There is some field information available regarding the practicality of reduction of radon emissions to levels approaching background. Tests conducted at a pile in Grand Junction, Colorado, showed that test plots of 3-meter covers made from four different earthen combinations reduced radon emissions to values ranging from 1.0 ± 1.1 to 18.3 ± 25.2 pCi/m^2s. The efficiencies of these covers ranged from 88.8 percent to 99.7 percent. These results apply to the first two years after emplacement and do not reflect performance after long-term moisture equilibrium is achieved (some cover moisture contents are still considerably elevated over prevailing levels). We believe ranges like these can generally be expected, because the radon control characteristics of earthen materials used for covers will vary from site to site. Three of the four covers studied satisfied 20 pCi/m^2s with a reasonable degree of certainty. The other cover (18.3 ± 25.2 pCi/m^2s) was uncompacted, and its poor performance can therefore be discounted. Exactly how much thicker these covers would need to be to reliably achieve a lower limit (e.g., 6 or 2 pCi/m^2s) over the required 1,000-year period is not known.

During hearings on the standards, experts commented that although covers can be designed to meet levels such as 20 pCi/m^2s, estimation models are not reliable at significantly lower emission levels.

We concluded that achieving conformance with a radon emission standard that is significantly below 20 pCi/m^2s (6 or 2 pCi/m^2s, for example) clearly would require designers to deal with unreasonably great uncertainty for this undemonstrated technology.

We could also have specified a much shorter period of performance, such as a few decades, for which the design to a lower emission level would have been feasible, but the gain in health protection is clearly greater for a slightly relaxed control level than for such a greatly relaxed longevity of control.

The risk from radon emissions diminishes rapidly with distance from the tailings pile (declining by a factor of three for each doubling of the distance beyond a few hundred meters). There currently are only about 30 individuals living so near to active piles that they might be subject to nearly maximum annual post-disposal risks. We expect that the actual number of people who might experience near maximal lifetime risk will be smaller, since they would have to maintain lifetime residence in the land area immediately adjacent to a tailings pile. In sum, we believe that the probability of a substantial number of individuals actually incurring these maximum calculated risks is small.

We conclude that it is not reasonable to reduce the emission standard below 20 pCi/m^2s because of (1) the uncertainty associated with the feasibility of implementing a requirement for a significantly lower standard, (2) the small reduction in total health benefit associated with such thicker covers, (3) the limited circumstances in which the maximum risk might be sustained, and (4) the uncertain, but substantial, cost of the added cover thicknesses needed for reasonable assurance of achieving levels that further reduce individual risk significantly.

APPENDIX A

HEALTH AND ENVIRONMENTAL PROTECTION STANDARDS FOR URANIUM AND THORIUM MILL TAILINGS

Appendix A: HEALTH AND ENVIRONMENTAL PROTECTION STANDARDS FOR URANIUM AND THORIUM MILL TAILINGS

In 40 CFR Chapter I, Part 192 is revised by adding Subparts D and E as follows:

PART 192 - HEALTH AND ENVIRONMENTAL PROTECTION STANDARDS FOR URANIUM AND THORIUM MILL TAILINGS

Subpart D -- Standards for Management of Uranium Byproduct Materials Pursuant to Section 84 of the Atomic Energy Act of 1954, as Amended.

Section
192.30 Applicability
192.31 Definitions and Cross-references
192.32 Standards
192.33 Corrective Action Programs
192.34 Effective Date

Subpart E -- Standards for Management of Thorium Byproduct Materials Pursuant to Section 84 of the Atomic Energy Act of 1954, as Amended.

Section
192.40 Applicability
192.41 Provisions
192.42 Substitute Provisions
192.43 Effective Date

AUTHORITY: Section 275 of the Atomic Energy Act of 1954, 42 U.S.C. 2022, as added by the Uranium Mill Tailings Radiation Control Act of 1978, Pub. L. 95-604, as amended.

Subpart D -- Standards for Management of Uranium Byproduct Materials Pursuant to Section 84 of the Atomic Energy Act of 1954, as Amended.

192.30 Applicability

This subpart applies to the management of uranium byproduct materials under Section 84 of the Atomic Energy Act of 1954 (henceforth designated "the Act"), as amended, during and following processing of uranium ores, and to restoration of disposal sites following any use of such sites under Section 83(b)(1)(B) of the Act.

192.31 Definitions and Cross-references

References in this subpart to other parts of the Code of Federal Regulations are to those parts as codified on January 1, 1983.

(a) Unless otherwise indicated in this subpart, all terms shall have the same meaning as in Title II of the Uranium Mill Tailings Radiation Control Act of 1978, Subparts A and B of this part, or Parts 190, 260, 261, and 264 of this chapter. For the purposes of this subpart, the terms "waste," "hazardous waste," and related terms, as used in Parts 260, 261, and 264 of this chapter shall apply to byproduct material.

(b) Uranium byproduct material means the tailings or wastes produced by the extraction or concentration of uranium from any ore processed primarily for its source material content. Ore bodies depleted by uranium solution extraction operations and which remain underground do not constitute "byproduct material" for the purpose of this Subpart.

(c) Control means any action to stabilize, inhibit future misuse of, or reduce emissions or effluents from uranium byproduct materials.

(d) Licensed site means the area contained within the boundary of a location under the control of persons generating or storing uranium byproduct materials under a license issued pursuant to Section 84 of the Act. For purposes of this subpart, "licensed site" is equivalent to "regulated unit" in Subpart F of Part 264 of this chapter.

(e) Disposal site means a site selected pursuant to Section 83 of the Act.

(f) Disposal area means the region within the perimeter of an impoundment or pile containing uranium byproduct materials to which the post-closure requirements of Section 192.32(b)(1) of this subpart apply.

(g) Regulatory agency means the U.S. Nuclear Regulatory Commission.

(h) Closure period means the period of time beginning with the cessation, with respect to a waste impoundment, of uranium ore processing operations and ending with completion of requirements specified under a closure plan.

(i) Closure plan means the plan required under Section 264.112 of this subpart.

(j) Existing portion means that land surface area of an existing surface impoundment on which significant quantities of uranium byproduct materials have been placed prior to promulgation of this standard.

192.32 Standards

(a) Standards for application during processing operations and prior to the end of the closure period.

(1) Surface impoundments (except for an existing portion) subject to this subpart must be designed, constructed, and installed in such manner as to conform to the requirements of Section 264.221 of this chapter, except that at sites where the annual precipitation falling on the impoundment and any drainage area contributing surface runoff to the impoundment is less than the annual evaporation from the impoundment, the requirements of Section 264.228 (a)(2)(iii)(E) referenced in Section 264.221 do not apply.

(2) Uranium byproduct materials shall be managed so as to conform to the ground water protection standard in Section 264.92 of this chapter, except that for the purposes of this subpart:

(i) to the list of hazardous constituents referenced in Section 264.93 of this chapter are added the chemical elements molybdenum and uranium,

(ii) to the concentration limits provided in Table 1 of Section 264.94 of this chapter are added the radioactivity limits in Table A of this subpart,

(iii) detection monitoring programs required under Section 264.98 to establish the standards required under Section 264.92 shall be completed within one (1) year of promulgation,

(iv) The regulatory agency may establish alternate concentration limits (to be satisfied at the point of compliance specified under Section 264.95) under the criteria of Section 264.94(b), provided that, after considering practicable corrective actions, these limits are as low as reasonably achievable, and that, in any case, the standards of Section 264.94(a) are satisfied at all points at a greater distance than 500 meters from the edge of the disposal area and/or outside the site boundary, and

(v) The functions and responsibilities designated in Part 264 of this chapter as those of the "Regional Administrator" with respect to "facility permits" shall be carried out by the regulatory agency, except that exemptions of hazardous constituents under Section 264.93(b) and (c) of this chapter and alternate concentration limits established under Section 264.94(b) and (c) of this chapter (except as otherwise provided in Section 192.32(a)(2)(iv)) shall not be effective until EPA has concurred therein.

(3) Uranium byproduct materials shall be managed so as to conform to the provisions of:

(a) Part 190 of this chapter, "Environmental Radiation Protection Standards for Nuclear Power Operations" and

(b) Part 440 of this chapter, "Ore Mining and Dressing Point Source Category: Effluent Limitations Guidelines and New Source Performance Standards, Subpart C, Uranium, Radium, and Vanadium Ores Subcategory."

(4) The regulatory agency, in conformity with Federal Radiation Protection Guidance (FR, May 18, 1960, pgs. 4402-3), shall make every effort to maintain radiation doses from radon emissions from surface

impoundments of uranium byproduct materials as far below the Federal Radiation Protection Guides as is practicable at each licensed site.

(b) Standards for application after the closure period.

At the end of the closure period --

(1) disposal areas shall each comply with the closure performance standard in Section 264.111 of this chapter with respect to nonradiological hazards and shall be designed* to provide reasonable assurance of control of radiological hazards to

(i) be effective for one thousand years, to the extent reasonably achieveable, and, in any case, for at least 200 years, and,

(ii) limit releases of radon-222 from uranium byproduct materials to the atmosphere so as to not exceed an average** release rate of 20 picocuries per square meter per second (pCi/m^2s).

(2) The requirements of Section 192.32(b)(1) shall not apply to any portion of a licensed and/or disposal site which contains a concentration of radium-226 in land, averaged over areas of 100 square

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* The standard applies to design. Monitoring for radon-222 after installation of an appropriately designed cover is not required.

**This average shall apply to the entire surface of each disposal area over periods of at least one year but short compared to 100 years. Radon will come from both uranium byproduct materials and from covering materials. Radon emissions from covering materials should be estimated as part of developing a closure plan for each site. The standard, however, applies only to emissions from uranium byproduct materials to the atmosphere.

meters, which, as a result of uranium byproduct material, does not exceed the background level by more than --

(i) 5 picocuries per gram (pCi/g), averaged over the first 15 centimeters (cm) below the surface, and

(ii) 15 pCi/g, averaged over 15 cm thick layers more than 15 cm below the surface.

192.33 Corrective Action Programs

If the ground water standards established under provisions of Section 192.32(a)(2) are exceeded at any licensed site, a corrective action program as specified in 264.100 of this chapter shall be put into operation as soon as is practicable, and in no event later than eighteen (18) months after a finding of exceedance.

192.34 Effective Date

Subpart D shall be effective 60 days after promulgation.

Table A

Combined radium-226 and radium-228	5 pCi/liter
Gross alpha-particle activity (excluding radon and uranium)	15 pCi/liter

Subpart E -- Standards for Management of Thorium Byproduct Materials Pursuant to Section 84 of the Atomic Energy Act of 1954, as Amended.

192.40 Applicability

This subpart applies to the management of thorium byproduct materials under Section 84 of the Atomic Energy Act of 1954, as amended, during and following processing of thorium ores, and to restoration of disposal sites following any use of such sites under Section 83(b)(1)(B) of the Act.

192.41 Provisions

The provisions of Subpart D of this Part, including Sections 192.31, 192.32, and 192.33, shall apply to thorium byproduct material and:

(a) provisions applicable to the element uranium shall also apply to the element thorium;

(b) provisions applicable to radon-222 shall also apply to radon-220; and

(c) provisions applicable to radium-226 shall also apply to radium-228.

(d) operations covered under Section 192.32(a) shall be conducted in such a manner as to provide reasonable assurance that the annual dose equivalent does not exceed 25 millirems to the whole body, 75 millirems to the thyroid, and 25 millirems to any other organ of any member of the public as a result of exposures to the planned discharge of radioactive materials, radon-220 and its daughters excepted, to the general environment.

192.42 Substitute Provisions

The regulatory agency may, with the concurrence of EPA, substitute for any provisions of Section 192.41 of this subpart alternative provisions it deems more practical that will provide at least an equivalent level of protection for human health and the environment.

192.43 Effective Date

Subpart E shall be effective 60 days after promulgation.

APPENDIX B

ESTIMATED COSTS FOR DISPOSAL OF URANIUM BYPRODUCT MATERIALS

Appendix B: ESTIMATED COSTS FOR DISPOSAL OF URANIUM BYPRODUCT MATERIALS

CONTENTS

TABLES

Appendix B: ESTIMATED COSTS FOR DISPOSAL OF URANIUM BYPRODUCT MATERIALS

B.1 Characteristics of Model Tailings Piles

The costs for disposal of uranium byproduct materials are estimated in this appendix for alternative disposal standards. The disposal methods, with one exception, use earth covers of various thicknesses which are stabilized with vegetation and rock. We believe this is the most likely method of disposal. The one exception is a tailings solidification method which is described in detail by the Nuclear Regulatory Commission (NRC80).

The costs of liners on the bottoms of tailings impoundments are included for completeness since they represent a significant capital cost. In practice, a liner is an operational control that protects groundwater during the operational phase of a tailings pond. Long-term protection of groundwater is provided by the cover. The estimates are arranged so that costs of liners can be easily subtracted for analysis purposes. Additional cost estimates for protecting groundwater are presented in Chapter 7.

Existing Tailings Piles

In early 1983, there were 26 licensed uranium mills with tailings piles. An analysis of these piles indicated that since they vary widely in size, control costs would also vary greatly. Consequently the piles were grouped into model piles as follows:

a. a <u>2-million-ton pile</u> on 122 acres with an average depth of 7.2 feet.

   Number of piles in this group = 11
   Average tons per pile = 1.9 million
   (Range = 0 to 3.2 million tons)
   Average area covered = 122 acres
   (Range = 47 to 200 acres)

b. a 7-million-ton pile on 180 acres with an average depth of 18.5 feet

Number of piles in this group = 12
Average tons per pile = 7.2 million
(Range = 4.5 to 10.9 million tons)
Average area covered = 180 acres
(Range = 85 to 400 acres)

c. a 22-million-ton pile on 279 acres with an average depth of 36.9 feet

Number of piles in this group = 3
Average tons per pile = 22.5 million
(Range = 19.2 to 27.6 million tons)
Average area covered = 279 acres
(Range = 210 to 328 acres)

Separate calculations are needed for each model pile and for each disposal method.

Another important feature of the model piles is the additional area that would be covered by tailings when the sides of the tailings piles, which consist of the sands (coarse fraction), are sloped or contoured to provide additional erosion control. Two values are used for the slopes of the pile edges after grading, 3:1 (H:V) and 5:1 (H:V). The volume of tailings moved is estimated by calculating the volume of the sloped tailings where the vertical distance is the average depth of the pile and the horizontal distance is 3 or 5 times the vertical. The pile is assumed to be square. The amount of additional land covered and the volume of tailings moved by sloping the edges of the piles are:

Pile Size	Additional Land Covered (acres)		Tailings Moved (thousands of cubic yards)	
	3:1 slope	5:1 slope	3:1 slope	5:1 slope
2 million tons	4.6	7.7	27	45
7 million tons	14.5	24.4	215	361
22 million tons	36.3	61.5	1,070	1,810

These values can increase the cost significantly for those methods involving disposal in place. It may be more economical to move the tailings into the center of the pile, thereby forming a hemisphere rather than cover the additonal land area with soil. However, it is not clear that this method would be less costly, since the grading and shaping of such large volumes is also costly.

New Tailings Piles

Information on tailings to be generated at a model new mill are taken from the NRC GEIS (NRC80). The NRC model mill has an ore-processing capacity of 1,800 MT per day. The ore grade is expected to average 0.1 percent uranium, and the uranium recovery efficiency is assumed to be 93 percent. The mill is operated 310 days per year (i.e., 85 percent capacity utilization rate), and the average annual production is 580 MT yellowcake, which is 90 percent U_3O_8. The model pile covers an area of 198 acres with earth embankments around the tailings, bringing the total area to 247 acres. The ultimate depth of the tailings is about 26 feet.

The tailings will be generated at a rate of 1,800 MT per day, or 558 thousand MT per year, or 8.4 million MT during the assumed 15-year operating period of the mill. The tailings are discharged to an impoundment in the base case, which is analyzed later in this appendix as case NT1.

B.2 Tailings Disposal Unit Costs

The most likely methods for disposal of the tailings involve covering the tailings with earth, as discussed in Chapter 8. The unit costs for earth work, transportation, fencing, landscaping, rock cover, and maintenance and inspection are shown in Table B-1. All costs (except the liner, maintenance, and inspection) were taken from Means (Me83).

The estimated 1980 cost of a Hypalon liner was $8.25 million (See Alternative 5 in NRC80). Correcting this cost to 1983 and adding 25 percent for overhead and profit, a plastic liner is estimated to cost $11.5 million for the 80-hectare model impoundment.

Maintenance and inspection costs are calculated for: (1) an irrigaton system for maintaining vegetation on thin earth covers, (2) fencing maintenance, and (3) annual inspections, including groundwater monitoring and repair and revegetation of eroded areas.

Irrigation

The irrigation system design was developed for EPA by PEDCO Environmental, Inc. (PE82). The design is for a 40-acre site (about 16 hectares) and consists of a 150-hp motor and pump unit, polyethylene piping, and plastic spray heads. The capital costs of this system are $127,000, and it is assumed that it must be replaced every 20 years. The present value of capital requirements for 100 years of operation is $149,000, using a 10 percent discount rate and replacement at 20, 40, 60, and 80 years. Annual costs of operation are $12,000 per year for maintenance and labor; $9,300 a year for electrical power; and $6,000 per year for overhead, assuming the system is operated 8 hours per week, 8 months per year. The present value of these annual costs is $273,000 for 100 years using a 10-percent discount rate. Therefore, the total

Table B-1 Unit Costs
(1983 Dollars)

Task	Cost
Earth work:	
Grading: Move and spread by scraper.	$1.07/yd/^3$
Placing earthern cover: Excavate, haul, spread, and compact by scrapers for 5,000 feet.	$4.14/yd^3$
Excavate, load, haul by truck for 2 miles off the highway; dump, spread, and compact.	$3.53/yd^3$
Excavating pits: Excavate, haul, and spread, by scrapers, for 5,000 feet.	$3.17/yd^3$
Moving tailings: Excavate by drag line. Load, haul 2 miles off highway, spread, and compact.	$4.60/yd^3$
Synthetic liners:	
Install flexible membrane liner in 200-acre impoundment.	$11.5 million
Transportation:	
Over highway hauling of earth, tailings, clay, loam, etc. (based on 4-mile roundtrips)	$0.75/yd^3/mile
Rock cover:	
Machine placed 18" thick.	$20/yd^2
Bank new gravel from borrow pit	$3.23/yd^2
Landscaping:	
Fine grading and seeding, including lime, fertilizer, and seed.	$6,900/acre
Fencing:	
Chain link, 6 feet high,. 6-gauge aluminum.	$15.25/ft
Maintenance and inspection:	
Installation and operation of an irrigation system for 100 years-present worth at 10% discount rate.	$11,000/acre

Table B-1. Unit Costs (Continued)
(1983 Dollars)

Task	Cost
Maintenance of fencing at 1% of capital cost per year. Present value at 10% discount rate for 100 years.	0.10 x capital cost of fencing
Annual inspections including ground-water monitoring and repair and revegetation of eroded areas. Present value at 10% discount rate for 100 years.	$100,000/site

present value of providing irrigation for 100 years is $422,000 for a 40-acre site, or $10,500 per acre. This was corrected for inflation (1981 to 1983) to $11,000 per acre.

Fencing

Maintaining the fence for 100 years is assumed to cost 1 percent of the installation cost annually. The present value of this maintenance cost for 100 years at 10-percent discount rate is:

Present Value of Fencing Maintenance = 0.10 x fencing capital cost.

Annual Inspections

The cost for annual inspections at a site is taken directly from Appendix R of (NRC80). For this purpose, we used NRC Scenario IV, which requires only limited maintenance. Their inspection costs are $10,500 annually. This includes $1,000 per year for maintenance of the fence. Since this cost is already considered, it is subtracted, giving an annual cost of $9,500 per site. The present value is $95,000 per site, using a 10 percent discount rate for 100 years. This was corrected for inflation (1981 to 1983) to $100,000 per site.

Borrow Pit Reclamation

The costs for reclaiming borrow pits were estimated for a borrow pit in flat terrain. Stripping and saving 15 centimeters of top soil and revegetation following replacement of the top soil were assumed. The four side walls in the flat terrain pit are graded to an 8:1 slope before top soil replacement and revegetation. The costs for the flat terrain case are presented in Table B-2.

Table B-2. Reclamation Costs for a Borrow Pit on Flat Terrain[a] (1983 dollars in millions)

Size of Tailings Pile	Cover Thickness on Tailings Pile			
	0.5 meter	1 meter	3 meters	5 meters
2 million tons				
3:1 slope	0.28	0.44	0.91	1.31
5:1 slope	0.29	0.45	0.93	1.34
7 million tons				
3:1 slope	0.37	0.58	1.24	1.97
5:1 slope	0.38	0.60	1.28	2.04
22 million tons				
3:1 slope	0.50	0.80	1.93	3.06
5:1 slope	0.51	0.84	2.04	3.22

(a)Where it is assumed that 15 cm of topsoil were stripped and saved, the four side walls of the pit were graded to an 8:1 slope, the top soil was replaced, and the area revegetated. The size and depth of the pit varied, depending on the amount of soil needed to cover the tailings; however, in no case was the borrow pit excavated deeper than 12 yards.

B.3 Descriptions and Costs of Disposal Methods

Calculation Procedures

Several assumptions are made in developing disposal costs. Assumptions related to determining the thickness of the cover are:

- the methods developed by Rogers (Ro81) and used by the NRC (NRC80) for estimating radon diffusion through earthen materials reasonably reflect the movement of radon
- the moisture in the cover (earthen material) is 8 percent
- the moisture in the tailings is 8 percent
- the effective bulk radon diffusion coefficient can be determined from the moisture content
- the total porosity of the tailings is the same as that of the cover

These assumptions are made in the context that the design of tailings disposal methods will be conservative so as to provide reasonable assurance that the radon emission limit will be achieved over the required period. For example, in actual design, soils with better moisture retention features (clays) are expected to be available at many sites. NRC reported that equilibrium in moisture in Western clays ranges from 9 to 12 percent (NRC80). Since the cover moisture will be greater than 8 percent in many cases, the net result is that the 8 percent assumed will tend to increase the cover thickness required over that calculated from "best estimated" values, which would yield an approximately equal probability of achieving above or below the design level.

Another conservative factor is related to the moisture content of the tailings themselves. In actual cases the tailings will usually have a greater initial moisture content than covers (Ha83). It is also reasonable to assume that the tailings will retain moisture for long periods due to their high salt contents. However, designers are expected to use values for tailings moisture that reflect a reasoned judgement of what the long-term equilibrium value of moisture will be. The design methods (Ro82) predict that thicker covers are needed, as tailings moisture content decreases, to achieve a given level of control. A value of 8 percent moisture in tailings is assumed for these estimates to reflect a conservative approach.

Rogers (Ro81) emphasizes that cover moisture is the dominant variable affecting radon attenuation. The sensitivity of cover thickness to variations in ore grade, tailings moisture, and porosity ratio (porosity of tailings to porosity of cover) is generally of secondary importance compared to cover moisture.

Another factor that must be considered is the uncertainty involved in measuring the attenuation characteristics of the particular earthen materials used for the cover. Conservative judgements will also be required regarding the values for these characteristics for use in actual calculations.

Existing Tailings Piles

Method B1-E

The edges of the square tailings pile are graded and contoured to a 3:1 (H:V) slope. The entire area is then covered with 0.5 meter of earth obtained nearby. A 6-feet high, 6-gage aluminum chain link fence is placed around the exclusionary zone, which is assumed to be 0.5 kilometer from all sides of the pile. The covered pile is landscaped, assuming that suitable loam or topsoil is available onsite. The borrow-pit reclamation cost is taken from Table B-2. Maintenance and inspection are added for a 100-year period. The costs for this method are summarized in Table B-3.

Table B-3. Disposal Cost Summary: Method B1-E
(1983 dollars in millions)

Task	Size of Pile (MT) 2	7	22
Grading slopes	0.03	0.23	1.14
Excavating, hauling, spreading and compacting cover material	1.18	1.82	2.95
Fencing	0.34	0.38	0.43
Landscaping	0.87	1.34	2.18
Reclaiming borrow pit	0.28	0.37	0.50
Maintain for 100 years	1.53	2.28	3.61
TOTAL	4.23	6.42	10.81
Composite Unit Costs:			
\$/MT Tailings	2.12	0.92	0.49
\$/MT U_3O_8	2,279	989	528

Method B2-E

The sides of the tailings piles are graded to 3:1 (H:V) slope. The tailings are covered with 1.5 meters of earth obtained nearby and the entire surface is landscaped. A fence is installed to form an exclusion area 0.5 kilometer wide all around the disposed tailings. The borrow pit is reclaimed as described in Section B.2. The costs for this method are shown in Table B-4.

Method B3-E

For this method the edges of the square tailings pile are graded to a 3:1 (H:V) slope. The entire tailings area is covered with 2.4 meters of earth obtained nearby or locally. The entire area (slopes and top) are landscaped after covering. A fence is installed to form an exclusion area 0.5 km wide around the edge of the tailings. The borrow pit is reclaimed as described in Section B.2. The costs for this option are listed in Table B-5.

Table B-4. Disposal Cost Summary: Method B2-E
(1983 dollars in millions)

Task	Size of Pile (MT) 2	7	22
Grading Slopes	0.02	0.23	1.14
Excavating, hauling, spreading and compacting cover material	3.55	5.45	8.64
Fencing	0.34	0.38	0.43
Landscaping	0.87	1.34	2.18
Reclaiming borrow pit	0.56	0.75	1.08
Mainenance	1.53	2.28	3.61
TOTAL	6.88	10.43	17.28
Composite Unit Costs			
$/MT Tailings	3.44	1.49	0.79
$/MT U_3O_8	3,698	1,602	844

Table B-5. Disposal Cost Summary: Method B3-E
(1983 dollars in millions)

Task	Size of Pile (MT) 2	7	20
Grading slopes	0.03	0.23	1.14
Excavating, hauling, spreading	5.67	8.71	14.1
Fencing	0.34	0.38	0.43
Landscaping	0.87	1.34	2.18
Reclaiming borrow pit	0.8	1.04	1.58
Maintenance	1.53	2.28	3.61
TOTAL	9.24	13.98	23.04
Composite Unit Costs:			
$/MT Tailings	4.62	2.00	1.05
$/MT U_3O_8	4,966	2,150	1,129

Method C1-E

The sides of the tailings piles are graded to a 5:1 (H:V) slope, after which the entire area is covered with 0.5 m of gravelly earth obtained nearby or locally. The slopes are covered with 0.5-meter rock cover. No fence is needed. The borrow pit is reclaimed as described in Section B.2. The costs for this option are presented in Table B-6.

Table B-6. Disposal Cost Summary: Method C1-E
(1983 dollars in millions)

Task	Size of Pile (MT) 2	7	22
Grading slopes	0.05	0.39	1.94
Excavating, hauling, spreading, and compacting cover material	1.21	1.91	3.18
Placing gravel cover	.87	1.27	1.98
Placing rock cover	.75	2.36	5.95
Reclaiming borrow pit	0.29	0.38	0.51
TOTALS	3.17	6.31	13.56
Composite Unit Costs:			
$/MT Tailings	1.59	0.90	0.62
$/MT U_3O_8	1,704	969	663

Method C2-E

The edges of the tailings piles are contoured to a slope of 5:1 (H:V). The entire area is then covered with 1.5 meters of earth obtained nearby except the top 0.5-meter of the cover is gravelly earth. The slopes are covered with a 0.5-meter thick rock cover. No fence is necessary. The borrow pit is reclaimed as described in Section B.2. The costs for this option are presented in Table B-7.

Method C3-E

The sides of the tailings piles are graded to a 5:1 (H:V) slope. The entire area is then covered with 2.4 meters of earth obtained nearby of which the top 0.5-meter layer is gravelly earth. A 0.5-meter rock cover is added to the slopes.

No fence is needed. The borrow pit is reclaimed as described in Section B.2. The costs for this method are listed in Table B-8.

Table B-7. Disposal Cost Summary: Method C2-E
(1983 dollars in millions)

Task	Size of Pile (MT) 2	7	22
Grading slopes	0.05	0.39	1.94
Excavating, hauling, spreading, and compacting cover material	3.63	5.73	9.54
Placing gravel cover	.87	1.27	1.98
Placing rock cover	.75	2.36	5.95
Reclaiming borrow pit	0.57	0.77	1.14
TOTALS	5.87	10.52	20.55
Composite Unit Costs:			
$/MT Tailings	2.94	1.50	0.93
$/MT U_3O_8	3,155	1,616	1,004

Method C4-E

The sides of the pile are graded to a 5:1 (H:V) slope. The entire area is covered with 3.4 meters of earth obtained nearby of which the top 0.5-meter layer is gravelly earth. A 0.5-meter rock cover is placed on the slopes. No fence is needed. The borrow pit is reclaimed as described in Section B.2. The costs for this method are listed in Table B-9.

Method C5-E

The sides of the pile are graded to a 5:1 (H:V) slope. The entire area is covered with 4.3 meters of earth obtained locally of which the top 0.5-meter layer is gravelly earth. A 0.5-meter rock cover is placed on the slopes. No fence is needed. The borrow pit is reclaimed as described in Section B.2. The costs for this method are shown in Table B-10.

Table B-8. Disposal Cost Summary: Method C3-E
(1983 dollars in millions)

Task	Size of Pile (MT) 2	7	22
Grading slopes	0.05	0.39	1.94
Excavating, hauling, spreading, and compacting cover material	5.81	9.15	15.24
Placing gravel cover	.87	1.27	1.98
Placing rock cover	.75	2.36	5.95
Reclaiming borrow pit	0.79	1.08	1.68
TOTALS	8.27	14.25	26.79
Composite Unit Costs:			
$/MT Tailings	4.14	2.04	1.22
$/MT U_3O_8	4,445	2,188	1,309

Table B-9. Disposal Cost Summary: Method C4-E
(1983 dollars in millions)

Task	Size of Pile (MT) 2	7	22
Grading slopes	0.05	0.39	1.94
Excavating, hauling, spreading, and compacting cover material	8.24	13.0	21.6
Placing gravel cover	.87	1.27	1.98
Placing rock cover	.75	2.36	5.95
Reclaiming borrow pit	1.01	1.43	2.28
TOTAL	10.92	18.45	33.75
Composite Unit Costs:			
$/MT Tailings	5.46	2.64	1.53
$/MT U_3O_8	5,870	2,833	1,649

Table B-10. Disposal Cost Summary: Method C5-E
(1983 dollars in millions)

Task	Size of Pile (MT) 2	7	22
Grading slopes	0.05	0.39	1.94
Excavating, hauling, spreading, and compacting cover material	10.41	16.4	27.3
Placing gravel cover	.87	1.27	1.98
Placing rock cover	.75	2.36	5.95
Reclaiming borrow pits	1.2	1.77	2.81
TOTAL	13.28	22.19	39.98
Composite Unit Costs:			
$/MT Tailings	6.64	3.17	1.82
$/MT U_3O_8	7,138	3,408	1,954

New Tailings Piles

Method A

This method is the same as the base case in the NRC analysis (NRC80). An initial square basin would be formed by building low earthen embankments along each side of 947 meters length at the centerline. The mill tailings would be slurried into the basin, and as the basin filled, the coarse fraction of the tailings (sands) would be used to raise and broaden the embankments. The final dimensions of the embankments would be 10 meters high and 13 meters wide at the top. When the mill ceases operations, no specific control measures for disposal would be used. The cost for this option is listed in Table B-11 and consists only of preparation of the initial basin.

Methods B1-N, B2-N, and B3-N

These methods use earth covers on the tailings and rely on institutional controls to prevent misuse and to maintain the covered pile. A pit is excavated close to the mill and measures 930 meters square by 2 meters deep. Embankments are constructed along each side, 947 meters long, 10 meters high, and 13 meters wide at the top. The pit is lined with a synthetic liner. Tailings are pumped directly into the pit during operation of the mill. It is assumed that water from the pond will be recycled to the mill, thereby negating the need for an evaporation pond.

At the end of mill life, the embankments are excavated and placed on top of the tailings. The slopes of the covered tailings are graded to 3:1 (H:V). The cover thickness is 0.5 meters for B1-N, 1.5 meters for B2-N, and 2.4 meters for B3-N. The entire area is landscaped. A fence is placed around the disposal area and provides a 0.5-kilometer exclusion zone. Borrow pits are reclaimed. The site is maintained for 100 years by irrigation of the vegetative cover and inspection and repair of the earth cover and fence. Costs are shown in Table B-11.

Methods C1-N, C2-N, C3-N, C4-N and C5-N

Passive controls are used in these methods. These methods use earth covers, 0.5-meter rock covers on the slopes and 0.5-meter gravel layers on the top. A pit is prepared and used in the same manner to that described for methods B1-N, B2-N, and B3-N, including the liner.

At the end of mill life, the embankments are excavated and placed on top of the tailings. The cover thickness is 0.5 meters for C1-N, 1.5 meters for C2-N, 2.4 meters for C3-N, 3.4 meters for C4-N, and 4.3 meters for C5-N. The slopes of the disposed tailings are graded to 5:1 (H:V) and then covered with rock to a depth of 0.5 meter. The top of the disposed tailings area (that part not covered with rock) is covered with a 0.5-meter layer of gravelly soil which replaces the top 0.5-meter of earth. No fence is needed. The costs are listed in Table B-11.

Methods D2-N, D3-N, D4-N, and D5-N

These methods are somewhat similar to the staged or phased disposal method described by the NRC's GEIS (NRC80). This method uses 6 pits, each 280 meters square at the bottom and with 2:1 (H:V) slopes. Two pits are constructed initially and lined with a synthetic liner. Tailings are pumped to the first pit until it is full and then pumped to the second pit. When the first pit is sufficiently dry, the third or fourth pit is excavated, and the excavated earth is used to cover the first pit to the original ground contour. The earth cover thickness is 1.5 meters for D2-N, 2.4 meters for D3-N, 3.4 meters for D4-N, and 4.3 meters for D5-N. This process continues sequentially until the end of mill life. An evaporation pond is needed in this method. Costs for this pond are taken from the NRC GEIS and corrected for inflation.

At the end of mill life there will likely be four completed pits, which are covered with earth to the original ground contour and 2 uncovered pits. When sufficiently dry, these last two pits are covered with excavated earth to the original ground contour. The disposed tailings area is landscaped. The areas covered by the evaporation pond and excess excavated earth are restored. The costs for this method are presented in Table B-11.

Table B-11. Disposal Cost Summary: Methods for Disposal of New Tailings Piles (1983 dollars in millions)

Task	Disposal Method A	B1	B2	B3	C1	C2	C3
Excavate pit and construct embankments	1.26	5.8	5.8	5.8	5.8	5.8	5.8
Placing liners	-	11.5	11.5	11.5	11.5	11.5	11.5
Grade slopes	-	0.9	0.9	0.9	0.54	0.54	0.54
Excavate, haul, spread and compact cover material[(a)]	-	-	3.04	6.64	-	4.0	7.64
Fence	-	0.4	0.4	0.4	-	-	-
Landscape	-	1.63	1.63	1.63	-	-	-
Place rock on slopes	-	-	-	-	3.68	3.68	3.68
Place gravel on top	-	-	-	-	1.41	1.41	1.41
Evaporation pond	-	-	-	-	-	-	-
Reclaim borrow pits	-	-	0.52	0.93	-	0.6	0.93
Maintenance for 100 years	-	2.7	2.7	2.7	-	-	-
TOTAL (includes O & P)	1.26	22.93	26.49	30.50	22.93	27.53	31.50
Unit Costs:							
\$/MT Tailings	0.15	2.73	3.15	3.63	2.73	3.28	3.75
\$/MT U_3O_8	161	2,935	3,386	3,902	2,935	3,526	4,031

Task	Disposal Method C4	C5	D2	D3	D4	D5
Excavate pit and construct embankments	5.8	5.8	26.2	28.5	31.4	34.0
Placing liners	11.5	11.5	8.08	8.08	8.08	8.08

See footnotes at end of table.

Table B-11. Disposal Cost Summary: Methods for Disposal of New Tailings Piles (1983 dollars in millions) (Continued)

Task	C4	C5	D2	D3	D4	D5
	Disposal Method					
Grade slopes	0.54	0.54	-	-	-	-
Excavate, haul, spread and compact cover material[a]	11.6	15.27	1.42	2.3	3.34	4.3
Fence	-	-	-	-	-	-
Landscape	-	-	1.06	1.08	1.11	1.13
Place rock on slopes	3.68	3.68	-	-	-	-
Place gravel on top	1.41	1.41	-	-	-	-
Evaporation pond	-	3.64	3.64	3.64	3.64	3.64
Reclaim borrow pits	1.3	1.65	-	-	-	-
Maintenance for 100 years	-	-	-	-	-	-
TOTAL (includes O & P)	35.83	39.85	40.40	43.60	47.57	51.15
Unit Costs:						
$/MT Tailings	4.27	4.74	4.81	5.19	5.66	6.09
$/MT U_3O_8	4,590	5,096	5,171	5,579	6,084	6,547

[a] Disposal Methods B1 and C1—the task is included in grading; for Disposal Methods D2 through D5--two pits only, remaining pits are covered during excavation of new pits.

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NRC80 Nuclear Regulatory Commission, "Final Generic Environmental Impact Statement on Uranium Milling," NUREG-0706, Washington, D.C., September 1980.

PE82 PEDCO Environmental, Inc., "Evaluation of Costs to Control Fugitive Dust from Tailings at Active Uranium Mills," EPA Contract No. 68-02-3173, Task No. 053, USEPA, Washington, D.C., March 1982.

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APPENDIX C

HEALTH BASIS FOR HAZARD ASSESSMENT

Appendix C: HEALTH BASIS FOR HAZARD ASSESSMENT

CONTENTS

TABLES

CONTENTS (Continued)

FIGURES

Appendix C: HEALTH BASIS FOR HAZARD ASSESSMENT

Introduction

Inhalation or ingestion of radionuclides or toxic chemicals can, have adverse effects on human and animal health. The adverse effects can be separated, generally, into stochastic and nonstochastic. Stochastic effects are those in which the probability of the effect is proportional to the exposure level, but the severity of the effect is independent of exposure. Nonstochastic effects are those in which the severity of the effect is proportional to the exposure level and there is usually a threshold level of exposure below which no effect is observed.

Low levels of radiation exposure, such as that associated with inhalation or ingestion of radionuclides transported into the environment from tailings piles, generally produce stochastic effects. Radiation from radionuclide particles deposited on the ground may also expose people causing stochastic effects. Ingestion or inhalation of toxic chemicals from tailings piles would cause nonstochastic effects.

For purposes of this analysis, only stochastic effects (e.g., cancer and inherited abnormalities) will be considered in the case of ionizing radiation exposure and only nonstochastic (e.g., acute and chronic poisoning) in the case of exposure to toxic elements. In Section C.1 below we describe how we estimate the risk due to external gamma radiation, ingested radioactivity, or inhaled radioactive particulates that are not radon progeny. In Section C.2 we describe how we estimate the risk of lung cancer due to the inhalation of radon and radon progeny.

C.1 Risk Models for Stochastic Effects

There are two kinds of risks from the low levels of ionizing radiation characteristic of exposures to radionuclides released into the environment. The most important of these is cancer, which is fatal at least half the time. The other risk is the induction of hereditary defects in descendants of exposed persons. The severity of these defects range from fatal to inconsequential. As mentioned above, we assume that at low levels of exposure the risk of cancer and hereditary effects is in proportion to the dose received, and that the severity of any induced effect is independent of the dose level. That is, while the probability of a given type of cancer occurring increases with dose, such a cancer induced at one dose is equally as debilitating as that same type of cancer induced at another dose. For these effects, we assume that there is no completely risk-free level of radiation exposure.

The risks and effects on health from low-level ionizing radiation were reviewed for EPA by the National Academy of Sciences in reports published in 1972 and in 1980 (NAS72a, NAS80b). We have used these studies and others to estimate the risks associated with the radiation doses described in this report. Byproduct materials from uranium ore processing are principally alpha particle emitters. Alpha particles are a form of ionizing radiation that has a high linear energy transfer (LET). As noted in the 1980 BEIR report, cited above, the dose response relationship for high LET radiations is linearly proportional to dose, and biological effects due to high LET radiations may increase rather than be reduced at low dose rates.

The individual lifetime risk can be estimated for the "most exposed individuals;" these people are located at the point of highest lifetime risk. The risk to the individual is the risk of premature death from cancer due to the radiation dose received. The risk calculation considers all important radionuclides, pathways, and organs of the body.

The risk to an individual can be subdivided and related to other parameters. For example, we can determine which part of the risk is committed by radionuclides moving through a specific pathway or which organ is at highest risk. This information is helpful when deciding which control strategies will be the most effective.

The risk to populations can also be estimated; that is, the number of future effects on health that are committed for each year that the source operates. The risks are associated with doses delivered to people over a time period which is longer than the average individual's lifespan. The dose is not necessarily delivered to people during the years of release because radionuclides with long half-lives may take a long time to move through environmental pathways to people.

Like the individual lifetime risk, the total risk to populations can be subdivided and related to other parameters, such as organ, radionuclide, or exposure pathway.

The genetic risk is the risk to future generations associated with the dose equivalent to the gonads of both exposed parents over the first 30 years of their lives. We calculate the total genetic risk for the same population for which we calculate the collective potential fatal cancer risk.

C.1.1 The RADRISK Code

The estimates of cancer and genetic risk are calculated using a computer code called RADRISK. In RADRISK, the group assumed to be at risk by the code is a hypothetical cohort of 100,000 people, all born simultaneously and subject to the same risks throughout their lives. Each member is assumed to be exposed at a constant rate to a unit concentration of radionuclides. For each radionuclide and for each pathway, the code calculates the number of premature deaths due to radiation and the number of years of life lost due to these deaths.

When radioactive particulates are inhaled, they enter the lung, and the ICRP Task Group lung model is used to predict where in the lung they go and how fast they are removed to other parts of the body. Depending on size and solubility class, there is removal of some of this material to the gastrointestinal (GI) tract and absorption by the blood. A GI tract model is used to estimate how much of the material reaching the tract is absorbed by the blood.

After absorption by the blood, radionuclides are distributed among the organs according to uptake and metabolic information supplied to RADRISK. Dose rates are calculated with the help of models that simulate the biological processes involved when radionuclides enter and leave organs.

Cancers do not appear immediately after exposure. There is a minimum induction time, latent period, before the cancers are observed; the length, usually years, varies with the type of cancer. Thereafter, there is a specified period when there is a finite probability of cancer, a "plateau" period, and it also varies with the type of cancer. For most cancers the latent period includes the balance of a person's lifetime. Table C-1 lists the risk parameters used in RADRISK.

Lifetime probabilities for many types of cancer, in many organs, are followed and risks calculated. At the same time, competing risks unrelated to the radiation exposure are accounted for. The RADRISK code does this; however, we do not yet understand how accurate these calculations are. In particular, cancer risks and metabolic parameters are uncertain, and since relative risk estimates are not available for all radiation-induced cancers, only an absolute risk estimate is made. We believe risks are accurate to an order of magnitude only and should never be reported to more than one significant figure.

Inherited abnormalities (genetic effects), as noted above, do not occur in those exposed to radiation but in their progeny. The genetic risk coefficient used in RADRISK is given in Table C-2.

Table C-1. Risk parameters for cancers considered (Su81)

Cancer	Latency (years)	Plateau (years)	Risk Factor: Low-LET radiation (deaths/10^6 rad person-years at risk)	Risk Factor: High-LET radiation (deaths/10^6 rad person-years at risk)	Number of premature deaths in cohort of 100,000 persons from chronic 1 mrad/y exposure*
Leukemia	2	25	2.3	**46	0.3
Bone	5	30	0.2	4	0.03
Lung	10	110	3.0	30	0.6
Breast	15	110	2.3	2.3	0.4
Liver	15	110	0.9	9	0.2
Stomach	15	110	0.5	5	0.09
Pancreas	15	110	0.7	7	0.1
Lower Large Intestine	15	110	0.4	4	0.07
Kidneys	15	110	0.2	2	0.04
Bladder	15	110	0.2	2	0.04
Upper Large Intestine	15	110	0.2	2	0.04
Small Intestine	15	110	0.1	1	0.02
Ovaries	15	110	0.1	1	0.02
Testes	15	110	0.1	1	0.02
Spleen	15	110	0.1	1	0.02
Uterus	15	110	0.1	1	0.02
Thymus	15	110	0.1	1	0.02
Thyroid	2	45	***0.4	***0.4	0.08

*Low-LET.
**Based on a quality factor of 20 for alpha particle irradiation (ICRP-26. In view of the leukemia incidence observed in persons exposed to bone seeking alpha particle emitters (Mo79), we believe a quality factor of 20 is highly conservative for leukemia, perhaps by an order of magnitude.
***0.04 for ^{131}I and longer-lived radioiodine.

Table C-2. Genetic Risk Parameters

	First Generation	All Generations
Risks per one million live-births per mrad low-LET radiation	0.04	0.2

A more detailed description of RADRISK can be found in ORNL/TM-7745, "Estimates of Health Risk from Exposure to Radioactive Pollutants" (Su81).

C.2 Risk Estimates for Inhaled Radon and Radon-Daughters (Radon Decay Products)

An estimate of the health risk from inhaling radon and its short-lived daughters has been done separately for both historic and technical reasons.

The history of the health impact of exposure to radon and its short-lived daughters has its roots in the past, before the discovery of x-rays or identification of radioactivity. The units of exposure, Working Level (WL), Working Level Month (WLM), are unusual and do not fit into the RADRISK computer code. The risk of radon, radon-daughter exposure has been calculated independently of the RADRISK program calculations for this analysis.

C.2.1 Risk of Lung Cancer from Inhaling Radon Decay Products

The high incidence of lung cancer mortality among underground miners is well documented (EPA79a, Ar79, Ar81). Uranium miners are particularly affected, but lead, iron, and zinc miners exposed to relatively low levels of radon decay products also show an increased lung cancer mortality that correlates with exposure to radon decay products. The type of lung cancer most frequently observed, moreover, is relatively uncommon in the general population.

Risk estimates for the general public based on these studies of miners are far from precise. First, and most important, the relatively small number of miners at risk injects considerable statistical uncertainty into estimating the number of excess lung cancer cases (see Figure C-1). Second, although the cumulative lifetime exposure in contaminated buildings can be comparable to that of some miners, most of the miners studied were exposed to much higher levels of radon decay products than usually occur in the general environment. Third, the exposure levels are uncertain. Fourth, significant demographic differences exist between miners and members of the general public--the miners were healthy males over 14 years old, many of whom smoked. However, information from the studies of miners can provide useful estimates, if not precise predictions, of the risks to the general population from radon decay products.(1)

Since the miners being studied have not all died, their eventual excess lung cancers must be projected from current data by using mathematical models. There are two ways to use the observed frequency of lung cancer deaths among the exposed miners to estimate the risk from inhaling radon decay products over a person's lifetime. One, commonly called the relative risk model, yields the percent increase in the normal incidence of cancer per unit of exposure. The other, called the absolute risk model, yields the absolute numerical increase in cancers per unit of exposure. In the relative risk model, it is assumed that the increased risk is proportional to the age-dependent natural incidence of the disease for each year an individual remains alive following exposure. In the absolute risk model, it is assumed that the added risk is independent of natural incidence, i.e., the risk is constant each year an individual remains alive following exposure.

As a basis for calculating estimates using the relative risk model, we conclude that a 3-percent increase in the number of lung cancer deaths per WLM is consistent with data from the studies of underground miners. However, because of the differences between adult male miners and the general population (EPA79a), we estimate that the risk to the general population may be as low as 1 percent or as high as 5 percent. This is consistent with a recent Canadian study where the best estimate of excess relative risk was 2.28 ± 0.35 percent (Th82). To develop absolute risk estimates in earlier reports, we used the estimate of 10 lung cancer deaths per WLM for 1 million person-years at risk reported by the National Academy of sciences (NAS76). In a 1978 paper, Land and Norman (La78) reported that in Japanese A-bomb survivors, radiation-induced lung cancers had a temporal distribution of occurrence similar to naturally-occurring cancers of the same site. Further, they concluded the cumulative distribution of radiation-induced lung cancer across time after exposure was consistent with a relative risk model of cancer incidence or with an age-specific absolute risk model.

In a paper at the same symposium, Smith and Doll (Sm78) reported the risk of cancer developing at most "heavily irradiated" sites in

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(1)See "Indoor Radiation Exposure Due to Radium-226 in Florida Phosphate Lands" (EPA 79a) for greater detail of such an analysis.

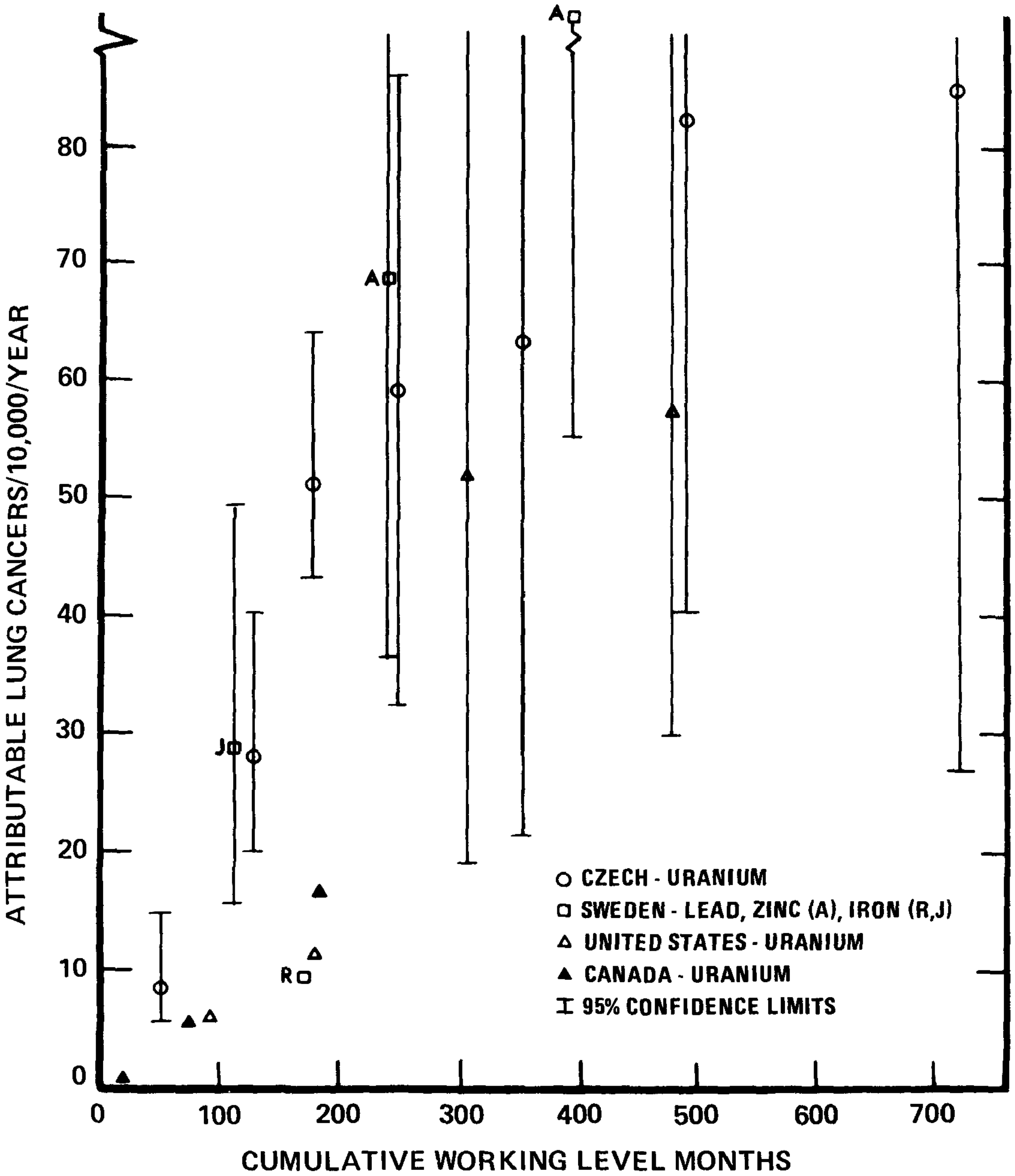

Figure C-1. Excess Fatal Lung Cancer in Various Miner Groups by Cumulative Exposure (Ar79).

ankylosing spondylitic patients treated with x-rays was directly proportional to the risk of a tumor in the absence of radiation; in other words, a relative-risk-like response. In the most recent report on the Japanese A-bomb survivors, Kato and Schull (Ka82) reiterated the observation that radiation-induced lung cancer develops only after the survivors attain the age at which this cancer normally develops. The evidence in these three reports of external radiation exposure points to relative-risk or age-specific absolute risk models as being appropriate for radiation-induced lung cancer.

Recent information from China provides similar evidence for exposure to radon, radon daughters. Shi-quan and Xiao-ou (Sh82) have reported that in Chinese tin miners exposed to radon and its daughters, the lung cancers developed at the age at which lung cancer normally develops. Those who started mining at age 8 or 9 had an induction-latent period about 10 years longer than those who started mining at age 19 or 20. Here, again, a simple absolute risk model will not fit the observations.

In view of these observations that a simple absolute risk model is inappropriate for estimating the risk of lung cancer due to radon daughter exposure, a simple absolute risk estimate was not calculated. An interagency comparison of risks calculated using the EPA relative-risk model and the age-specific absolute risk model from BEIR III (NAS80b) showed them to be nearly identical numerically (860 cases/10^6 person-WLM versus 850 cases/10^6 person-WLM) (RPC80). Because of the similarity in risk estimates, only relative risk estimates for radon daughter exposures are used in this document.

Unless we state otherwise, we estimate excess cancer fatalities, i.e., those caused by elevated radiation levels that are in addition to those from other causes.

To estimate the total number of lung cancer deaths from increased levels of radon in the environment, we have used a life-table analysis of the additional risk due to radiation exposure (Bu81). This analysis uses the risk coefficients just discussed. It also takes into account the length of time a person is exposed and the number of years a person survives other potential causes of death based on 1970 U.S. death rate statistics. The result is expressed as the number of premature lung cancer deaths that would occur due to lifetime radiation exposure of 100,000 persons. We assume, further, that injury caused by alpha radiation is not repairable so that exposed persons remain at risk for the balance of their lifetimes.

Using the relative risk model, we estimate that a person exposed to 0.01 WL ([illegible] WLM) over a lifetime incurs a 1.7 percent (1 in 60) additional chance of contracting a fatal lung cancer. This estimate was made assuming children are no more sensitive than adults. If exposure to radon decay products during childhood carries a three times greater risk, this estimated lifetime relative risk would increase by about 50 percent ([illegible]). Using a similar lifetable analysis and an absolute risk model, we would have estimated that a person exposed to 0.01 WL over a lifetime incurs a 0.7 percent (1 in 140) additional chance of contracting a fatal lung cancer. Again, equal child and adult sensitivities are assumed (EPA79a). For comparison, a lifetable analysis for the same population not exposed to excess radiation yields a 2.9 percent chance of lung cancer death.

Even though, under either of these models, the risk of radon-induced lung cancer varies with age, it is sometimes convenient to express these risks on an average annual basis. We have calculated a person's average annual risk from a lifetime of exposure by dividing the lifetime risk estimates given above by an average lifespan of 71 years.(1) Based on the risk model and assumptions just described for lifetime exposure, we estimate an average of 2.4 lung cancer deaths per year for each 100 person-working-levels of such exposure. "Person-working-levels" is the population's collective exposure; that is, the number of people times the average concentration of radon decay products (in working levels) to which they are exposed.

For the entire U.S. population, the estimated number of cancers is large using the relative risk model, but this estimate does not hold for all locations because the lung cancer rate varies considerably in different parts of the country. Therefore, we can base our relative risk estimate for each source on the lung cancer death rate for the State in which the source is located. Lung cancer death rates are lower than the national average in several of the States, so at some localities the relative risk is lower than at others.

Radiation risk can also be stated in terms of years of life lost due to cancer death. In the relative risk model, the distribution of ages at which lung cancer caused by radiation occurs is the same as that for all lung cancer in the general population. Since lung cancer occurs most frequently in people over 70 years of age, the years of life lost per fatal lung cancer--14.5 years on the average--is less than for many other fatal cancers. The absolute risk model wrongly assumes that lung cancer fatalities occur at a uniform rate throughout life and, therefore, each fatality reduces the lifespan by a larger amount--an average of 24.6 years.

Because we used recent population data, our assessments are for current conditions. If the population lifestyle, medical knowledge, and other patterns of living affecting mortality remain unchanged, then these rates of lung cancer death could persist for the indefinite future. We have not attempted to assess the effects of future change, which may either increase or decrease our risk estimates. It is prudent, we believe, to assume that estimated risks based on current data could persist over the indefinite future.

(1) Note that this is not the same as applying the risk coefficient for 71 years, since the lifetable analysis accounts for other causes of death.

Table C-3. Lifetime Risk of Excess Cancer in a Cohort of 100,000 from Continuous Exposure to ^{210}Pb

Organ	Inhalation (1 pCi/y) Particle Size 0.3 μm	7.75 μm	54.2 μm	Ingestion (1 pCi/y)	Ground Deposition (1 pCi/cm^2)
Red Marrow	3.6E-4	4.1E-4	3.9E-4	1.3E-4	1.3E-3
Endosteum	1.8E-4	2.1E-4	2.0E-5	6.4E-4	1.4E-4
Pulmonary Lung	2.0E-6	3.8E-7	1.8E-7	3.6E-8	1.0E-3
Breast	4.5E-6	5.0E-6	4.9E-6	1.6E-6	9.1E-4
Liver	3.4E-4	3.9E-4	3.8E-4	1.2E-4	2.0E-4
Stomach Wall	7.3E-9	1.4E-8	1.4E-8	1.6E-8	1.3E-4
Pancreas	1.0E-5	1.1E-5	1.1E-5	3.6E-6	1.1E-4
Lower Large Intestine Wall	6.8E-8	5.3E-7	6.0E-7	1.2E-6	5.6E-5
Kidneys	3.8E-5	4.1E-5	3.9E-5	1.3E-5	4.9E-5
Bladder Wall	1.5E-6	1.6E-6	1.6E-6	5.0E-7	3.5E-5
Upper Large Intestine Wall	1.0E-8	5.9E-8	6.6E-8	1.3E-7	3.5E-5
Small Intestine Wall	2.1E-9	5.1E-9	5.5E-9	7.8E-9	1.5E-5
Ovaries	1.5E-6	1.6E-6	1.6E-6	5.1E-7	3.0E-5
Testes	1.5E-6	1.6E-6	1.6E-6	5.1E-7	4.6E-5
Spleen	1.7E-6	1.6E-6	1.5E-6	4.9E-7	2.1E-5
Uterus	1.5E-6	1.6E-6	1.6E-6	5.1E-7	6.4E-6
Thymus	1.5E-6	1.6E-6	1.6E-6	5.1E-7	2.5E-5
Thyroid	1.0E-6	1.2E-6	1.1E-6	3.6E-7	2.0E-4
TOTAL	9.5E-4	1.1E-3	1.0E-3	3.4E-4	4.3E-3

C.3 Risk Factors per Unit Exposure

Risk factors computed in the RADRISK program or in the radon risk program for unit exposure are listed in Tables C-2 through C-9.

C.4 Risks From Toxic Materials, Nonstochastic Effects

Toxic materials have been considered in this analysis if they are in substantially greater concentration in the source than in native rocks or soils or in a relatively mobile form (anionic or cationic). Materials that are harmful to livestock and plants as well as those potentially affecting humans directly have been included. Evaluating the potential risks from nonradioactive toxic substances requires

Table C-4. Lifetime Risk of Excess Cancer in a Cohort of 100,000 from Continuous Exposure to Polonium-210

Organ	Inhalation (1 pCi/y) Particle Size 0.3 μm	7.75 μm	54.2 μm	Ingestion (1 pCi/y)	Ground Deposition (1 pCi/cm²)
Red Marrow	2.6E-4	3.8E-4	3.6E-4	1.8E-4	3.1E-6
Endosteum	5.6E-6	8.1E-6	7.6E-6	3.8E-6	3.1E-7
Pulmonary Lung	4.1E-2	5.9E-3	1.4E-3	7.0E-12	5.1E-6
Breast	1.6E-5	2.3E-5	2.1E-5	1.0E-5	3.6E-6
Liver	1.9E-4	2.7E-4	2.6E-4	1.3E-4	1.2E-6
Stomach Wall	8.2E-8	1.6E-7	1.7E-7	2.0E-7	6.9E-7
Pancreas	4.8E-5	6.9E-5	6.5E-5	3.2E-5	9.1E-7
Lower Large Intestine Wall	2.6E-6	5.2E-6	5.5E-6	6.2E-6	4.1E-7
Kidneys	2.4E-4	3.5E-4	3.3E-4	1.6E-4	2.9E-7
Bladder Wall	6.8E-6	9.8E-6	9.2E-6	4.6E-6	2.7E-7
Upper Large Intestine Wall	4.3E-7	8.6E-7	9.2E-7	1.0E-6	2.7E-7
Small Intestine Wall	3.7E-8	7.3E-8	7.8E-8	8.8E-8	1.2E-7
Ovaries	6.8E-6	9.8E-6	9.2E-6	4.6E-6	8.0E-8
Testes	6.8E-6	9.8E-6	9.2E-6	4.6E-6	1.5E-7
Spleen	2.1E-4	3.0E-4	2.4E-4	1.4E-4	1.6E-7
Uterus	6.8E-6	9.8E-6	9.2E-6	4.6E-6	1.1E-7
Thymus	6.8E-6	9.8E-6	9.2E-6	4.6E-6	1.0E-7
Thyroid	3.3E-6	4.8E-6	4.5E-6	2.2E-6	5.6E-7
TOTAL	4.2E-2	7.4E-3	2.8E-4	6.9E-4	1.7E-5

Table C-5. Lifetime Risk of Excess Cancer in a Cohort of 100,000 from Continuous Exposure to Radium-226

Organ	Inhalation (1 pCi/y) Particle Size 7.75 μm	54.2 μm	Ingestion (1 pCi/y)	Ground Deposition (1 pCi/cm^2)
Red Marrow	8.9E-4	8.6E-4	5.9E-4	3.9E-3
Endosteum	3.6E-4	3.4E-4	2.4E-4	4.0E-4
Pulmonary Lung	7.2E-3	1.8E-3	7.0E-7	4.5E-3
Breast	1.7E-5	1.6E-5	1.1E-5	3.0E-3
Liver	5.8E-5	5.6E-5	3.8E-5	1.0E-3
Stomach Wall	2.6E-7	2.6E-7	2.5E-7	4.8E-4
Pancreas	4.8E-5	4.6E-5	3.2E-5	5.9E-4
Lower Large Intestine Wall	1.1E-5	1.2E-5	1.3E-5	3.2E-4
Kidneys	1.3E-5	1.2E-5	8.5E-6	2.1E-4
Bladder Wall	6.9E-6	6.6E-6	4.5E-6	1.9E-4
Upper Large Intestine Wall	1.3E-6	1.3E-6	1.5E-6	2.1E-4
Small Intestine Wall	1.1E-7	1.1E-7	1.1E-7	1.0E-4
Ovaries	6.9E-6	6.6E-6	4.5E-6	7.6E-5
Testes	6.9E-6	6.6E-6	4.5E-6	1.8E-4
Spleen	6.4E-6	6.2E-6	4.2E-6	1.1E-4
Uterus	6.9E-6	6.6E-6	4.5E-6	8.1E-5
Thymus	6.9E-6	6.6E-6	4.5E-6	1.1E-4
Thyroid	3.6E-6	3.4E-6	2.3E-6	7.1E-4
TOTAL	8.7E-3	3.1E-3	9.6E-4	1.6E-2

Table C-6. Lifetime Risk of Excess Cancer in a Cohort of 100,000 from Continuous Exposure to ^{230}Th

Organ	Inhalation (1 pCi/y) Particle Size 7.75 μm	54.2 μm	Ingestion (1 pCi/y)	Ground Deposition (1 pCi/cm²)
Red Marrow	2.3E-2	1.5E-2	2.4E-4	2.9E-4
Endosteum	1.6E-2	1.1E-2	1.7E-4	3.0E-5
Pulmonary Lung	6.6E-2	1.6E-2	3.7E-10	2.7E-4
Breast	8.0E-6	5.2E-6	8.4E-8	2.5E-4
Liver	1.5E-4	9.7E-5	1.6E-6	5.3E-5
Stomach Wall	1.7E-7	1.8E-7	1.8E-7	3.1E-5
Pancreas	2.4E-5	1.6E-5	2.5E-7	3.3E-5
Lower Large Intestine Wall	6.0E-6	6.2E-6	6.3E-6	1.9E-5
Kidneys	6.9E-6	4.5E-6	7.3E-8	1.2E-5
Bladder Wall	3.5E-6	2.3E-6	3.6E-8	9.9E-6
Upper Large Intestine Wall	1.0E-6	1.0E-6	1.0E-6	1.0E-5
Small Intestine Wall	8.5E-8	8.8E-8	8.9E-8	4.9E-6
Ovaries	3.5E-6	2.3E-6	3.6E-8	4.7E-6
Testes	3.5E-6	2.3E-6	3.6E-8	1.3E-5
Spleen	3.5E-6	2.3E-6	3.6E-8	5.7E-6
Uterus	3.5E-6	2.3E-6	3.6E-8	3.0E-6
Thymus	3.5E-6	2.3E-6	3.6E-8	5.4E-6
Thyroid	1.8E-6	1.1E-6	1.8E-8	4.6E-5
TOTAL	1.1E-1	4.2E-2	4.2E-4	1.1E-3

Table C-7. Lifetime Risk of Excess Cancer in a Cohort of 100,000 from Continuous Exposure to ^{234}U

Organ	Inhalation (1 pCi/y) Particle Size 7.75 μm	54.2 μm	Ingestion (1 pCi/y)	Ground Deposition (1 pCi/cm^2)
Red Marrow	2.4E-5	1.6E-5	2.3E-4	1.4E-4
Endosteum	1.6E-5	1.1E-5	1.5E-4	1.5E-5
Pulmonary Lung	6.7E-2	1.6E-2	1.7E-6	1.1E-4
Breast	1.3E-7	8.4E-8	1.2E-6	1.9E-4
Liver	4.7E-7	3.2E-7	4.5E-6	1.6E-5
Stomach Wall	2.0E-7	2.0E-7	4.2E-7	1.3E-5
Pancreas	3.6E-7	2.5E-7	3.5E-6	1.4E-5
Lower Large Intestine Wall	6.1E-6	6.3E-6	5.3E-6	1.0E-5
Kidneys	1.1E-5	7.5E-6	1.1E-4	3.4E-6
Bladder Wall	5.7E-8	3.9E-8	5.5E-7	2.8E-6
Upper Large Intestine Wall	1.0E-6	1.1E-6	9.5E-7	2.8E-6
Small Intestine Wall	9.1E-8	9.2E-8	1.2E-7	1.4E-6
Ovaries	5.2E-8	3.6E-8	5.0E-7	1.9E-6
Testes	5.2E-8	3.6E-8	5.0E-7	9.6E-6
Spleen	5.2E-8	3.6E-8	5.0E-7	1.9E-6
Uterus	5.2E-8	3.6E-8	5.0E-7	7.6E-7
Thymus	5.2E-8	3.6E-8	5.0E-7	1.6E-6
Thyroid	2.7E-8	1.8E-8	2.5E-7	1.6E-5
TOTAL	6.7E-2	1.6E-2	5.1E-4	5.4E-4

Table C-8. Lifetime Risk of Excess Cancer in a Cohort of 100,000 from Continuous Exposure to ^{238}U

Organ	Inhalation (1 pCi/y) Particle Size 7.75 μm	54.2 μm	Ingestion (1 pCi/y)	Ground Deposition (1 pCi/cm²)
Red Marrow	2.0E-5	1.4E-5	1.9E-4	7.6E-5
Endosteum	1.3E-5	9.0E-6	1.3E-4	8.3E-6
Pulmonary Lung	6.1E-2	1.5E-2	1.5E-6	5.2E-5
Breast	2.7E-7	1.2E-7	1.2E-6	1.3E-4
Liver	5.1E-7	3.0E-7	3.9E-6	4.6E-6
Stomach Wall	2.9E-7	2.1E-7	3.7E-7	6.3E-6
Pancreas	3.8E-7	2.4E-7	3.2E-6	7.0E-6
Lower Large Intestine Wall	9.2E-6	7.0E-6	5.1E-6	5.8E-6
Kidneys	9.8E-6	6.7E-6	9.5E-5	1.0E-6
Bladder Wall	5.4E-8	3.6E-8	4.9E-7	7.4E-7
Upper Large Intestine Wall	1.5E-6	1.1E-6	8.7E-7	7.9E-7
Small Intestine Wall	1.3E-7	9.6E-8	1.1E-7	3.6E-7
Ovaries	4.8E-8	3.1E-8	4.3E-7	9.2E-7
Testes	4.7E-8	3.1E-8	4.3E-7	6.8E-6
Spleen	5.4E-8	3.4E-8	4.5E-7	8.0E-7
Uterus	5.0E-8	3.3E-8	4.5E-7	1.3E-7
Thymus	5.9E-8	3.5E-8	4.5E-7	5.3E-7
Thyroid	5.6E-8	2.6E-8	2.7E-7	6.0E-6
TOTAL	6.1E-2	1.5E-2	4.3E-4	3.1E-4

Table C-9. 30-Year Genetic Dose Commitment
(mrad)

Organ	Lead-210	Polonium-210	Radium-226	Radium-230	Thorium-234	Uranium-238
			INHALATION			
			(7.75 m particle size)			
Ovary						
Low-LET	9.6E-5	1.6E-9	7.1E-5	2.0E-6	1.8E-7	6.7E-6
High-LET	2.5E-4	1.7E-3	1.2E-3	5.8E-4	8.8E-6	7.3R-6
Testis						
Low-LET	9.4E-5	5.9E-10	3.9E-5	1.8E-6	2.4E-8	5.0E-6
High-LET	2.5E-4	1.7E-3	1.2E-3	5.8E-4	8.8E-6	7.4E-6
			(54.2 m particle size)			
Ovary						
Low-LET	9.3E-5	1.6E-9	7.1E-5	1.4E-6	1.8E-7	2.6E-6
High-LET	2.4E-4	1.6E-3	1.2E-3	3.8E-4	6.0E-6	5.1E-6
Testis						
Low-LET	9.1E-5	5.6E-10	3.7E-5	1.2E-6	1.7E-8	1.9E-6
High-LET	2.4E-4	1.6E-3	1.1E-3	3.8E-4	6.0E-6	5.1E-6
			INGESTION			
Ovary						
Low-LET	3.1E-5	1.3E-9	6.2E-5	2.0E-7	3.7E-5	1.5E-5
High-LET	7.8E-5	7.8E-4	7.6-6	6.2E-5	8.6E-5	7.2E-5
Testis						
Low-LET	2.9E-5	3.2E-10	2.7E-5	2.4E-8	2.2E-7	1.4E-5
High-LET	7.8E-5	7.8E-4	7.1E-4	6.2E-6	8.6E-5	7.2E-5
			GROUND DEPOSITION			
Ovary	4.0E-2	1.4E-4	1.3E-1	8.1E-3	3.2E-3	1.6E-3
Testis	7.9E-2	2.6E-4	3.1E-1	2.3E-2	1.7E-2	1.2E-2

different methods from those used for radioactive substances.[1] As noted earlier, with nonradioactive toxic materials, the type of effect varies with the material; the severity of the effect--but not its probability of occurring--increases with the dose. Moreover, because the body can detoxify some materials or repair the effects small doses, often no toxic effects occur below a threshold dose.

We cannot construct a numerical risk assessment for nonradioactive toxic substances because we do not have enough information. We can, however, qualitatively describe risks of toxic substances in terms of their likelihood of reaching people (or animals, or agricultural products), concentrations at which they may be harmful, and their toxic effects. No acute effects--death in minutes or hours--are expected at concentrations addressed in this analysis. Severe sickness, or death within days to weeks, from the use of highly contaminated water is possible, but unlikely.

Chronic toxicity from the continuous consumption of contaminants at low concentrations could be a problem. Toxic substances can accumulate slowly in tissues, causing symptoms only after some minimum amount has accumulated. Such symptoms of chronic toxicity develop slowly, over months or years.

An extensive section in the EIS for inactive sites (EPA82-83) was devoted to toxicity of elements found in uranium mill tailings and tailings ponds and problems associated with them. Only an abreviated discussion will be presented here. For the more detailed discussion, the EIS for remedial action at inactive sites should be consulted.

At active uranium milling sites, inorganic toxic elements are expected to be the major cause of concern (see Table C-10).

Organic chemicals used in processing ore are recycled and only fugitive releases to tailings ponds might occur. The principal organics associated with uranium milling are kerosene, di (2-ethylhexyl) phosphoric acid (EHPA), tributyl phosphate, tertiary amines (e.g., almine-336) and isodecanol (NRC80).

Although the organic chemicals used in uranium milling are not expected to be released with mill tailings to any appreciable extent, background levels in surface and ground water should be established for both inorganic and organic potential pollutants. Both inorganic chemicals and some organic chemicals may be transported long distances so local levels in water may reflect distant industrial sources of pollution rather than mill operations.

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(1)Many nonradioactive substances can induce cancer in experimental animals (Go77, Ve78). However, for nonradioactive substances found in uranium mill tailings, we do not feel that dose-response relationships adequate for estimating such risks for oral intake have been developed.

Table C-10. Selected Potentially Toxic Substances Associated with Uranium Mill Tailings

Arsenic	Iron	Radium
Barium	Lead	Selenium
Boron	Manganese	Silver
Cadmium	Mercury	Thorium
Chromium	Molybdenum	Uranium
Copper	Nickel	Vanadium
Cyanide	Nitrates	

C.4.1. Estimates of Chronic Toxicity in Humans

Data reviewed by the National Academy of Sciences showed that for elements essential to human nutrition, there is a margin of safety between the amount required for good nutritiion and the amount which is toxic. The margin of safety may be narrow; e.g., 10 times the daily recommended intake of arsenic is toxic; or wide, e.g., 1,000 times the daily recommended intake of chromium is toxic (NAS80a). Table C-11 lists selected substances found in uranium mill tailings and estimated toxic levels. Note that these estimates are derived from a number of sources of data and are not adjusted for chemical form of the element, age or sex of subject, or any other factors. The estimates should be viewed as very broad estimates of where toxicity might be expected.

C.4.2 Estimates of Chronic Toxicity in Animals and Plants

Although there is potential for causing acute toxic conditions to develop in plants or animals if tailings pond water or other highly contaminated standing water is used for plants or animals, this is considered unlikely to occur. Induction of chronic toxicity in plants or animals by using contaminated surface water, or more likely, contaminated groundwater is deemed more plausible.

Maintaining water quality no worse than levels specified in the interim primary (EPA76) or secondary (EPA79b) drinking water regulations would also protect plants and animals in most cases. However, these limits may not be adequate to protect dairy cattle, and not all possible contaminants would be covered. Likewise, not all elements potentially toxic to plants would be covered. For a more extended discussion of elements toxic to plants and animals, the National Academy of Sciences 1972 publication, "Water Quality Criteria," (NAS72b) can be consulted.

Table C-11. Daily Intake Levels of Selected Elements Estimated to be Toxic (NAS80a, EPA82)

Element	Ratio of Toxic Intake to Adult Required Intake	Potentially Toxic Intake in Humans (mg)	
		Acute	Chronic
Arsenic	10	23[a]	0.2-0.5
Barium	NE	550-600[a]	?
Boron	NE	15000-30000[a]	?
Cadmium	NE	15-30	0.6
Chromium	1000	?	5-200
Copper	40-135	175-200[a]	80-400
Cyanide	NE	50-200[a]	10
Iron	340-1700	70,000+ [a]	3000-30000
Lead	NE	?	0.1-3
Manganese	120	?	300-600
Mercury	NE	10-200[a]	0.3-3
Molybdenum	10-40	?	2-20
Nickel	112	250	6
Nitrates	NE	8400-42000[a]	10
Radium	NE	?	?
Selenium	100	?	5-20
Silver	NE	140[a]	0.1
Thorium	NE	?	?
Uranium	NE	350[a]	0.6
Vanadium	40-280	1700-17000[a]	1-3

NE - Not reported to be essential in humans.
[a]Deaths are expected.

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APPENDIX D

WATER MANAGEMENT AT URANIUM ORE PROCESSING SITES

APPENDIX D: WATER MANAGEMENT AT URANIUM PROCESSING SITES

CONTENTS

APPENDIX D: WATER MANAGEMENT AT URANIUM ORE PROCESSING SITES

D.1 Summary

Operating uranium mills produce effluents containing radioactivity and toxic materials which are potential contaminants to groundwater. Large amounts of tailings effluents placed in unlined evaporation ponds on permeable soil at existing mill sites have seeped into the sandstone bedrock that contains groundwater. Investigations of the altered bedrock along the seepage pathways show attenuation of most of the radionuclides and some of the toxic elements during the neutralization phase of the leachate. Some of the highly mobile and soluble heavy metals, (Mo, V, Mn, Pb, As, and Se) have migrated beyond the neutralization zone into the groundwater. The presence of diagnostic chemical species related to seepage plumes and higher-than-normal concentrations of toxic materials above groundwater background levels disclose the presence of tailings contaminants in the groundwaters close to the uranium mills.

The characteristics of seepage migration are site specific and controlled by the relatively complex hydrogeology of the typical uranium mill site. No satisfactory method exists to abate or predict contaminant movement from these unlined tailings ponds.

Using synthetic liners, clay liners, or a combination of both in the tailings pond seems to be the most effective method of confining mill tailings effluents. The type of liner used is usually determined by the nature of the waste and conditions of the site. Both clay and synthetic liners are similar in cost. Synthetic liners are more impervious and if adequately guarded by clay layer cushions can be protected from tear or puncture and chemical alteration.

Clay liners, properly designed with structural integrity, can provide a tight seal by the precipitation of some solids into pore spaces as a result of neutralization reactions attending the interaction of acid waste water and the liner materials. However, the impermeability achieved is somewhat less assured than the synthetic liners.

D.2 Introduction

The water used in the recovery of uranium contains toxic materials that must be effectively managed to prevent potential surface water or groundwater contamination. It has been estimated that as much as 85 percent of the mill tailings effluents are lost to groundwater during the mill's operation (Ja79). Thus, confining water during the mill operating phase is critical in controlling the amount of contaminants available for potential pollution.

Mill tailings effluents discharged to unlined evaporation ponds have resulted in seepage loss of some of the contaminants to groundwater during the operation phase of the mills. Tailings pond seepage has been detected in the groundwater at a number of sites. The maximum distance of migration reported at one site was 1.5 miles (UI80). Within a few years after the mill closes, tailings ponds will evaporate in the arid to semi-arid climate of western United States; this leaves a tailings pile vulnerable to wind and water erosion.

Over the past several years, there have been a number of core hole borings and water monitoring investigations to better understand and develop methods to mitigate the migration from uranium tailings impoundments. These site-specific studies have traced the extent and travel rates of seepage plumes, have identified the attenuation of radionuclides and toxic material by the geologic media, and have contributed to the understanding of the physicochemical factors involved. The migration of highly mobile contaminants requires further study. Emphasis presently is placed on the confinement and retention of effluents in the tailings ponds by synthetic liners, clay liners, or a combination of both; however, some natural media may be impervious to seepage. Future technology directed toward changing the chemistry of tailings pond effluents may help contain the mobile toxic materials that contaminate groundwater.

D.3 Uranium Recovery Processes

There are two basic conventional processes for recovering uranium from the ore: the acid-leach process and the alkaline-leach process. The acid-leach process is used when the ore contains less than 12 percent limestone and generally accounts for 80 percent of the uranium recovery. The alkaline-leach process is used on the remaining 20 percent of the ore milled. Both processes involve an initial dry crushing and grinding, then water is introduced as the ore is wet ground to a pulp density of 50 to 65 percent solids. Water consumption at this step is reduced by recirculating the water.

A leaching process removes the uranium from the crushed ore, with sulfuric acid as the leaching agent in the acid-leach process; a mixed sodium carbonate-sodium bicarbonate solution is the leaching agent in the alkaline-leach process (NRC80a). After ore leaching is completed, the "pregnant" leach liquor containing the dissolved uranium is removed from the tailings solids by a counter current decantation (CCD) circuit. The leach solution is sent to a solvent extraction for further processing, and the remaining solids are washed and pumped as a slurry to the tailings ponds. Water in the tailings ponds generally is characterized by total dissolved solids in the range of 12,000 to 90,000 mg/L with an abundance of dissolved radionuclides and heavy metals. The pH of the water averages about 1.8 for mills using the acid-leach process and about 10.2 for mills that use the alkaline-leach process.

The acid-leach and alkaline-leach processes have considerable chemical differences. A larger fraction of thorium is solubilized in the acid-leach process, but the thorium is precipitated in the tailings pond when the acidity is reduced. In addition to variations in the chemical composition from the milling process used, other variations exist from differences in the composition of the ores related to their origin.

D.4 Contaminants in Uranium Waste

The waste from the milling operations of uranium ore contains all the toxic contaminants present in the original ore, about 10 percent of the uranium not recovered in the process, and a variety of chemicals used in the extraction process. The nature of the contaminants vary in relation to the source of the ore and the type of process used. Radionuclides reported include uranium, thorium, and radium, and toxic materials include arsenic, lead, molybdenum, and selenium. Other elements and parameters reported include iron, manganese, sulfate, chloride, total dissolved substances (TDS), and acidity index (pH). Many levels of toxic materials are more than two orders of magnitude above EPA drinking water standards. Additional heavy metals and chemicals existing in uranium mill wastewater which are locally important, include Sb, Be, Cd, Cr, Cu, Ni, Zn, V, Mn, Al, and ammonia.

The solid portion of the tailings is comprised of particles ranging in size from coarse sands to fine slimes. Quartz and feldspar comprise the major portion of the sands, while fines contain appreciable amounts of clay minerals, gypsum, calcite, and barite in addition to quartz and feldspar (Dr81). In both the acid process and the alkaline process, the residual uranium and radium content of slimes (fines) is about twice that of sands; this is undoubtedly due to the greater concentration of sorptive minerals, e.g., clay minerals, in the slimes. In the acid-leach process, about 95 percent of the thorium in the original ore remains in the solid tailings waste. Less than one percent of the radium is dissolved in the liquids. Even more of the thorium and radium remains in the solid waste from the alkaline-leach process.

Radon gas is released as a daughter radionuclide from the decay of radium-226, which is largely retained in the solid waste. Because radon is chemically inert, it migrates by diffusion from the tailings pile to the atmosphere. Radon emissions rates have been calculated at between 200 to 900 pCi/m^2s. Uncontaminated soils average about 1 pCi/m^2s by comparison. Standing water and entrapped water in the tailings pile inhibit the release of radon gas so that calculated release rates cited may be high.

D.5 Water Use and Retention at Operating Mills

Water conservation is desirable in many mining and milling operations for uranium recovery. Mine waters are treated to recover uranium and/or to remove radium, heavy metals, and suspended solids. The treated mine waters are used at the mill as feed water or discharged to the watershed. Currently, only the Uravan, Colorado, mill discharges treated wastes to surface water. Water is used to slurry the tailings (the wastes) from the mill to an impoundment. This water can evaporate, be pumped to evaporation ponds, recycled to the mill, or discharged to surface waters. Water decanted from the ponds in the impoundment system may be recycled to the mill, decreasing fresh water usage.

The quantity of water used in milling is variable and depends on the process used and the degree of recycling. The acid-leach process requires greater amounts of fresh water than mills using the alkaline-leach process. Fresh water is usually required in acid leach mills for ore grinding, leaching (as steam), counter current decantation washing, and precipitation (Ja79). The alkaline-leach process normally employs a mixed sodium carbonate-sodium bicarbonate leach solution in the grinding circuit with fresh water used for post-leaching filtration and second-stage precipitation (Ja79). The waste streams from the milling process are partially or totally segregated for disposal, especially if recycling from the impoundment system is practiced. Segregation and disposal in separate ponds allow reuse of less contaminated wastes while providing for containment of liquid wastes which contain high concentrations of contaminants.

D.6 Design of Tailings Impoundments

The predominant method of disposal of all solid and liquid wastes generated in the uranium mill today is impoundment of the wastes in a tailings retention system. This system consists of an earthen dam or embankment and an evaporation basin or pond behind the dam. The dam is located to minimize the upstream catchment area. Ditches are also constructed to direct the water around the impoundment. The evaporation basin on the upstream side of the dam is lined with a clay or synthetic liner to prevent seepage loss to the underlying soil.

The NRC has issued Regulatory Guide 3.11, "Design, Construction, and Inspection of Embankment Retention Systems for Uranium Mills" which provides the design goals for tailings impoundments (NRC77). The design takes into consideration the protection of the embankment retention systems from the Probable Maximum Flood (PMF). The PMF is defined as the flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the region (NRC77). The regulatory guide lists appropriate guidance for determining the Probable Maximum Flood. Methods for estimating return intervals of paleofloods in the particular acute semiarid regions have been described by Kochel and Baker (Ko82).

D.7 Clay and Synthetic Liners

In the early days of uranium milling, not much attention was given to the protection of the subsurface hydrogeologic environment. Most of the mill wastes generated before 1977 are stored in unlined tailings ponds, and some of these have leaked. Most waste disposal sites are located in hydrogeologic environments that consist of nonindurated and/or indurated sediments that were deposited in fluvial environments. Buried river deposits are coarse grained and difficult to detect because of their braided, band-like occurrence in such terrain. High seepage rates of migrating solutions can take place if such formations occur beneath an unlined uranium mill tailings evaporation pond.

Since groundwater monitoring was initiated in 1977, seepage from tailings ponds has been detected in groundwater from a number of sites, with migration as much as 1.5 miles at one of the sites (UI80). The seepage plumes were traced by one or more of several chemical parameters found in the seepage water, particularly sulfate and total dissolved solids. In some cases, this monitoring effort has identified contamination problems which require the use of recovery wells to return contaminated water from seepage plumes back to lined tailings ponds. (UI80).

The technology of pond liners is a relatively recent development. Generally speaking, synthetic liners are used for evaporation ponds of mine waters or less contaminated effluents, and thicker clay liners are used in tailings ponds. Synthetic liners of polyvinyl chloride (PVC), chlorinated polyethylene (CPE), and hypalon (synthetic rubber) used at uranium mills are less permeable (10^{-10} cm/s) than clay liners (Ja79). Synthetic liners, however, are subject to loss of seal by puncture or tearing during installation. Thus, they must be protected with some layers of clay. The clay layers act as a cushion to prevent rupture and to neutralize the leachate and potential chemical alteration of the synthetic liner.

Clay liners, in addition to having structural stability, are effective in sealing ponds because of their layered structure and their high sorptive properties. The desorption of Na^+ from montmorillonite in the mill tailings of the Grants Mineral Belt has been described as being desirable because pollutants are probably being adsorbed in their place on this clay mineral (Lo82). Leaching of clay into liner pores (caused by precipitation) can also increase the impermeability of the clay liner; this enhances the long-term stability of the clay liners (Pe82). Natural clays treated with polymeric materials have also been shown to improve the sealing properties of clay, and permeabilities as small as 10^{-6} to 10^{-8} cm/s have been achieved (Ja79).

The uncertainty of maintaining an acceptable level of environmental control with unlined tailings ponds warrants the use of synthetic liners, clay liners, or a combination of clay and synthetic liners that prevent the seepage of contaminants into groundwater.

D.8 Groundwater Monitoring Results

D.8.1 Introduction

Before 1977 most mill wastes were stored in unlined tailings ponds. Seepage from these ponds has contaminated groundwater. The characteristics of seepage movement are site specific, and a number of methods can identify the pathways and extent of pollution to groundwater. Some of the data that were collected at uranium mill disposal sites are incomplete, and some were collected by methods that are not state of the art. The most reliable method of characterizing groundwater contamination is by identifying the chemicals in tailings ponds that are also in groundwater above background levels.

The methods used to delineate the migration path of the seepage plume and the actual groundwater monitoring results at the active mill tailings sites are reviewed in the next section.

D.8.2 Composition of Tailings Ponds

The dissolved radionuclides of primary concern within most tailings ponds include radium-226, thorium-230, uranium-238, lead-210, and polonium-210. Heavy metals found in varying quantities among the uranium mill sites include molybdenum, arsenic, selenium, lead, iron, chromium, manganese, magnesium, cobalt, nickel, barium, vanadium, and copper. Toxic heavy metals are higher in concentration in acid mill waste than in alkaline mill waste. Anions of toxic heavy metals are generally more soluble and, thus, potentially more hazardous than the cationic species of the same element which can be precipitated with lime or sulfide. Major anions formed by heavy metals in tailings ponds include species of arsenic, chromium, molybdenum, uranium, and vanadium. Inorganic anions, notably sulfate, nitrate, and chloride, are present in significant quantities in acid leach mill wastes. Other inorganic anions found in minor amounts in most wastewater include sulfide, cyanide, fluoride, and total dissolved solids (Ja79). Light elements in tailings ponds include potassium, sodium, aluminum, beryllium, calcium, magnesium, and titanium.

While organics are widely used in the extraction process, most of these chemicals are removed, and quantities of organic compounds in mill liquid wastes are low. Typical concentrations of total organic carbon in acid mill waste range from 6 to 24 mg/L in acid mill waste and 1 to 450 mg/L in alkaline mill waste; oil and grease is generally 1 mg/L in acid mill waste and 3 mg/L in alkaline mill waste; MBAS surfactants average 0.5 mg/L in acid mill waste and 0.02 mg/L in alkaline mill waste; phenol is less than 0.2 mg/L for both types of wastes (Ja79). The pH of the waters in the tailings ponds averages about 1.8 for mills using the acid-leach process and about 10.2 for mills using the alkaline extraction process.

D.8.3 The Neutralization Zone

The acid seepage plumes are normally neutralized by carbonate minerals in the bedrock within a few hundred yards of most tailings ponds. At a distance of a few hundred yards, the total dissolved substances can be expected to range from 5,000 to 10,000 mg/L, as contrasted to the 25,000-35,000 mg/L found in normal tailings pond water (UI80). The pH change gradually increases to that of the normal groundwater, and minerals are precipitated that are not generally native to the bedrock in this same distance of transport.

Several investigators have attempted to characterize the transition zone between the mill tailings pond water and the point where it becomes indistinguishable from native groundwater. A recent investigation describes the interaction between the seepage from the tailings ponds and the natural soils by thermodynamic principles; this interaction is based on minerals identified as precipitates and dissolved minerals (Ma82). Gypsum precipitation, for example, results when calcite comes in contact with sulfuric acid; carbon dioxide gas is produced and the calcium reacts with the sulfate to produce gypsum. Barium will also precipitate as $BaSO_4$ and in the process remove radium from solution (Ma82). Conclusions drawn, however, are almost entirely on solid-phase data, and the liquid-phase chemistry is ignored.

Another line of investigation utilizes an analytical hydrogeochemical model based upon acid consumption-neutralization front movement. In this model it is possible to identify and characterize zones within migrating plumes of tailings-derived water by the chemical characteristics of the water (Sh82). An investigation of the seepage from an unlined mill tailings pond in the Wyoming Gas Hills district describes radionuclide retention within the first 40 to 60 cm beneath the pond. The neutralization zone to an 11-meter depth is delineated by typical gypsum precipitation and carbonate removal and increases to the 8.2 pH background level (Er82).

The foregoing investigations describe the retention of certain radioactive and toxic materials attending the neutralization of mill pond seepage and the nature of transition zones. Of major concern is determining what portion of the seepage has gone beyond the neutralization zone to become part of groundwater contamination. This is best determined by groundwater monitoring.

D.8.4 Monitoring Groundwater Contamination

Several groundwater monitoring investigations of uranium mill sites have disclosed chemical pollutants above background levels that are attributed to seepage from unlined mill tailings ponds. A description of these site-specific monitoring findings follows.

Canon City, Colorado

Before 1979, the Cotter Corporation near Canon City, Colorado, used the alkaline-leach process and disposed of mill tailings wastes in a series of unlined tailings ponds. The seepage waste is typical of both the alkaline and acidic types and is described as concentrated sodium sulfate waters with high levels of molybdenum, selenium, and emitters of radiation (UI80).

Concentrations of molybdenum at levels of 16.7 mg/L at a well approximately 8000 feet from the Cotter tailings pond, within an isoconcentration delineated zone, are evidence of pollution from a point source in the tailings pond. The maximum background level of molybdenum in the vicinity of the mill is 1.1 mg/L, and the Drinking Water Standard for molybdenum is 0.05 mg/L (UI80).

A Soil Conservation Reservoir near the tailings pond (3000 feet) has elevated levels of sodium, sulfate, radionuclides, and selenium (in addition to elevated levels of molybdenum) which appear to be related to the seepage effluents from the pond. The complex nature of the hydrogeology around the Cotter Mill, however, makes migration pathways difficult to interpret for engineering corrective measures.

Ford, Washington

The Dawn Mining Company mill near Ford, Washington, has acid-leach process effluent seepage from existing unlined tailings ponds that has contaminated the groundwater beneath the site. Sulfate is the primary tracer of the contamination plume that is easily traced through the highly permeable sand and gravel glacial sediments to an underlying glacial lake, derived clay stratum. At the impervious clay stratum, a groundwater mound gradient is created that causes discharge in a direction approximately 0.5 miles west of the tailings pond to a nearby surface stream (UI80). Uranium concentration in the seepage emergence zone is 0.06 mg/L, whereas uranium in springs not affected by the tailings pond is 0.004 mg/L. However, the only contaminant in the seepage emergence zone that exceeds Drinking Water Standards is nitrate, which occurs in levels of 35 mg/L and is three and one-half times the maximum permissible concentration specified. Sulfate, manganese, and total dissolved solids occur in excess of "recommended" limits for drinking water. Pump-back systems are being considered as engineering control measures to control the pollution.

Gas Hills, Wyoming

The Union Carbide Gas Hills, Wyoming, uranium mill near Riverton, Wyoming, has contributed groundwater contaminants from an unlined tailings disposal pond containing acid-leach process effluents. Water quality in the water-bearing horizons of the Wind River Formation used as background indicator wells barely exceeds the Drinking Water Standards for total dissolved solids, sulfate, selenium, and radium-226 (UI80).

Monitoring wells around the mill tailings pond indicate that migration of contaminants is occurring in the upper alluvial layer and middle sandy layer of the Wind River Formation which has a thickness of 400 feet.

Typical water contamination from a monitoring well to a depth of 140 feet and at a distance of 700 feet from the disposal pond indicate the following: sulfate 2932 mg/L, with 250 mg/L the irrigation standard; selenium 0.26 mg/L, with 0.01 mg/L the irrigation standard; total dissolved solids 5760, with 250 mg/L the irrigation standard; nitrate 150 mg/L, with 10 mg/L the irrigation standard; aluminum 59 mg/L, with 20 mg/L the irrigation standard; manganese 7 mg/L, with 0.05 mg/L the irrigation standard; chloride 893 mg/L, with 250 mg/L the irrigation standard (NRC80b). More monitoring wells would be required to determine how far the seepage has migrated because of the complex hydrogeologic conditions and the interpretation of data required.

Jeffrey City, Wyoming

Groundwater has been contaminated by the acid-leach effluent seepage from the Western Nuclear, Inc., Split Rock uranium mill near Jeffrey City, Wyoming. The unlined tailings pond leaked contaminants into the underlying Split Rock Formation comprised of fine-grained sandstone having a hydraulic conductivity of 1.4×10^{-2} to 1×10^{-4} cm/s (UI80). Groundwater degradation occurs beyond the site boundary in the direction of Jeffrey City.

Arsenic contamination has been detected up to 2900 feet from the tailings pond. A chemical analysis of sediments shows a decrease in contaminants with depth and distance from the tailings pond. Due to high levels of iron and manganese in the tailings pond (300 mg/L and 17 mg/L respectively), it appears that oxyhydroxides of these elements are readily formed and coprecipitate other heavy metals under governing chemical conditions in the host media. The sorption of cationic species by clay minerals as well as change in redox potential (Eh) and pH are other factors that control the migration distance of contaminants. Arsenic is the exception with the media effecting less control on its migration.

Fremont County, Wyoming

The Federal American Partners mill tailings pond located in the Gas Hills area of Fremont County, Wyoming, has leaked seepage to groundwater beneath the site. The unlined tailings pond is situated on weathered sandstone of the Wind River Formation. The acid-leach effluents have migrated approximately 3200 feet with chloride, sulfate, nitrogen, lead, and total dissolved solids found above background levels (UI80). Isoconcentration maps delineate the direction of migration of the contaminants with test data from 27 monitoring wells ranging in depth from 20 to 105 feet. Seepage migration appears to be confined to the deeper aquifer. Buried stream channels in the area could constitute zones of higher hydraulic conductivity so that groundwater migration could become greater without corrective action.

La Sal, Utah

The Rio Algom Corporation's Lisbon Valley mill tailings pond near La Sal, Utah, has seeped alkaline-leach process effluents to a perched groundwater mound in the vicinity of the tailings pond (UI80). The unlined pond is located on a thin layer of terrestrial deposits (10 feet or less) that overlie the Dakota-Burro Canyon sandstones. Contamination is restricted to the Dakota-Burro Canyon Formation with Drinking Water Standards exceeded approximately 1500 ft. away from the tailings ponds (UI80). Conclusions regarding the migration are based on isoconcentration maps for alkalinity (CO_3), chloride, nitrate sodium, sulfate, boron, total uranium, and radium-226. A major northwesterly-trending fault present near the site (3,000 ft. away) may influence the movement of the seepage plume at the site.

Milan, New Mexico

The Homestake uranium mill near Milan, New Mexico, has sustained 440 m^3/d or 6 percent seepage loss of alkaline-leach process effluents discharged to unlined tailings ponds (Ja79). The seepage has penetrated the highly permeable and saturated alluvium which blankets (up to 75 feet thick) the more massive, less permeable Chinli Formation bedrock of shale and sandstone (Pi81). A mound of contaminated groundwater underlies the tailings ponds, and elevated levels of uranium, radium, selenium, and nitrate-nitrogen, in excess of New Mexico Drinking Water Standards, have been found in surrounding wells used as drinking water by nearby residents (Pi81).

Selenium ranges up to 2.0 mg/L (limit is 0.05 mg/L); nitrate-nitrogen, up to 14.1 mg/L (limit is 10.0 mg/L); uranium, up to 5 mg/L (limit is 0.5 mg/L); radium-226, up to 9.5 picocuries/L (limit is 5.0 picocuries/L). Background levels and preoperational levels of selenium, nitrate, and sulfate have also at times exceeded New Mexico Drinking Water Standards. Such variations and potential faults beneath the tailings piles have made it difficult to determine the extent of contamination. Homestake is attempting to mitigate the groundwater pollution by pumping contaminated alluvial groundwaters back to tailings ponds and injecting better quality waters into the alluvium (Pi81). Some monitoring wells show water quality deterioration while others show improvement (UNHP80). The monitoring program in a complex hydrogeologic setting is compounded by potential faults which makes an assessment of the situation exceptionally difficult.

D.9 Control of Toxic Materials to Groundwater

Monitoring investigations of the migration pathways from unlined mill tailings pond have determined that radionuclides and some of the toxic heavy metals are attenuated within a few feet of the tailing pond but that some toxic heavy metals are highly mobile and have contaminated the groundwater. The mobile species include molybdenum, selenium, chlorine, sulfate, nitrate, arsenic, lead, and vanadium. Under existing hydrogeologic conditions and the chemical makeup of the seepage from the tailings pond, this condition prevails unless protective controls are utilized. Controls that exist to prevent groundwater contamination include, (a) complete containment by impervious seals (clay or synthetic liners), and/or (b) altering the chemistry of tailings pond effluents.

Synthetic and clay liners were mentioned earlier and are probably the most positive long-term controls for containment of both the acid-leach and alkaline-leach process effluents in tailings ponds. The long-term stability of earthen materials or clay liners in contact with acid tailings solutions has been investigated by the Pacific Northwest Laboratory (PNL) under NRC contract (Pe82). The highly acid condition of the acid-leach tailings slurry (1.8 pH) leach some of the clay. The PNL laboratory investigation disclosed that materials containing over 30 percent clay showed a decrease in permeability with time (Pe82). Such findings, however, are limited to laboratory studies and do not ncessarily reflect long-term field conditions.

The decreases in permeability for a number of clay materials considered were attributed to pore plugging resulting from the precipitation of minerals and solids. X-ray diffraction and geochemical predictions confirm that gypsum, jarosite, and other minerals precipitate after the tailings solution reacts with the earth material comprising the liners (Pe82). To ensure that the initial permeability of the liner is minimized, the liner should be compacted to at least 90 percent of its maximum capacity as determined by a standard Proctor test (Pe82). A one-meter clay liner compacted with a calcium carbonate content of 4 percent or greater could be expected to impede the pH front advance into the surrounding geologic materials for hundreds of years and to neutralize the total acidity of a typical tailings pond (Pe82).

The concept of altering the chemistry of the uranium mill wastewater by precipitation to control the removal of toxic materials in tailings ponds has been investigated by the Environmental Protection Agency. This study was performed for both acid and alkaline waste streams and considered a number of processes. The most promising finding is the combining of acid waste streams with alkaline waste streams to precipitate metals that occur as anions (We80). Mobile metals, such as Mo and V, present in anionic form as molybdates and vanadates, are effectively removed from solution at a pH range of 5.8 to 6.1 achieved by mixing the acid and alkaline mill waste at a 5:3 ratio by volume (We80). Other metals largely removed at this pH include iron, aluminum, chromium, and nickel. However, few alkaline-process mills and acid-process mills are located close enough to accomplish this mixing.

A recent Pacific Northwest Laboratory investigation of the neutralization, fixation, and specific constituent removal methods for treatment of uranium mill wastes to mitigate groundwater contamination found the neutralization process to be the most effective (Sh83).

The fixation process adds materials to mill waste to produce physically stable compounds that resist leaching of hazardous materials, but this process is very expensive, not completely effective over tens of years, and substantially increases the volume and weight of the wastes. Specific constituent removal methods include ion exchange processes, selective precipitation, or alternate ore leaching processes that reduce specific concentrations in tailings solutions. To date, the only specific constituent removed is radium-226 by co-precipitation with $BaSO_4$ when $BaCl_2$ is added to the waste stream of the acid waste treatment process.

The neutralization process, by contrast to the fixation and specific constituent methods, limits the pollutants in the tailings solution at a reasonable cost. In this process, a combnation of limestone and lime added to the acid leach tailings waste adjusts the pH to 8.0; this pH constitutes the optimum level found for heavy metal removal (Sh83).

The neutralization process has been practiced by the Canadians with 90 percent reduction of dissolved solids and 99 percent reduction in radionuclides as compared to untreated U.S. tailings solutions. While Canadian tailings ponds after neutralization contain sulfate, nitrate, ammonia, and radium-226 in excess of water quality control standards, it is expected that any effluent discharged through the substrata to groundwater would attenuate or reduce these pollutants by natural processes of adsorption and precipitation.

Since the primary goal of groundwater protection is prevention of contaminant seepage into groundwater, it appears that reliance should be placed on synthetic liners or a combination of synthetic and clay liners. While laboratory studies by Pacific Northwest Laboratory show that permeability decreases in time with clay liners containing over 30 percent clay, complete reliance cannot be guaranteed for prototype conditions. Therefore, the state of the art for achievement of least migration of pollutants from mill tailings ponds appears to be the synthetic liners with adequate protection from physical rupture using protective clay layers.

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APPENDIX E

CURRENT ESTIMATED POPULATIONS NEAR ACTIVE URANIUM ORE PROCESSING SITES

Appendix E: Current Estimated Populations Near Active Uranium Ore Processing Sites

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Tables

APPENDIX E: CURRENT ESTIMATED POPULATIONS NEAR ACTIVE URANIUM ORE PROCESSING SITES

EPA contracted with Battelle Pacific Northwest Laboratories (PNL) to count the number of people living near existing tailings piles. PNL conducted these population counts during May and June 1983.

PNL obtained these data by visiting each site and counting the occupied dwellings out to 5 kilometers (km) from the center of the tailings pile. In some of the heavily populated areas, populations were estimated from census tract and block data, city zoning maps, information obtained from city planners, and direct observations of population densities. Census data (1980) on the average number of persons per household per county were used to translate dwelling counts to population.

Some difficulties were encountered in determining whether a habitable dwelling was occupied, as for instance, in houses "for sale" or seasonal houses. In these cases, PNL used their best judgment since they did not directly contact any householders. Also, PNL did not take any road labelled "no trespassing" or any private road; they relied on visual sitings from public roads.

The data are presented in the following tables in area segments as determined by annular rings and 16 compass points. The center of each pile is identified by its geographical coordinates (latitude and longitude) and is at the centroid of the tailings area. The radial distances of the annular rings are measured from the centroid.

Table E-1. Estimated Population Living Near the Tailings Pile at Canon City, Colorado, June 1983
(Latitude 38°23'46"; Longitude 105°13'45")
Total Population (0.0-5.0 km): 5933

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	5	935	1158
NNE	-	-	-	124	899	715
NE	-	-	-	39	715	303
ENE	-	-	-	-	88	52
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	5	-
S	-	-	-	-	3	8
SSW	-	-	-	-	-	-
SW	-	-	-	-	-	-
WSW	-	-	-	16	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	47
NNW	-	-	-	-	122	699
Total	-	-	-	184	2,767	2,982

- Indicates 0.

Table E-2. Estimated Population Living Near the Tailings Pile at Uravan, Colorado, June 1983
(Latitude 38°22'N.; Longitude 105°45'W.)
Total Population (0.0-5.0 km): 349

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	45	108	-	-	-
NNE	-	77	9	-	-	-
NE	-	-	-	-	-	-
ENE	-	11	-	-	-	-
E	-	14	28	-	-	-
ESE	-	-	-	6	3	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	48	-	-	-
Total	-	147	193	6	3	-

- Indicates 0.

Table E-3. Estimated Population Living Near the Tailings Pile at Ambrosia Lake, New Mexico, June 1983
(Latitude 35°23'39"N.; Longitude 107°49'47"W.)
Total Population (0.0-5.0 km): 1

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-		-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	1	-	-
Total	-	-	-	1	-	-

- Indicates 0.

Table E-4. Estimated Population Living Near the Tailings Pile at Bluewater, New Mexico, June 1983
(Latitude 35°16'12"N.; Longitude 107°56'44"W.)
Total Population (0.0-5.0 km): 907

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	6	-
SE	-	-	-	38	10	13
S	-	-	6	29	13	-
SSW	-	-	-	41	13	19
SW	-	-	-	6	171	-
WSW	-	-	-	16	418	-
W	-	-	-	3	16	-
WNW	-	-	-	3	19	54
NW	-	-	-	-	-	13
NNW	-	-	-	-	-	-
Total	-	-	6	136	666	99

- Indicates 0.

Table E-5. Estimated Population Living Near the Tailings Pile at Church Rock, New Mexico, June 1983
(Latitude 35°38'47"N.; Longitude 108°30'08"W.)
Total Population (0.0-5.0 km): 312

Direction	Radial Distance (km) 0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	7	-	-	-
NNE	-	-	-	-	15	-
NE	-	-	-	-	19	-
ENE	-	-	-	-	7	-
E	-	-	-	-	-	15
ESE	-	-	-	-	7	19
SE	-	-	-	4	11	19
SSE	-	-	7	4	4	22
S	-	-	-	-	-	41
SSW	-	-	-	15	22	19
SW	-	-	-	4	-	15
WSW	-	-	-	7	-	-
W	-	-	4	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	11	-	-
NNW	-	-	7	7	-	-
Total	-	-	25	52	85	150

- Indicates 0.

Table E-6. Estimated Population Living Near the Tailings Pile at Marquez, New Mexico, June 1983
(Latitude 35°18'59"N.; Longitude 107°16'28"W.)
Total Population (0.0-5.0 km): 15

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	-
W	-	-	-	15	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	-	15	-	-

- Indicates 0.

Table E-7. Estimated Population Living Near the Tailings Pile at Milan, New Mexico, June 1983
(Latitude 35°14'31"N.; Longitude 107°51'46"W.)
Total Population (0.0-5.0 km): 396

Direction	Radial Distance (km) 0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	3	-
ENE	-	-	-	-	-	-
E	-	-	3	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	3	-	-	-
S	-	-	51	22	-	-
SSW	-	-	67	16	29	41
SW	-	-	44	3	-	10
WSW	-	-	22	63	13	6
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	190	104	45	57

- Indicates 0.

Table E-8. Estimated Population Living Near the Tailings Pile at Seboyeta, New Mexico, June 1983
(Latitude 35°11'09"N.; Longitude 107°20'09"W.)
Total Population (0.0-5.0 km): 166

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	-	-
WSW	-	-	-	-	32	19
W	-	-	-	-	-	35
WNW	-	-	-	-	10	70
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	-	-	42	124

- Indicates 0.

Table E-9. Estimated Population Living Near the Tailings Pile at Edgemont, South Dakota, June 1983 (Latitude 43°17'43"N.; Longitude 103°48'46"W.) Total Population (0.0-5.0 km): 1,421

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	5	8	-	-
NNE	-	-	3	5	8	10
NE	-	-	-	3	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	3	3	-
SE	-	-	-	-	3	-
SSE	-	-	-	-	3	-
S	-	-	-	-	-	3
SSW	-	-	-	-	-	-
SW	-	-	20	-	3	5
WSW	3	-	63	-	-	-
W	18	20	306	58	-	-
WNW	10	18	612	94	8	-
NW	-	-	83	-	-	10
NNW	-	-	33	-	-	-
Total	31	38	1,125	171	28	28

- Indicates 0.

Table E-10. Estimated Population Living Near the Tailings Pile at Panna Maria, Texas, June 1983
(Latitude 28°57'33"N.; Longitude 97°56'31"W.)
Total Population (0.0-5.0 km): 453

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	3	-	-	9
NE	-	-	3	-	6	3
ENE	-	-	-	6	-	18
E	-	-	9	12	21	68
ESE	-	-	9	3	9	-
SE	-	-	6	-	-	3
SSE	-	6	-	-	-	-
S	-	6	9	-	-	6
SSW	-	-	3	-	6	24
SW	-	-	-	-	3	6
WSW	-	-	-	6	12	9
W	-	-	-	3	15	136
WNW	-	-	-	-	6	-
NW	-	-	-	3	3	-
NNW	-	-	-	-	-	3
Total	-	12	42	33	81	285

- Indicates 0.

Table E-11. Estimated Population Living Near the Tailings Pile at Falls City, Texas, June 1983
(Latitude 28°54'03"N.; Longitude 98°05'40"W.)
Total Population (0.0-5.0 km): 42

Direction	Radial Distance (km)					
	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	3	-	3
NE	-	-	-	3	6	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	3	3
SSE	-	-	-	-	-	6
S	-	-	-	-	-	6
SSW	-	-	-	-	-	-
SW	-	-	-	6	-	-
WSW	-	-	-	-	-	-
W	-	-	3	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	3	12	9	18

- Indicates 0.

Table E-12. **Estimated Population Living Near the Tailings Pile at Ray Point, Texas, June 1983**
(Latitude 28°31'11"N.; Longitude 98°06'05"W.)
Total Population (0.0-5.0 km): 130

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	3	9	6	14
NE	-	-	3	3	-	-
ENE	-	-	-	3	3	3
E	-	-	6	3	9	6
ESE	-	-	9	-	6	-
SE	-	-	-	-	3	-
SSE	-	-	-	3	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	3	35
WSW	-	-	-	-	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	21	21	30	58

- Indicates 0.

Table E-13. Estimated Population Living Near the Tailings Pile at Blanding, Utah, June 1983
(Latitude 37°31'37"N., Longitude 109°30'33"W.)
Total Population (0.0-5.0 km): 8

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	4
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	4
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	-	-	-	8

- Indicates 0.

Table E-14. Estimated Population Living Near the Tailings Pile at Rio Algom Site, La Sal, Utah, June 1983
(Latitude 38°16'N.; Longitude 109°16'30"W.)
Total Population (0.0-5.0 km): 343

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	53	85	12	-
NNE	-	8	28	57	-	40
NE	-	-	4	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	4	-
NW	-	-	-	-	-	4
NNW	-	-	20	12	16	-
Total	-	8	105	154	32	44

- Indicates 0.

Table E-15. Estimated Population Living Near the Tailings Pile at Moab, Utah, June 1983
(Latitude 38°35'59"N.; Longitude 109°35'44"W.)
Total Population (0.0-5.0 km): 2361

Direction	Radial Distance (km) 0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	6	-	-	-
E	-	-	3	3	-	-
ESE	-	-	-	9	674	668
SE	-	-	-	-	420	557
SSE	-	-	-	-	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	21	-	-
NNW	-	-	-	-	-	-
Total	-	-	9	33	1094	1225

- Indicates 0.

Table E-16. Estimated Population Living Near the Tailings Pile at Hanksville, Utah, June 1983
(Latitude 37°43'06"N.; Longitude 110°40'51"W.)
Total Population (0.0-5.0 km): 171

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	171
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	-	-	-	171

- Indicates 0.

Table E-17. Estimated Population Living Near the Tailings Pile at Dawn Mill, Ford, Washington, June 1983
(Latitude 47°54'06"N.; Longitude 117°49'58"W.)
Total Population (0.0-5.0 km): 411

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	20	12	15	-
NNE	-	-	20	3	6	-
NE	-	-	15	12	20	12
ENE	-	-	29	29	6	-
E	-	3	-	-	-	-
ESE	-	-	-	-	-	3
SE	-	-	-	-	3	35
SSE	-	-	-	-	-	-
S	-	-	-	3	3	3
SSW	-	-	-	-	9	-
SW	-	-	-	-	3	3
WSW	-	-	-	3	15	-
W	-	-	-	58	6	3
WNW	-	-	-	23	-	-
NW	-	-	-	3	-	-
NNW	-	-	9	12	-	-
Total	-	3	93	157	96	62

- Indicates 0.

Table E-18. Estimated Population Living Near the Tailings Pile at Wellpinit, Washington, June 1983 (Latitude 47°52'27"N.; Longitude 118°07'00"W.) Total Population (0.0-5.0 km): 49

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	3	6
SE	-	-	-	-	3	-
SSE	-	-	-	-	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	3
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	3
W	-	-	-	-	26	-
WNW	-	-	-	-	-	5
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	-	-	32	17

- Indicates 0.

Table E-19. Estimated Population Living Near the Tailings Pile at Powder River, Converse County, Wyoming, June 1983
(Latitude 43°05'N.; Longitude 105°30'W.)
Total Population (0.0-5.0 km): 6

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	6	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	-	-	6	-

- Indicates 0.

Table E-20. Estimated Population Living Near the Tailings Pile at Gas Hills, (Federal American Partners) Fremont County, Wyoming, June 1983 (Latitude 42°47'59"N.; Longitude 107°30'08"W.) Total Population (0.0-5.0 km): 0

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	-	-	-	-

- Indicates 0.

Table E-21. Estimated Population Living Near the Tailings Pile at Red Desert, Sweetwater County, Wyoming, June 1983 (Latitude 42°02'56"N.; Longitude 107°53'28"W.) Total Population (0.0-5.0 km): 0

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	-	-	-	-

\- Indicates 0.

Table E-22. Estimated Population Living Near the Tailings Pile (Pathfinder Mines) at Gas Hills, Fremont County, Wyoming, June 1983
(Latitude 42°49'55"N., Longitude 107°29'23"W.)
Total Population (0.0-5.0 km): 0

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	-	-	-	-

- Indicates 0.

Table E-23. **Estimated Population Living Near the Tailings Pile (Pathfinder) at Shirley Basin, Carbon County, Wyoming, June 1983**
(Latitude 42°20'N.; Longitude 106°12'W.)
Total Population (0.0-5.0 km): 0

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	*
S	-	-	-	-	*	*
SSW	-	-	-	-	*	*
SW	-	-	-	-	*	*
WSW	-	-	-	-	-	*
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	-	-	-	-

- Indicates 0.
* Area covered by intersecting Petrotomics Shirley Basin Mill to the South.

Table E-24. Estimated Population Living Near the Tailings Pile (Petrotomics) at Shirley Basin, Carbon County, Wyoming, June 1983 (Latitude 42°20'N.; Longitude 106°12'W.) Total Population (0.0-5.0 km): 357

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	*	*
NNE	-	-	-	-	*	*
NE	-	-	-	-	*	*
ENE	-	-	-	-	-	*
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	-
S	-	-	-	-	178	-
SSW	-	-	-	-	179	-
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	-	-	357	-

- Indicates 0.
* Area covered by intersecting Pathfinder Shirley Basin Mill to the North.

Table E-25. Estimated Population Living Near the Tailings Pile (Rocky Mountain Energy) at Powder River, Converse County, Wyoming, June 1983
(Latitude 43°16'N.; Longitude 105°37'W.)
Total Population (0.0-5.0 km): 0

Direction	Radial Distance (km) 0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	-	-	-	-

- Indicates 0.

Table E-26. Estimated Population Living Near the Tailings Pile at UCC-Gas Hills, Natrona County, Wyoming, June 1983 (Latitude 42°49'45"N.; Longitude 107°29'34"W.) Total Population (0.0-5.0 km): 0

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	-	-	-	-	-
SE	-	-	-	-	-	-
SSE	-	-	-	-	-	-
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	-	-
WSW	-	-	-	-	-	-
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	-	-	-
NNW	-	-	-	-	-	-
Total	-	-	-	-	-	-

- Indicates 0.

Table E-27. Estimated Population Living Near the Tailings Pile at Jeffrey City, Fremont County, Wyoming, June 1983 (Latitude 42°30'32"N.; Longitude 107°47'14"W.) Total Population (0.0-5.0 km): 906

	Radial Distance (km)					
Direction	0.0-0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-4.0	4.0-5.0
N	-	-	-	-	-	-
NNE	-	-	-	-	-	-
NE	-	-	-	-	-	-
ENE	-	-	-	-	-	-
E	-	-	-	-	-	-
ESE	-	3	-	-	-	-
SE	-	-	-	21	6	-
SSE	-	-	-	3	-	9
S	-	-	-	-	-	-
SSW	-	-	-	-	-	-
SW	-	-	-	-	140	-
WSW	-	-	-	-	551	167
-						
W	-	-	-	-	-	-
WNW	-	-	-	-	-	-
NW	-	-	-	3	-	-
NNW	-	-	-	3	-	-
Total	-	3	-	30	697	176

- Indicates 0.

APPENDIX F

OTHER MINERAL RESOURCES

IN URANIUM MINING REGIONS

APPENDIX F

OTHER MINERAL RESOURCES IN URANIUM MINING REGIONS

CONTENTS

APPENDIX F

OTHER MINERAL RESOURCES IN URANIUM MINING REGIONS

F.1 Summary and Conclusions

Many uncertainties are associated with predicting the continued isolation of mill tailings piles that are now seemingly remote. Estimates regarding the continued isolation of uranium mill tailings sites are obviously speculative and will, therefore, provide only rough estimates to address the issue.

By the beginning of the twenty-first century, we estimate that mill tailings piles will be about three times as large as the 1982 volumes. Possibly one-third of the sites will be relatively isolated. Fevelopment of other mineral resources on or near the sites will affect population growth and the degree to which the sites are isolated.

Metal resources that have potential development are those that are mined as coproducts or byproducts of sedimentary uranium deposits, such as vanadium and molybdenum. Vanadium resources are associated with uranium production in the Colorado Plateau resource region. The volume of vanadium ore mined at some of the current uranium mill sites as a coproduct or byproduct is five times the volume of uranium ore. Any increased demand for vanadium and molybdenum could reactivate existing mills or result in development of these resources near existing uranium mills.

Other metals such as copper, cobalt, nickel, tungsten, lead, zinc, silver, and gold also occur within the uranium resource regions and constitute potential resources that could affect population increases to the region.

The Wyoming Basins and the Western Gulf Coastal Plain resource regions contain fossil fuels, generally at greater depth, but within the sedimentary rock sequence containing the uranium ore. Development of coal, oil, and gas resources could affect population growth and the degree of isolation of the tailings piles in these areas.

Potential solar energy expansion in the sun belt and increased tourist and recreational facilities also influence the potential isolation of the uranium tailings.

F.2. Introduction

The purpose of this review is to focus on the probable mineral developments that could occur in the future near the 27 uranium mill tailings sites considered in this report. Qualitative judgments will be based on (a) known reserves of other minerals in the area, (b) probable mineral resources, based on reconnaissance information and geologic setting, (c) the possibility of reactivating those uranium mills that have closed or will close in the next few decades. The effect of recreational or national park growth on the isolation of the sites is also an important consideration but will not be part of the qualitative judgement made regarding future minerals development near the uranium mill sites. The likelihood of future minerals development at each of the 27 uranium mills tailings sites is summarized in Table F-1. The qualitative rating assigned will be considered in the following sections.

The uranium milss being considered are listed in Table F-1 in relation to their location within the uranium resource regions defined by the Department of Energy (DOE80). This DOE classification is based on geologic and physiographic characteristics and will simplify discussions regarding other possible mineral development near the uranium mill sites.

F.3 Uranium Resources

The Colorado Plateau resource region contains most of the uranium produced in the United States (DOE80). This region contains the Morrison Formation of Jurassic age in the Grants Mineral Belt of New Mexico and Uravan Mineral Belt of Utah and Colorado and the Chinli Formation of Triassic age in Utah and Arizona. The uranium ore occurs in fluvial, lenticular, cross-bedded, quartzose, or arkosic sandstones associated with vanadium deposits which today are mined as a byproduct with the uranium ore.The sandstones containing the uranium deposits are interbedded with mudstones. The uranium deposits are believed to be transported by groundwater as a leachate from granitic rocks or volcanic rock exposed along the margins of the sedimentary basins to the deposition site. Precipitation of the uranium into the pore spaces of the sandstone probably occurred under reducing conditions.

The uranium deposits of the Wyoming Basins, Colorado and Southern Rockies, Great Plains, and Western Gulf Coastal Plain Resource Regions are similar to the Colorado Plateau resource region in being contained in sedimentary sandstone formations. The uranium deposits of the Columbia Plateau resource region are vein type deposits in fissures of the crystalline bedrock from a primary source rock of nearby Cretaceous plutons from the resource regions.

The production of uranium ore from the uranium resource regions will depend on the use of nuclear power as an energy source in the future. At the very least, uranium will be needed to fuel existing reactors until the end of their lives. Thus, it is likely that the uranium industry will recover somewhat from its currently depressed condition. While it is difficult to project the relative contributions the United States and other uranium producing nations will make to the demand, it is reasonable to predict a continuing role for the U.S. uranium industry because of the political stability and proven ability of the United States to produce uranium (Na83). In this light, the reactivation potential of existing uranium mills for uranium or uranium byproducts is considered reasonable for all the uranium mill sites except the skeletonized or removed mills at Edgemont, South Dakota, and Ray Point, Texas (Table F-1).

F.4. Vanadium Resources

The Colorado Plateau region and the Colorado and Southern Rockies resource regions are the largest producers of vanadium in the United States. In 1980, Colorado was the leading producer of vanadium, with Utah second, and New Mexico fifth. Colorado vanadium is largely a coproduct or byproduct of uranium production; it averages about 5 pounds of vanadium oxide for each pound of uranium oxide (BM80).

In 1980 vanadium was produced at uranium mills in Canon City and Uravan, Colorado, and at uranium mills in Moab and Blanding, Utah (Table F-1). In New Mexico, vanadium production, although small, doubled in value and almost doubled in quantity; the vanadium was recovered as a byproduct of uranium output from uranium-vanadium ores mined in McKinley County (BM80).

With the increased demand for vanadium in high-strength low-alloy steels and superalloys by the aerospace industry and other applications, the production of vanadium may possibly increase in the long term. Uranium mills in which vanadium was previously a byproduct may be reactivated, and more Colorado Plateau sites in the Morrison Formation could also be developed. The long-term effect on population growth will tend to decrease the isolation of mill tailings piles.

F.5. Molybdenum Resources

The Climax and Henderson, Colorado, mines and the Questa, New Mexico, mine produced 70 percent of the total output of molybdenum in the United States in 1980 (BM80). Most of the remainder was supplied as a byproduct or coproduct of copper mining. A small amount, less than 0.3 percent, was produced as a byproduct from uranium ore at the Ambrosia Lake uranium mill in the Grants Mineral Belt, McKinley County, New Mexico. Molybdenum production as a byproduct is also a potential consideration for some of the other uranium mills in Utah and Colorado.

Molybdenum is one of the metal ores that has potential resource development near the two uranium mills at Ford, Washington (Dawn Mining Company), and Wellpinit, Washington (Western Nuclear Corporation), in the Columbia Plateau Resource Region.

Molybdenum consumption and uses have gradually increased despite fluctuations over the last 25 years, and the demand for molybdenum is expected to continue in the long term.

F.6. Fossil Fuel Resources

F.6.1 Wyoming Basins

The Wyoming Basins contain thick sedimentary rock units that contain considerable reserves of oil, gas, and coal deposits (DOE82a, DOE82b). The basins were formed in Cretaceous time, and continental deposits of Tertiary age were deposited on Paleozoic and Mesozoic sedimentary rock units. The fossil fuel resources occur within the same vertical sequence of sedimentary formations as the uranium deposits but from older geologic formations of greater depth.

F.6.1.1 Powder River Basin

The Rocky Mountain Energy and Exxon uranium mill sites are located in the Powder River Basin in Converse County, Wyoming. Oil and gas are produced from Cretaceous sandstones located a few thousand feet below the uranium-bearing Fort Union Formation of Tertiary age. Coal is produced from the Fort Union and Wasatch Formation of Tertiary age.

Coal production is limited to one mine which fuels the Pacific Power and Light Company power plant. The 3.5 million tons of coal mined annually in Converse County is minor compared to that of Campbell County (71 m tons), Sweetwater County (21 m tons), Carbon County (8 m tons), and Lincoln County (5 m tons) (DOE82a). Although current use of coal is low in Converse County, the mere fact that it has been developed can lead to additional development and increasing population.

Oil and gas production in the Powder River Basin, however, is significant with production in billions of barrels and with the likely discoveries of large deposits in yet unexplored areas (NRC77). Oil is produced about one mile east of the Rocky Mountain Energy Company uranium mill. The population may increase with the growth of the oil and gas production in this area.

F.6.1.2 Great Divide Basin

The Red Desert Uranium Mill of the Minerals Exploration Company is located in the Great Divide Basin in Sweetwater County, Wyoming. Coal reserves of this county are estimated at 700 million tons; however, the deposits are low grade, high sulfur, subbituminous coal (NRC78). The closest active coal mines are 50 miles away. Oil and gas production is active in the area with the Bison Basin oil field 20 miles northwest and the Siberian Ridge gas field 15 miles south (NRC78).

While development of fossil fuel resources in this basin is not expected to proceed as rapidly as in other Wyoming basins because of the quality or quantity of the deposits, it is expected that in the long term the tailings piles will be less isolated as a result of oil, gas, and coal production.

F.6.1.3 Shirley Basin

The Pathfinder Mines Mill and Petrotomics Mill are located in the Shirley Basin in Carbon County, Wyoming. The areas surrounding these sites are generally large ranch areas and are sparsely populated.

Coal production in Carbon County in 1981 ranked third in the State of Wyoming with 39 million tons of bituminous coal and 2.2 billion tons of subbituminous coal (DOE82a). Seven active mines in the county had a production of 8.6 million tons in 1981. The coal production anticipated in the long term could be expected to increase the population in this region and decrease the isolation of the tailings piles.

F.6.1.4 Wind River Basin (Gas Hills)

The Union Carbide Corporation, Pathfinder Mines, Western Nuclear, and Federal American uranium mills are located in the Gas Hills region of the Wind River Basin. Mesozoic and Paleozoic formations are important gas and oil producers in this portion of the Wind River Basin (NRC77). Oil reserves in Fremont County, where three mill sites are located, are estimated to be about 60 x 10^6 bbl, but it is anticipated that oil production will continue to slowly decline; natural gas production, however, is expected to increase (NRC80).

Coal is no longer being mined in the Gas Hills area, and the 733 x 10^6 tons of subbituminous grade coal in Fremont County are not strippable (NRC80). Coal production is, therefore, not considered a viable economic potential for this part of the basin in the future.

F.6.2. Western Gulf Coastal Plain

The Falls City, Ray Point, and Panna Maria uranium mills are located in the Western Gulf Coastal Plain of Texas, a region underlain by thick sedimentary rock units ranging from Triassic to Tertiary in age. Limited oil and gas reserves in this relatively dense rural area are not expected to change the population density significantly in the long term.

F.7. Other Mineral Resources

The ten-year National Uranium Resource Evaluation (NURE) program for uranium exploration was completed this year by the Department of Energy. This program, in addition to searching for uranium concentrations, reported on elements that are associated with uranium and serve as indicators of uranium concentrations. These elements included molybdenum, sulphur, lead, arsenic, vanadium, zinc, copper, nickel, and cobalt, while other elements such as gold, silver, tin, and tungsten, also tested for, were analyzed for their own worth (Bo80). If mineral resources near uranium sites are developed, the isolation of tailings piles could be affected.

The Colorado Plateau and Colorado and Southern Rockies resource regions contain areas of potential mineral resources. The uranium mills at Blanding and Moab, Utah, currently produce copper as a byproduct material (BM80).

The two uranium mills in the Columbia Plateau resource region are in a mineralized area containing potential tungsten, molybdenum, silver, copper, lead, and zinc resources. This area is currently being explored for its resource potential.

In the Laramide Range to the west of the two uranium mills in the Powder River Basin, Wyoming, there are indications of potential for mineral production. Copper, chromium, iron, tungsten, asbestos, and vermiculite deposits are reported from Pre-Cambrian rocks in the Laramide Range, as well as traces of gold, silver, beryl, zinc, bismuth, and rare earths, but the magnitude of these deposits has not been determined (NRC78).

Wyoming ranked first in the nation in 1980 for production of trona (sodium carbonate) and bentonite clay and fourth in production of iron ore, and most of these resources are located in two of the counties containing uranium mills (BM80). However, these resources probably will have no influence on the degree of isolation of the tailings piles at these mills, because of the large size of the counties and the locations of these resources at appreciable distances from the uranium mills.

F.8. Recreational and Other Activities

Recreational activities and tourism in the scenic West will undoubtedly affect the isolation of some of the uranium mill tailings piles. Three of the mill sites are located in scenic southeastern Utah and one is near the Black Hills area.

The Hanksville, Utah (Plateau Resources), uranium mill is located a few miles from Lake Powell, a manmade lake on the Colorado River in southeastern Utah (NRC79). In addition to this recreational area, the Arches National Park, Canyonlands National Park, Natural Bridges National Monument, and other unusual and historic sites of this area threaten the isolation of tailings piles at La Sal, Utah (Rio Algom Corporation), and Moab, Utah (Atlas Minerals), in the long term. At the Edgemont, South Dakota (TVA), mill site, the growth of that town could conceivably double by the mid-1980's as a result of its location near the Black Hills (NRC81).

F.9. Factors Relating to Mineral Production

The long term isolation of mill tailings piles depends on the population growth of the region. An important factor controlling population growth is the development of other mineral resources in uranium mining regions.

The uranium mills may be reactivated by demands for uranium or the metal coproducts or byproducts mined with uranium. The demand for molybdenum and vanadium could activate at least four of the uranium mills. Exploration discoveries of molybdenum, vanadium, and other metals in the geologic formations of these regions could also result in future production of mineral resources at or near these mill sites.

Coal production in Wyoming was more than 12 percent of the U.S. production by tonnage in 1981 (DOE82a). Coal reserves in the Wyoming Basins are extensive, and Sweetwater and Carbon counties rank second and third in coal production. The population near the tailings piles in these counties will undoubtedly increase in the long term as a result of expanding mining activities. Coal production in Converse County (Powder River Basin) is limited to that needed by a local utility. While production is expected to remain restricted to that use in the near term, the abundance of low grade coal could become a resource of production in the long term.

Gas and oil production is expected to increase in the Powder River Basin, Great Divide Basin, and the Wind River Basin (Gas Hills) in the future. While production of this resource moves less population into a region than coal mining or mining of metals, the activities and production of gas and oil will contribute to the reduction of the degree of isolation of uranium tailings piles.

The NURE program has included testing for other metals in addition to uranium, and other potential metal resources are known in the resource regions listed in Table F-1. The region surrounding the two Washington mills and the Laramide Range adjacent to Wyoming mill sites are examples of potential production of these metals should further exploration prove their potential.

The southeastern Utah area and Black Hills area may become less isolated because of recreational and scenic attractions. As solar power becomes established, these arid sites may become less isolated.

The foregoing factors suggest that mineral production is highly probable in the future. The likelihood of future mineral production at the 27 uranium mill sites is qualitatively assessed in Table F-1.

Table F-1. Potential Resource Development Near Currently Licensed Uranium Mills

Location/ Owner	Pontential reactivation of mill	Resource Development: Fossil fuels: Oil & Gas	Fossil fuels: Coal	Metals[a]: V	Metals[a]: Mo	Metals[a]: Other	Other activities[b]	Likelihood of Future Minerals Development
			Colorado Plateau Resource Region					
New Mexico								
Ambrosia Lake (Kerr-McGee Nuclear)	X	-	-	-	X	-	-	High
Bluewater (Anaconda Minerals Co.)	-	-	-	-	-	-	-	Low
Church Rock (United Nuclear Co.)	X	-	-	-	-	-	-	Low
Marquez (Bokum Resources)	X	-	-	-	-	-	-	Low
Milan (Homestake Mining)	X	-	-	-	-	-	-	Low
Seboyeta (Sohio-Reserve)	X	-	-	-	-	-	-	Low
Utah								
Blanding (Energy Fuels Nuclear)	X	-	-	X	-	X	-	High
Utah								
Hanksville (Plateau Resources)	X	-	-	X	-	-	X	High
Moab (Atlas Minerals)	X	-	-	X	X	X	X	High
La Sal (Rio Algom Corporation)	X	-	-	X	-	-	X	High

See footnotes at end of table.

Table F-1. Potential Resource Development
Near Currently Licensed Uranium Mills
(Continued)

Location/ Owner	Pontential reactivation of mill	Resource Development: Fossil fuels: Oil & Gas	Coal	Metals[a]: V	Mo	Other	Other activities[b]	Likelihood of Future Minerals Development
Colorado								
Uravan (Union Carbide Corporation)	X	-	-	X	-	-	-	High
		Colorado and Southern Rockies Resource Region						
Canon City (Cotter Corporation)	X	-	-	X	X	-	-	High
		Wyoming Basins Resource Region						
Wyoming								
Gas Hills (Pathfinder Mines)	X	X	-	-	-	-	-	High
Gas Hills (Union Carbide)	X	X	-	-	-	-	-	High
Wyoming								
Gas Hills (Federal-American Partners)	X	X	-	-	-	-	-	Medium
Jeffrey City (Western Nuclear)	X	X	-	-	-	-	-	Medium
Powder River (Rocky Mountain Energy)	X	X	X	-	-	X	-	High
Powder River (Exxon Minerals)	X	X	X	-	-	X	-	High
Red Desert (Minerals Exploration Company)	X	X	X	-	-	-	-	High

See footnotes at end of table.

Table F-1. Potential Resource Development Near Currently Licensed Uranium Mills (Continued)

Location/ Owner	Pontential reactivation of mill	Resource Development: Fossil fuels: Oil & Gas	Coal	Metals[a]: V	Mo	Other	Other activities[b]	Likelihood of Future Minerals Development
Shirley Basin (Pathfinder Mines)	X	-	X	-	-	-	-	High
Shirley Basin (Petrotomics)	X	-	X	-	-	-	-	High
			Great Plains Resource Region					
South Dakota								
Edgemont (Tennessee Valley Authority)	-	-	-	-	-	-	X	Low
			Western Gulf Coastal Plain Resource Region					
Texas								
Falls City (Conoco-Pioneer Nuclear)	X	X	-	-	-	-	-	Medium
Panna Maria (Chevron Resources)	X	X	-	-	-	-	-	Medium
Ray Point (Exxon (Susquehanna-Western))	-	X	-	-	-	-	-	Medium
			Columbia Plateau Resource Region					
Washington								
Ford (Dawn Mining Company)	X	-	-	-	X	X	-	Medium
Wellpinit (Western Nuclear)	X	-	-	-	X	X	-	Medium

(a) V = Vanadium; Mo = Molybdenum; Other = copper, gold, silver, tungsten, cobalt, nickel, lead, and zinc.
(b) Other activities include recreational and tourist establishments.

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APPENDIX G

THORIUM MILL TAILINGS

APPENDIX G

THORIUM MILL TAILINGS

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TABLES

FIGURES

Appendix G: THORIUM MILL TAILINGS

G.1 Introduction

This Appendix discusses the potential pathways and health effécts which might be connected with thorium tailings piles. As noted in Chapter 1, there are no large scale commercial thorium milling operations now in existence, and there appears to be little potential for future growth. Existing locations at which thorium byproduct materials are present vary widely in nature and are not susceptible to generic analysis. In addition, the ores have a wide range of thorium content and may contain substantial amounts of thorium-232. All these considerations make it difficult to define a "model" mill in the sense of the uranium mill described in Chapter 4. Any analysis would be extremely sensitive, for example, to the thorium content of the tailings pile since its long half-life (14.1 billion years) would pose a threat over extremely long periods as compared to its decay products which are short-lived and essentially decay to negligible levels in about 35 years.

Thorium is found primarily in monazite ore which is an anhydrous phosphate of the rare earths. Cerium and lanthanum oxides are generally found in greatest abundance in monazite. Thorium oxide in monazite is highly variable, ranging between 3 and 10 percent, but as much as 31 percent has been reported (Me79, Dr58, Be59).

A description of a monazite processing method is included in Kerr-McGee's "Stabilization Plan-License #STA583-West Chicago, Illinois" (Ke79). The ore was ground and reacted with excess caustic soda to separate the phosphate from the rare earths. Selective dissolution with hydrochloric acid allowed separation of the thorium from the rare earths. The rare earths were processed through solvent extraction and, selectively, ion exchange. The thorium fraction, along with some rare earths not requiring high purity, were processed through a series of chemical steps using caustic soda, and chloride, fluoride, and nitrate treatments. Further treatment was also given to produce oxides of rare earths.

In order to afford a direct comparison between uranium and thorium tailings, we have elected to use as a base case a thorium tailings pile which has physical characteristics similiar to those of the model mill described in Chapter 4. Instances in which different physical parameters are used are noted below.

G.2 Tailings Piles

Due to the diversity in thorium ores, content, and the purpose for which it was processed, it is difficult to postulate a standard configuration for a thorium mill tailings pile. However, if thorium is to be mined commercially on a large scale, the milling processes should be similiar to those involved in uranium milling. Most of the thorium would be extracted, and the tailings pile would be comprised predominantly of the radioactive decay products of the thorium series. Figure G-1 depicts the decay chain for this series. There are many points of similiarity between the uranium and thorium series: both are long-lived, naturally-occuring radionuclides; each, at one point in the decay chain, produces a gaseous isotope of radon; the decay products of both emit gamma radiation; and the decay products in both chains are isotopes of the same chemical elements. The major difference between the two series, from a radiological point of view, is the relatively short half-lives of the decay products of the thorium series as compared to those of the uranium series. Thus, as may be seen by comparing Figures 3-2 and G-1, the hazard presented by thorium tailings would be of much shorter duration if the thorium-232 content were small.

To make a direct comparison between uranium and thorium tailings, we have assumed a thorium pile with the same basic specifications as those given in Chapter 4 for the model uranium mill. The specifications required for the thorium analysis are primarily those regarding the meteorology and physical charateristics of the pile; this does not represent a composite of existing thorium piles, most of which are smaller, have higher decay product concentrations, and retain appreciable amounts of thorium. Radiological differences occasioned by the behaviour of thorium and its decay products are discussed in the following sections. Since the chemical elements in the thorium series are identical to those in the uranium series, nonradiological considerations would be similar to those discussed in the text.

G.3 Thoron and its Immediate Decay Products

One of the decay prducts in the thorium series is a gaseous isotope of radon, radon-220, usually referred to as thoron to distinguish it from the radon-222 of the uranium series. Since the thoron is also a chemically inert gas, it can diffuse through the tailings pile and be transported, with its decay products, through the atmosphere. While the transport and decay processes are roughly analogous to those of radon, the short half-lives of thoron (55.6 seconds) and its precursor, radium-224 (3.62 days) significantly affect the nature of these processes.

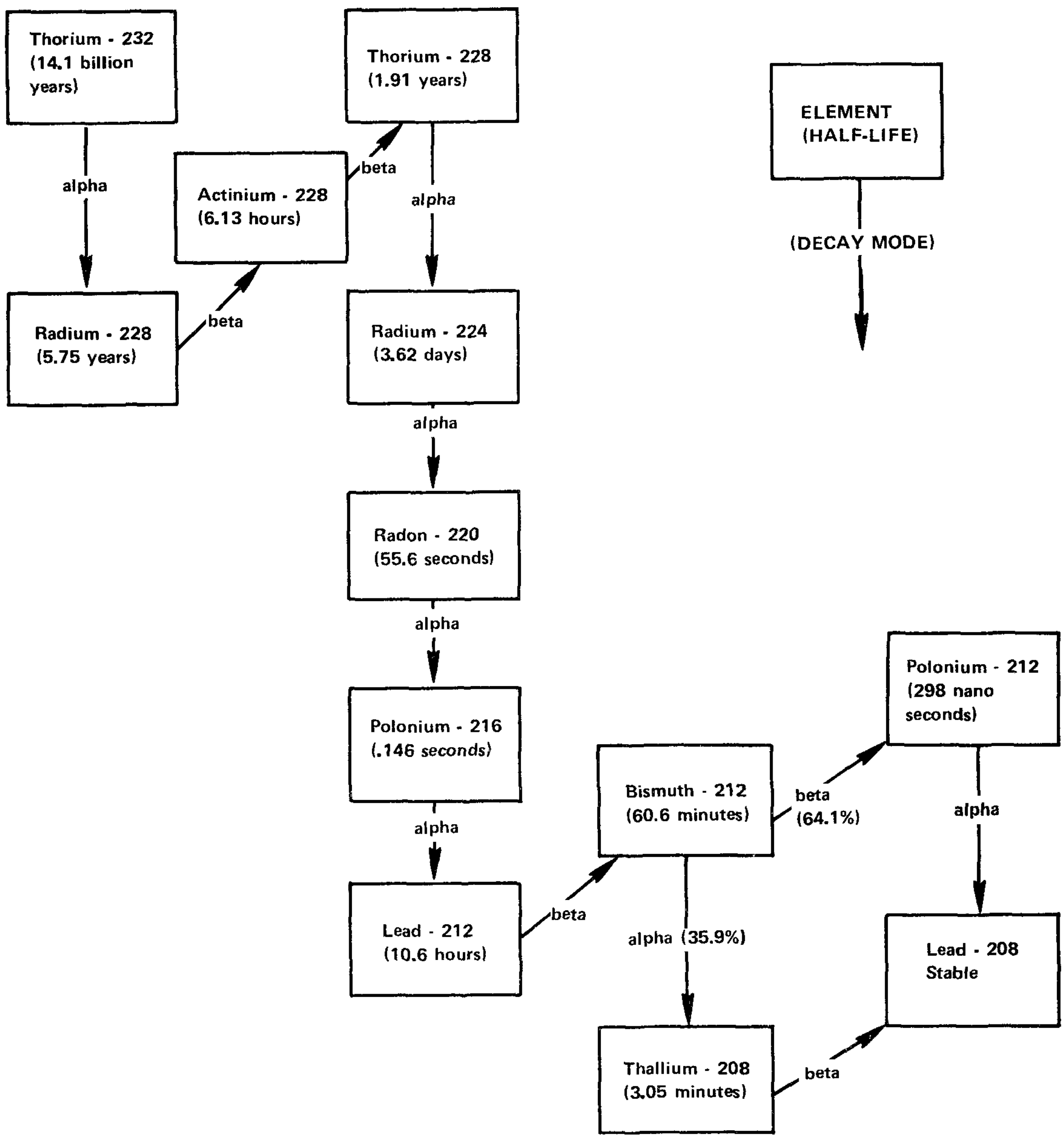

Figure G-1. Thorium-232 Decay Series.

A general expression for the thoron (or radon) source term (Ro81) is

$$Q = R \rho_b E \lambda$$

where

R = radium-224 content (pCi/g)
ρ_b = bulk density (g/m^3)
E = emanating power
λ = decay constant for thoron

Since the same equation holds for radon ($\lambda = 2.1 \times 10^{-6}$/sec), the thoron ($\lambda = 1.25 \times 10^{-2}$/sec) production rate will be in the same ratio as the decay constants or nearly 6,000 times larger, for the same radium density, than that for radon. The higher thoron production rate is, however, offset by its shorter half-life since, once the thoron has decayed, it no longer migrates freely through the tailings or cover material. For example, the thoron flux at the surface of a bare tailings pile containing 280 pCi/g of radium-224 is about 21,600 pCi/m^2s rather than the 280 pCi/m^2s of radon for the same radium-226 density. The analytical techniques described in Section 8.3.1 may also be used to determine the thickness of an earthen cover required to attenuate the thoron flux. Based on the nominal thoron flux value given above, some typical thoron reduction thicknesses are shown in Table G-1.

Table G-1. Estimated Cover Thickness (in meters) to Reduce Thoron Emissions to 20 pCi/m^2s

Thoron Emission from Tailings	Percent Moisture Content of Cover			
(pCi/m^2s)	6	8	10	12
10,000	0.0826	0.0637	0.0491	0.0379
20,000	.0918	.0708	.0546	.0421
30,000	.0972	.0750	.0578	.0446
40,000	.1010	.0779	.0601	.0463

The epidemiology and dosimetry of thoron and its decay products have recently been reviewed by the International Commission on Radiological Protection (ICRP81). They concluded that, because of the short half-life of thoron and its first decay product, the radiation hazard from the short lived progeny of thoron is normally well represented by the potential alpha energy exposure of lead-212 and bismuth-212. Based on this conclusion, the effective dose equivalent for the thoron decay products is about one-third that of the short-lived radon decay products.

Effects of Thoron Emissions from Tailings Piles

Regional air concentrations for thoron and its decay products due to atmospheric transport are shown in Table G-2 (ground surface concentrations are in Table G-3). These were calculated using the computer programs described in Chapter 5 and assuming the same meteorology and physical characterictics described for the operational phase of the model mill in Chapter 4. The source term is based on a thoron surface flux, as given above, of 21,600 pCi/m^2s which yields a total emission rate of $3.39x10^5$ Ci/y (see Table G-4) from the bare tailings pile. The calculated health impact for airborne thoron and its decay products is shown in Table G-5. These risks are calculated on the same basis as those described in Chapter 6. The risk due to windblown tailings material has not been included in this table since no information is available regarding possible particle size distributions.

Table G-2. Regional Air Concentration (Ci/m^3) for Radionuclides[(a)]

Distance (meters)	^{220}Rn Average	^{220}Rn Maximum	^{212}Pb, ^{212}Bi Average	^{212}Pb, ^{212}Bi Maximum	^{208}Tl Average	^{208}Tl Maximum
600	7.2E-9	1.5E-8	1.2E-10	2.0E-10	4.4E-11	7.1E-11
1000	1.1E-9	2.7E-9	4.2E-11	7.4E-11	1.5E-11	2.7E-11
2000	4.2E-11	1.2E-10	1.2E-11	2.5E-11	4.3E-12	8.9E-12
3000	2.6E-12	7.8E-12	5.9E-12	1.2E-11	2.1E-12	4.5E-12
4000	2.2E-13	6.6E-13	3.7E-12	7.9E-12	1.3E-12	2.8E-12
5000	2.1E-14	6.2E-14	2.6E-12	5.5E-12	9.3E-13	2.0E-12
10000	2.7E-19	8.3E-19	8.0E-13	1.7E-12	2.9E-13	6.2E-13
20000	1.5E-28	4.6E-28	2.7E-13	5.9E-13	9.6E-14	2.1E-13

(a) Average: value averaged over all directions.
Maximum: value for direction of greatest risk.

Effects of Ground Deposited Decay Products of Thoron

Although the half-lives in the thoron series are shorter than those of the uranium series, there is still a potential for ground deposition and buildup of the thorium decay products. Regional ground concentrations of these isotopes due to airborne deposition are given in Table G-3. The corresponding health impact is included in Table G-5 which contains the external irradiation hazard due to both ground deposition and airborne material. The ingestion pathway has been omitted since it is negligible compared to the external pathway. No attempt has

Table G-3. Regional Ground Surface Concentrations (Ci/m^2) for Radionuclides[(a)]

Distance (meters)	^{212}Pb Average	^{212}Pb Maximum	^{212}Bi Average	^{212}Bi Maximum	^{208}Tl Average	^{208}Tl Maximum
600	1.3E-8	2.0E-8	1.4E-8	2.2E-8	4.9E-9	8.0E-9
1000	4.4E-9	7.8E-9	4.8E-9	8.5E-9	1.7E-9	3.1E-9
2000	1.3E-9	2.7E-9	1.4E-9	2.9E-9	5.2E-10	1.1E-9
3000	6.6E-10	1.4E-9	7.1E-10	1.5E-9	2.6E-10	5.5E-10
4000	4.2E-10	9.0E-10	4.6E-10	9.8E-10	1.6E-10	3.5E-10
5000	3.0E-10	6.4E-10	3.2E-10	7.0E-10	1.2E-10	2.5E-10
10000	9.7E-11	2.1E-10	1.1E-10	2.3E-10	3.8E-11	8.4E-11
20000	3.4E-11	7.6E-11	3.7E-11	8.2E-11	1.3E-11	3.0E-11

(a) Average: value averaged over all directions.
Maximum: value for direction of greatest risk.

Table G-4. Release Rates for Thorium Assessment

Nuclide	Release Rate (Ci/y)
Radon-220	3.39E+5
Lead-212	493.
Bismuth-212	493.
Thallium-208	177.

Table G-5. Regional Individual Lifetime Risk of Fatal Cancer from Radon-220 and Decay Products

Distance (meters)	Inhalation Average	Inhalation Maximum	External Average	External Maximum	Total Average	Total Maximum
600	7.4E-3	1.2E-2	4.3E-5	6.9E-5	7.5E-3	1.2E-2
1000	2.4E-3	4.3E-3	1.5E-5	2.6E-5	2.4E-3	4.4E-3
2000	6.7E-4	1.4E-3	4.3E-6	8.8E-6	6.8E-4	1.4E-3
3000	3.3E-4	6.9E-4	2.1E-6	4.5E-6	3.3E-4	7.0E-4
4000	2.1E-4	4.4E-4	1.3E-6	2.9E-6	2.1E-4	4.4E-4
5000	1.4E-4	3.1E-4	9.5E-7	2.0E-6	1.5E-4	3.1E-4
10000	4.4E-5	9.6E-5	3.0E-7	6.5E-7	4.5E-5	9.8E-5
20000	1.5E-5	3.3E-5	1.0E-7	2.3E-7	1.5E-5	3.3E-5

(a)Average: value averaged over all directions.
Maximum: value for direction of greatest risk.

been made to calculate national impact since the short half-lives of the thoron and daughter products should make this contribution relatively small.

G.4 Effects of Gamma Radiation from Tailings

As noted in Section 6.2.3, gamma radiation exposure depends on the proximity of individuals to the tailings pile as well as the distribution of windblown material. Individual doses can only be assessed on a case-by-case basis since details on shielding and distance are critical to the calculation. The remaining considerations noted in that Section will, in general, hold true for thorium tailings. The thorium series, however, has a higher gamma flux density than the uranium series. The properties of the gamma radiation field at one meter above the ground surface have been calculated for both series (NCRP75) and are shown in Table G-6.

Table G-6. Gamma Radiation Flux Density and Absorbed Dose Rate for the Uranium and Thorium Series

Radionuclide Series	Ground Concentration (pCi/g)	Gamma Flux Density ($\gamma/cm^2 s$)	Absorbed Dose Rate (mrad/y)
Uranium and Decay Products	1(a)	2.82	13.9
Thorium and Decay Products	1(b)	3.81	21.6

(a)Uranium-238.
(b)Thorium-232.

The absorbed dose rates for the thorium series are seen to be about fifty percent greater than those for the uranium series.

G.5 Groundwater

As with uranium mill tailings, the effect on groundwater of thorium milling operations would be highly site specific and depend on the ore constituents and beneficiation process. If the site characteristics of the model mill are used, the radiological impact of the thorium decay products would be negligible due to the short half-lives of the decay products, the absence of nearby aquifers, and the long transport times involved in movement through the environment. The nonradiological impact, in the absence of detailed information on the extraction process and ore constituents, would be expected to be similiar to that for uranium tailings discussed in Section 6.4.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

The Environmental Protection Agency has issued health and environmental protection standards for the control of uranium and thorium tailings during ore processing operations and for final disposal. These standards will apply to tailings licensed by the U.S. Nuclear Regulatory Commission and the States under Title II of the Uranium Mill Tailings Radiation Control Act of 1978 (Public Law 95-604). This Final Environmental Impact Statement examines health, environmental, technical, and cost considerations and other factors important to developing the standards.

Volume II of this document contains the Agency responses to comments received as a result of the public review that is part of the regulatory process.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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