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Long-Term Surveillance and Monitoring of Decommissioned Uranium Processing Sites and Tailings Piles

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Pacific Northwest Laboratory
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Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

Natural processes and human activities could expose the public to radioactive and nonradioactive toxic materials from uranium processing sites in the years following decommissioning. This report describes security, surveillance, and monitoring methods that can be used to prevent or detect the spread of these materials and to determine when cleanup or preventive maintenance is required. Visual observations carried out at least annually can be used to detect any rapidly developing conditions that could expose the public to toxic materials. If no such conditions develop during the first several years following decommissioning, then visual observations can be made at less frequent intervals to detect more gradual changes. Gamma-radiation, ^{226}Ra, and ^{238}U measurements at locations showing significant deterioration can be used to determine whether residual radioactive materials that exceed existing standards have been exposed. Measurements of contaminant concentrations in standing surface water and groundwater can detect the spread of water containing elevated contaminant concentrations. Durable signs and stone markers can be used to warn of the possible dangers associated with these sites.

EXECUTIVE SUMMARY

Uranium processing sites should not represent a significant threat to public health at the time they are decommissioned, but natural processes and human activities could expose the public to radioactive and nonradioactive toxic materials in the years following closure. This report describes 1) security measures that can be used to inhibit human activities that could lead to the exposure of uranium mill tailings and 2) surveillance and monitoring methods that can be used to detect the spread of toxic materials and to determine when preventive maintenance is required.

Because conditions leading to the spread of toxic materials develop differently from site to site, the frequency of observations and measurements at a site should depend on site characteristics and the results of previous observations and measurements. Visual observations should be made at least annually for five years following decommissioning to detect any rapid structural deterioration of the site. In most cases, sites with no evidence of significant deterioration during that time could be inspected less frequently during subsequent years to identify more gradual changes. Photographs should be taken to facilitate the detection of gradual changes.

A record of present gamma-radiation exposure rates is necessary so that increases in the exposure rates can be used to detect the spread of tailings that might occur in the future. Since decommissioning surveys usually provide this record, it should not be necessary to conduct gamma-radiation surveys of the mill site and surrounding areas until there is visual evidence of surface disruption (e.g., erosion). If disruption occurs, surface gamma-radiation measurements should be made around the disruption. If exposure rates greater than 4 μR/h above background rates are measured around a large-scale disruption, gamma-radiation measurements should be made 1 m above the surface along radials extending from the location where elevated exposure rates were detected. Any contaminated areas discovered should then be surveyed using 1-m-height exposure-rate measurements at the grid points of a 10 m x 10 m grid. Contact measurements should also be made around grid points where elevated exposure rates are detected. Soil samples should be analyzed for ^{226}Ra at locations with the highest exposure rates. If concentrations exceeding the Environmental Protection Agency (EPA) standards are measured, soil samples should be analyzed for a spectrum of ^{238}U daughters to determine whether the ^{226}Ra is due to tailings.

There are several processes that could lead to gradual increases in the gamma-radiation exposure rates and radon fluxes without producing obvious visual evidence. Therefore, gamma-radiation surveys of the tailings piles should be carried out every 5 to 10 years. The gamma-radiation measurements should be made 1 m above the surface at the grid points of a 10 m x 10 m grid on covered tailings piles. Locations with exposure rates greater than 4 μR/h above background should be visually inspected to determine the source of the exposure, and soil samples should be analyzed for ^{226}Ra at locations where the highest exposure rates are indicated.

The nature and extent of vegetation and animal burrowing should be observed for transfer of radioactive and nonradioactive toxic materials to the surface. Methods such as those reported by McKenzie et al. (1983) should be used to calculate the surface accumulation of toxic materials. Whenever these calculations indicate that significant accumulation could have occurred, samples of plant material should be analyzed for toxic trace elements. Gamma-radiation measurements, followed by soil ^{226}Ra analysis at locations where maximum exposure rates are detected, should also be taken to determine whether the ^{226}Ra standard is being exceeded.

The evaporation of water at the surface of a covered tailings pile could lead to the capillary flow of water containing dissolved contaminants to the surface. Therefore, any salt deposits or standing water that appears on or around the pile should be photographed and analyzed.

Processed uranium (yellowcake) does not emit high-energy gamma rays, but it does emit beta particles that can be detected using Geiger Mueller (GM) counters. Therefore, areas that could be contaminated with yellowcake should be surveyed using GM counters. Samples should be analyzed at locations with elevated exposure rates.

Contaminant concentrations in standing surface water and in groundwater should be measured. Groundwater monitoring wells should be located upgradient of, within, and downgradient of tailings piles. It is necessary to analyze only a few of the most mobile of the possible contaminants unless these contaminants reflect elevated levels, in which case a wide spectrum of contaminants should be measured. Model calculations and previous contaminant and groundwater flow measurements should be used to determine the frequency of the measurements. Initially the measurements should be made at least yearly, but if no contamination is observed during the first several years following closure, the frequency can be reduced during subsequent years.

The removal and use of tailings material must be prevented in order to protect the environment and public health. However, it would be impractical, and probably unnecessary (at least in nonurban areas), to require active measures, such as guards and security fences, to prevent the misuse of tailings for periods as long as 1000 years. In most cases, the thick earthen cover required to reduce radon emissions to acceptable levels would provide adequate protection against the misuse of tailings. However, durable signs should be placed around tailings piles warning of the dangers involved in tailings misuse. These signs would be expected to deteriorate and should be inspected during regular surveillance of the site. Since it would not be possible to guarantee that these signs would be maintained for 1000 years, stone markers should also be placed beside access roads.

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APPENDIX A.1

INTRODUCTION

On November 8, 1978, Congress enacted Public Law 95-604, the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA). This act states that because uranium mill tailings may pose a potentially significant radiation hazard to public health, every reasonable effort should be made to provide for the stabilization, disposal, and control of such tailings in a safe and environmentally sound manner. This is to be done to prevent or minimize the diffusion of radon gas from these tailings into the environment and to prevent or minimize other environmental hazards from such tailings. The Administrator of the Environmental Protection Agency (EPA) was directed to set standards to govern this process of stabilization, disposal and control. The Nuclear Regulatory Commission (NRC) was given the responsibility of establishing technical, engineering, and management regulations needed to implement these standards.

When uranium processing sites cease operations they must be decontaminated before they can be decommissioned. Uranium mill site decontamination normally includes the stripping of contaminated soil and the removal, washing, or demolishing of buildings, equipment, and facilities. Contaminated soil and other materials are normally buried in the tailings pile. The tailings pile is covered with a layer of earthen material, followed by a layer of rock. In some cases, the site may be considered unsuitable for long-term disposal, so the tailings may be removed to another disposal site.

After decommissioning operations are complete and compliance surveys have verified that the levels of hazardous materials do not exceed standards, responsibility for the sites will be transferred to the United States or to the state in which the land is located. Following transfer, periodic surveillance of the site and tailings pile will be necessary to confirm the integrity of the stabilized tailings and to determine the need for maintenance or monitoring. This report, produced by Pacific Northwest Laboratory (PNL)[a] for the NRC, describes security, surveillance, and monitoring methods necessary to provide reasonable assurance that site integrity is maintained and that the performance standards continue to be met after the state or federal government assumes site control.

The methods described are designed to ensure that in future years releases from the decommissioned sites will not exceed existing federal standards, such as 40 CFR 192 and the Solid Waste Disposal Act (SWDA). "Environmental Standards for Uranium and Thorium Mill Tailings at Licensed Commercial Processing Sites" (Chapter 1, Subpart F, 40 CFR 192) was published by the EPA on September 28, 1983. 40 CFR 192 describes the standards that apply after the final disposal of the tailings. It also guides the activities that are to be carried out during the closure period to ensure adequate final disposal and governs the design of the disposal system. 40 CFR 192 requires that the disposal areas should be closed in a manner that:

(a) Operated for the U.S. Department of Energy (DOE) by Battelle Memorial Institute.

- minimizes the need for further maintenance

- controls, minimizes, or eliminates, to the extent necessary to prevent threats to human health and the environment, post-closure escape of nonradioactive hazardous waste constituents, leachates, contaminated rainfall, or waste decomposition products to the ground or surface waters or to the atmosphere

- provides reasonable assurance that control of radiological hazards will 1) remain effective for at least 200 years; and, to the extent reasonably achievable, for 1000 years and 2) limit releases of ^{220}Rn or ^{222}Rn to 20 pCi/m^2-s.

The radon flux standard only requires that the cover for the tailings pile be designed to provide reasonable assurance that the average flux for the tailings pile will not exceed 20 pCi/m^2-s. It does not require that measurements be performed to verify that the average flux is below this limit.

The above requirements apply to any portion of a licensed uranium mill or disposal site that contains ^{228}Ra or ^{226}Ra concentrations (averaged over areas of 100 m^2), which, as a result of uranium or thorium byproduct material, exceed the background level by more than 1) 5 pCi/g, averaged over the first 15 cm below the surface, or 2) 15 pCi/g, averaged over 15-cm-thick layers more than 15 cm below the surface.

The SWDA rules specify quantitative limits for groundwater contamination. These rules specify that the owner or operator must take corrective action if releases from disposal sites cause concentrations of hazardous materials in groundwater that exceed background concentrations or concentrations beyond the compliance point specified in Table I of 40 CFR 264 (or any future regulations that might supersede 40 CFR 264). The point of compliance is defined as a vertical surface at the hydrological downgradient limit of the waste management area that extends down into the uppermost aquifer. The EPA regional administrator is allowed to exclude a constituent listed in Table I of 40 CFR 264 from the list of hazardous constituents if he finds that the constituent is not capable of posing a substantial present or future potential hazard to human health or to the environment. He is also allowed to establish an alternative concentration limit for a hazardous constituent if he finds that the constituent will not pose a substantial present or future potential hazard to human health or to the environment as long as the alternative limit is not exceeded. 40 CFR 192 adds the chemical elements molybdenum and uranium to the list of hazardous constituents specified in 40 CFR 264, sets limits of 5 pCi/liter for combined ^{226}Ra and ^{226}Ra, and limits gross alpha activity (excluding radon and uranium) to 5 pCi/liter.

SURVEILLANCE AND MONITORING PROCEDURES

This section presents recommended general procedures for surveying and monitoring tailings piles, and discusses the quality assurance and time schedule aspects of these activities.

QUALITY ASSURANCE

A comprehensive quality assurance (QA) plan should be established to provide the necessary control, verification, and documentation to ensure that survey results are valid and that deficiencies can be identified and corrected. The quality assurance procedures should specify methods that are consistent with standard practices for monitoring, recording results, making duplicate measurements to determine measurement variability, and calibrating instruments. The final aspect of the QA plan is records management. The status of the site should be thoroughly and carefully documented whenever the site is inspected. Records should be retained in a permanent archive and be in a readily retrievable form. The NRC should be informed of the development of any conditions that are in violation of federal or state standards and/or could lead to the exposure of the population to hazardous materials.

TIME SCHEDULE

The geological, hydrological, and meteorological characteristics of a site, the design of the tailings pile and its cover, and the population density nearby determine the rate at which conditions develop that could lead to the spread of tailings and to the exposure of the population to radioactive and nonradioactive toxic contaminants. Therefore, the frequency with which observations and measurements should be made depends on these factors and on the results of previous observations and measurements.

Surveillance and monitoring of the sites should be carried out annually for five years following decommissioning to detect any rapid structural deterioration caused by processes such as erosion, subsidence, or human activities that could lead to the exposure of toxic materials. Annual inspections should be continued as long as there is evidence of such deterioration. Sites exhibiting no evidence of rapid deterioration could be inspected less frequently after the first five years. The frequency of these inspections should depend on the probability of site deterioration leading to the exposure of the population to toxic materials. This probability depends on the site characteristics, the population density, and the results of previous observations and measurements.

Tables 1 through 3 list inspection frequencies that are recommended for various site characteristics and population densities. Table 1 presents a guide for estimating the effects of population, potential surface and groundwater use, and the characteristics of the tailings pile cover on the maximum allowable time intervals between inspections of the uranium processing site and tailings pile. Tables 2 and 3 indicate the effects of the potentials for surface and groundwater contamination, respectively, on the maximum time intervals. For each site there is one or more site characteristic that leads to the highest recommended inspection frequency. The site should be inspected at that frequency, because the inspection frequency should be based on the site characteristic most likely to lead to the exposure of the population to toxic materials. A site located in an urban center should be inspected at least once a year, for example, even if the recommended frequency based on the rainfall rate or the possibility of groundwater contamination is lower.

TABLE 1. Estimated Maximum Time Intervals Between Site Inspections After the First Five Years

Critical Parameter	Time Interval in Years <1	1	2	4	10
Population centers within 50 miles[(a)]					
a) >1,000,000 persons	X				
b) <1,000,000 persons		X			
c) <100,000 persons			X		
d) <10,000 persons				X	
e) <1000 persons					X
Ground/Surface water use within 10 miles of the site[(b)]					
a) drinking water - municipalities		X			
b) drinking water - private sources			X		
c) commercial or irrigation use, not used for drinking				X	
d) not usable for drinking water (e.g., polluted, saline aquifer)					X
Site Construction Characteristics[(c)]					
a) <1 m soil cover		X			
b) 1 to 2 m soil cover			X		
c) earth and rock cover				X	
d) earth, rock, and asphalt or paved cover					x

(a) Distance to the nearest population center is used as an indicator of the likelihood of human intrusion into the site.
(b) Ground/surface water use within 10 miles of the site is used as an indication of potential impact of contaminated water on the population.
(c) Site construction characteristics are used as an indication of the potential for release of pollutants from the site.

TABLE 2. Estimated Maximum Time Intervals Between Site Inspections to Ensure Detection of Potential Surface Water Contamination

Maximum 24-h Rainfall in.[a]	Time Interval in Years Between Site Inspections			
	<0.5[b]	0.5-1.0[b]	1.0-2.0[b]	>2.0[b]
<1	10	10	10	10
1 to 2	2	4	4	10
2 to 4	1	2	4	10
>4	1	1	2	10

(a) Maximum 24-h rainfall in one year provides an indication of the potential for heavy rainfall to cause surface water contamination as a result of run-off, erosion, or flow over dykes or river banks. This information can be obtained from sources such as Rainfall Frequency Atlas of the United States, Technical Paper No. 40, U.S. Department of Commerce, U.S. Government Printing Office, Washington, D.C., 1963.

(b) Distance in miles to nearest surface water; used as an indication of the potential for pollutants flowing overland and into surface water bodies.

Annual visual inspections should be resumed (for five years) any time observations or measurements have identified a rapid deterioration of a site. Additional inspections should also be made following any natural occurrence, such as an earthquake or flooding, that could damage the tailings pile. Arrangements could be made for a local resident or agency to provide notification of such occurrences. The local resident could even make a preliminary inspection of the site. If this inspection were to uncover possible problems, then a more detailed official inspection of the site should be made.

PHOTOGRAPHS OF SITES

During the visual inspection, a description of the condition of the site should be recorded. However, reference to recorded notes, or to memory, would probably not be adequate to identify gradual changes in the sites. Therefore, sufficient photographs to completely characterize the sites should be taken during the first visual inspection. The exact locations of these photographs should be recorded. During subsequent inspections additional photographs should be taken of any area of the site that was significantly changed.

TABLE 3. Estimated Maximum Time Interval Between Site Inspections to Ensure Detection of Potential Groundwater Contamination

Average Annual Net Precipitation, in.[a]	Time Interval in Years Between Site Inspections 0-20[b]	20-40[b]	40-60[b]	>160[b]
-10	10	10	10	10
-10 to 5	2	4	4	10
>5 to 15	2	4	4	10
>15	1	1	2	10

(a) Net precipitation (precipitation minus evaporation) indicates the potential for leachate generation at the site. If net precipitation is not available, it may be calculated by subtracting the mean annual lake evaporation for the region from the annual precipitation. This information can be obtained from sources such as the Climatic Atlas of the United States, U.S. Department of Commerce, National Climatic Center, Ashville, North Carolina, 1979.

(b) Depth to groundwater in ft is used as an indication of the potential for pollutants to contaminate the groundwater in the vicinity of the site.

EVIDENCE OF EROSION BY WATER

Water can erode tailings piles in different ways. Erosion due to overbank flooding, river meandering, rainfall run-off, differential settlement, and embankment side-slope failure are discussed in this section.

Erosion Due to Overbank Flooding

Erosion by water typically represents the most serious threat to the integrity of uranium processing sites and tailings piles. Catastrophic erosion could occur if a nearby river or stream overflowed its banks. The forces and shear stresses generated by the overflowing water are fully capable of rapidly eroding most, if not all, of an above-ground tailings pile. The extent of the erosion would depend on the location, depth, velocity, and duration of the flooding. Erosion due to overbank flooding would occur quite rapidly, making it difficult, if not impossible, to monitor the erosion during the flood. After the recession of the flood the extent of the erosional damage could be determined using aerial photography and ground-level surveying. In cases where riprap protection is present, a close onsite inspection of the surface would be necessary to determine whether any dislodgement of rock or damage to the underlying filter had occurred. Any failure of the rock cover is most likely due to the washing out of the filter material. If enough filter material is washed out, a gully can form under the rock layer and eventually cause the collapse of the layer. This can be easily determined by visual inspection.

Erosion Due to River Meandering

Uranium tailings piles located on river flood plains may be subject to undercutting and erosion as a result of river meandering, a natural process that is an integral part of flood-plain construction. Meandering involves the migration of the river channel across the flood plain by bankline erosion and can erode the flood plain soil to the depth of the river. During time spans of hundreds of years, alluvial river channels can migrate from one side of a flood plain to the other. A meandering river can destroy any earthen structure in its path.

The migration of river channels is episodic since the maximum rate of erosion of channel bendways occurs during and immediately following the larger flood events of the river system. Since meandering involves large areas of the flood plain, the simplest method of monitoring the meandering process involves the use of sequential aerial photographs backed by periodically updated U.S. Geological Survey (USGS) quadrangle maps. If the tailings pile is located near a river channel, a detailed contour map should be constructed using aerial photogrammetry and ground-level surveying. Sequential mapping would reveal any major shifts in the channel position. Recent or periodic bankline caving should be documented during onsite inspections.

Overland Erosion

Another geomorphic process that could erode above-ground tailings impoundments is overland erosion from rainfall/run-off events. Erosion could result from rainsplash, infiltration of water into the soil, surface overland flow, and interflow of water moving through the soil just below the surface. Rainsplash and surface overland flow are the primary contributors to overland erosion. The erosion rates produced by these processes will depend primarily on precipitation frequency and intensity.

A serious consequence of overland erosion is the development of gullies. These may begin as small rills that gradually enlarge as more of the run-off becomes concentrated in the channels. Gullies can form rapidly and breach the impoundment during high-intensity precipitation. The side slopes of the tailings are especially susceptible to gully development. Gullies resulting from the headward extension of watershed drainage channels downstream of the tailings pile may reach the pile and cut into the embankment.

Gullies can be produced in the tailings pile as a result of several other processes, all of which work in concert with overland flow to rapidly form drainage channels. Gullies can develop in low areas (depressions) of the land surface that channel run-off, causing flow depth and velocity to increase as erosion proceeds. Differential settlement of the surface of the tailings pile can produce a discontinuity where run-off can collect and eventually scour a channel. A slump failure of the side slope of the tailings pile can create an unstable bluff face of exposed soil that could easily develop into a gully. Channels (pipes) that form beneath the soil surface can lead to gully development when the pipe becomes large enough to cause the surface to collapse. Conditions that can lead to the development of pipes include the presence of 1) a hydraulic head, 2) sufficient clay content to produce a potential for swelling or shrinkage, 3) a permeable soil horizon over an impermeable soil horizon, 4) cracks and bedding planes for drying, 5) a percentage of exchangeable sodium in the soil, and 6) burrowing by animals.

Gullies can develop over large areas of a site. Therefore, the rate of development of gullies can best be determined by sequential aerial photographs followed by onsite surveying. The aerial photographs, together with profile leveling, would quantify the progressive changes in the cross-sectional shape, size, and gradient of the gully channel. These changes should be correlated with rainfall records since a single high-intensity storm can produce significant erosion. If significant erosion is determined to have resulted from such a storm or a series of such storms, the site should be inspected in the future at a frequency related to the frequency of the storms. In the case of gully channels that are relatively close to the base of the tailings pile, the inspections should include sequential engineering surveys of the gully system to quantify the rate and extent of gully development.

It is extremely important to determine the possible causes of any gullies that develop. If they are due solely to erosion by overland flow, then any further monitoring would employ aerial photography and ground surveying. Gullying due to pipe collapse should be carefully investigated, since the pipe collapse could continue to occur at unpredictable locations. If animal burrows are the primary cause, the extent of burrowing and the type of animal should be identified to determine the probability that further gully development may result. Excavation of the earthen cover may be necessary to identify other, less obvious causes.

Overland erosion can lead to sheet and rill erosion in which the surface is eroded rather uniformly over a relatively large area. This type of erosion can be difficult to detect visually. The best method for monitoring the rate of sheet erosion is to establish several well-fixed benchmarks (similar to USGS monuments) and to check for any significant soil loss with profile leveling. Engineering levels can be read to a fraction of an inch. Soil erosion of this small magnitude would be of little consequence. However, average soil losses of more than an inch per year could be significant.

Stainless steel rods driven several meters into the tailings pile can also be used to estimate erosion rates. The rods should extend well below the freeze-thaw level of the soil. The rods would not need to extend above the surface initially, but could be buried to the depth at which the top of the rod would extend above the surface when soil loss became significant. Any subsequent exposure of the rods would provide a measure of the average rate of soil loss. Several rods could be buried at different depths to provide for long-term monitoring. This procedure would reduce the visibility of the rods and partially solve the problem of vandalism.

Inspecting vegetation on the cover surface for root exposure would provide an estimate of the amount of erosion. This method would not be affected by vandalism, but the reliability of measurements of soil loss by this method is questionable.

Another possible method for measuring sheet erosion is to monitor the accumulation of soil deposits at the base of the tailings pile. The accumulation of soil deposits is easier to detect than the loss of soil by sheet or rill erosion, because the deposits are concentrated in a small area.

Differential Settlement of the Tailings Piles

Differential settlement usually occurs when the foundation of a structure allows more settlement at one location than another. This could result from the use of heterogeneous foundation soils or from the dewatering of the residual moisture within the tailings pile. The accompanying settlement would initially lead to the cracking of the tailings pile cover, with one side of the crack normally being at a lower elevation than the other. This would allow a concentration of run-off to develop into a gully.

If a riprap cover is in place, it may be difficult to identify a small amount of differential settlement (several inches) because the rock surface is irregular. The rock cover may partially or completely "heal" the rock surface, since the rock blanket is held together by gravity and would adjust to any new difference in elevation. However, any noticeable differences in rock layer elevation should be investigated to determine whether differential settlement has occurred. Also, the integrity of the underlying gravel filter should be examined during the inspection. If separation of the rock cover has occurred, further investigation and engineering analysis may be warranted.

Embankment Side-Slope Failure

Almost any degree of side-slope failure could lead to serious erosion of the tailings pile. This type of failure would most likely lead to severe gully erosion. Therefore, the tailings pile should be inspected to determine whether slope failure is occurring each time the site is inspected. Sometimes there are indications that a slope failure is imminent (e.g., tension cracks along the upper surface indicate the soil mass is beginning to slump). This type of failure is primarily due to the buildup of moisture in the embankment soil, usually a result of poor drainage conditions coupled with an overly steep side slope. If the failure involves only a slight degree of slumping, a rock cover may inhibit gully development. If there is a noticeable separation of the rock cover and an exposed small bluff face of soil, then a slope failure is indicated. Such a failure requires reconstruction of the embankment and repair of the rock cover and underlying filter.

EVIDENCE OF EROSION BY WIND

The wind erosion of a tailings-pile cover should generally be considerably slower than that due to water, especially when a layer of rock is placed on top of the cover. In most cases a 3-m-thick cover would be expected to provide long-term protection lasting up to 1000 years, even if it did not include a rock layer (EPA 1983c). However, because it depends on many factors (e.g., the effectiveness of a vegetative cover), the rate of wind erosion can vary greatly from site to site. In addition, wind erosion would be expected to be greater for tailings disposed of above-grade. Therefore, wind erosion could cause a serious loss of cover material.

The erosion of the tailings pile cover by wind would generally be difficult to detect visually, because such erosion would often cause a general loss of material, rather than a large loss at any one location. However, the procedures described above for monitoring sheet and rill erosion would, in fact, measure the combined losses due to wind erosion and sheet and rill erosion.

EVIDENCE OF MISUSE BY HUMAN ACTIVITIES

During the visual inspections of the tailings piles, any possible removal of tailings or cover material by humans should be noted and photographed. Any activities that could lead to the deterioration of the pile, such as the digging of wells or the operation of off-road vehicles, should also be noted. Such activity could lead to an increased rate of erosion of the tailings pile and to the exposure of the population to radioactive and toxic nonradioactive contamination. If any misuse is noted, additional security measures, such as the placement of additional signs or even the enclosure of the pile inside a fence, might be required to prevent future misuse of the tailings site.

GROWTH OF VEGETATION

Because of plantings designed to stabilize the earthen cover or because of natural plant succession, vegetation is likely to become established on tailings piles that do not have thick rock covers (Yamamoto 1982). The roots of this vegetation could penetrate the cover and either reach the tailings below or reach soluble material that had diffused upward through residual water in the cover material or had been drawn upward by capillary action as a result of evaporation at the surface. Soluble material reached by the roots of plants would be expected to become distributed throughout the plants and eventually become deposited on the cover surface.

Root intrusion into covered tailings could be discouraged by the use of barriers (Cline et al. 1980, 1982) or of relatively deep earth and rock covers. The probability of root penetrations through covers and into raw tailings would increase over time after site stabilization if erosion decreased the cover thickness, deeper-rooted plants became established, or root intrusion barriers failed. However, it is likely that it would be decades or longer before vegetation would transport significant toxic material to the surface, especially if a rock cover were used.

The most direct human exposure pathway involving plants would be via human food crops or forage for domestic animals grown directly over the tailings impoundment. This pathway might be insignificant within a 1000-yr time frame because of the presence of rock covers, because of the low suitability of most tailings sites for agriculture, and because institutional controls are expected to limit such uses of the sites. However, if good-quality topsoil and little or no rock were used to construct the cover, it could be attractive for agriculture, especially if good topsoil were scarce in the area. Human exposure could result from the ingestion by range animals of natural vegetation or soil (Zach and Mayoh 1983) that had become contaminated by radioactive and nonradioactive hazardous materials from tailings. It has been found that range cattle and sheep graze on most active and inactive mill sites (EPA 1983b).

There have been numerous reports of plant species having root systems deep enough to penetrate earthen tailings covers (Whicker 1978). Research has shown that the potential exists for the significant uptake of radioactive and hazardous trace elements by plants on bare tailings or tailings with only a thin cover (Dreesen et al. 1980). However, there are few data that provide guidance on the importance of plant uptake of hazardous contaminants in the case of tailings having a thicker cover (Whicker 1978, 1981). The role of vegetation in the long-term transport and accumulation on the surface of radionuclides from commercial low-level nuclear waste burial sites has only recently been studied (McKenzie et al. 1982). The results of McKenzie et al. suggest that the cumulative transport of toxic materials over hundreds of years by plant roots could result in elevated radionuclide concentrations of toxic materials at the tailings cover surface.

When and if vegetation that could have roots extending downward into toxic tailings material becomes established, the rate of accumulation of toxic materials on the surface produced by the vegetation should be estimated using techniques, such as those described by McKenzie et al. (1982), that are based on site-specific characteristics. These characteristics include the concentrations of toxic materials, the composition and depth of the overburden, the root depth, and the annual productivity. However, considerable uncertainties would be expected in the calculated rates of transport. Therefore, if the calculations indicate that there could have been significant transport of toxic materials to the surface, measurements should be made to check the results of the calculations.

The concentrations of ^{226}Ra and toxic trace elements, such as selenium, should be measured in plant materials. Locations likely to have elevated ^{226}Ra concentrations should be identified from gamma-radiation surveys conducted using procedures described below in the section describing gamma-radiation measurements on covered tailings piles. Soil samples should be analyzed for ^{226}Ra at locations where maximum gamma-radiation exposure rates are indicated. Once visual observations and calculations indicate that transport of toxic materials could have become significant, measurements should be repeated each time the tailings pile is inspected. The NRC should be notified of any elevated trace element concentrations in plant material or any ^{226}Ra concentrations that exceed standards.

BURROWING BY ANIMALS

Thick rock covers would eliminate, or at least severely reduce, burrowing by animals. However, extensive burrowing could occur if the rock cover was inadequate. Burrowing by animals on a covered tailings pile could lead to 1) the transport of tailings to the surface; 2) increased infiltration, leaching, and seepage of water; 3) increased slumping and erosion; 4) increased radon fluxes; and 5) the degradation of dams used to protect the tailings piles from surface water. Therefore, the extent of animal burrowing should be observed and photographed each time the tailings pile is visually inspected. Because the depth and extent of the burrows depend on the animals producing the burrows, the species involved should be identified if burrowing is extensive.

Populations of burrowing animals around covered tailings piles require a suitable sustaining plant community. If vegetation is absent (as may be the case if the cover has a thick rock layer), few, if any, burrowing animals will inhabit the site. Therefore, observable evidence of burrowing is not expected until stable vegetation is established.

Well-designed animal barriers, if used, will minimize the transport of tailings to the surface by burrowing animals (Cline et al. 1980, 1982). In the absence of animal barriers, however, the probability of tailings transport would probably depend primarily upon the composition and thickness of the cover. Transport could be common for covers that are 1 m or less in thickness. For example, cast deposits of raw tailings were common at the entrances of prairie dog and ant burrows on the Grand Junction tailings piles in 1980. The tailings had been transported through a 15- to 20-cm earthen cover by the animals. On the other hand, much less transport is expected through a cover thickness of 3 m or more because of limitations in the depths of animal burrows (Gano and States 1982). However, ants have been observed at depths of about 3 m (Headlee and Dean 1980), and some mammals burrow beyond 4 m (Sheets et al. 1971; Whitehead 1972). Erosion, or other processes that reduce the cover thickness, might permit future increases in the transport of tailings by burrowing animals.

Animal tunnels can also channel surface water through cover systems, causing increased erosion, leaching, and downward percolation of soluble contaminants. Little is known about the impact of animal tunnels on groundwater contamination, pile instability, and the growth of vegetation. However, it is likely that extensive burrowing would be detrimental to the long-term stability of the piles.

It appears that animal burrows on flat areas of the cover surface would not enable large amounts of water to enter the pile, at least in arid regions, because there would be an insignificant watershed to direct water flow into the burrow system. However, burrowing on the sloped sides of a pile could result in significant mass wasting (earthslides) and a greater potential for the entry of water into the interior of the pile, particularly if the slopes were covered with a layer of rock. Some burrowing animals prefer slopes, so the slopes should be examined carefully when inspecting for evidence of burrowing.

Particular attention should be given to the burrows of prairie dogs (Gennus cynomys) in areas where they occur. These animals construct deep, extensive burrow systems. Their burrows are relatively large, and could conduct significant quantities of water below ground if they were located in areas subject to channelized water flow. These animals prefer habitats similar to those that occur if the flat areas on covered tailings piles become vegetated. Prairie dogs became established on the surface of the Grand Junction tailings piles only a few years after the piles were covered and revegetated.

If surveillance indicates that material is being transported to the surface by burrowing animals, the responsible animal species should be identified so that the specific parameters of the populations can be obtained from the literature to determine whether these animals are likely to burrow deeply enough to bring tailings material to the surface. Rates of contaminant transport to the surface by animal burrowing may be estimated using methods such as those described by McKenzie et al. (1982). However, gamma-radiation measurements around the entrance of the burrows, followed by measurements of ^{226}Ra concentrations in soil samples from locations with maximum gamma-radiation exposure rates, should be used to determine whether tailings have been brought to the surface. The gamma-exposure rates from raw tailings would greatly exceed background levels. These gamma-radiation measurements should be repeated during any site inspection that reveals visual evidence of animal burrowing.

Defects in the tailings pile covers due to animal burrows, fissures, or erosion gullies could lead to increased radon fluxes from the piles. Cover defects that penetrate the entire cover and reach the tailings result in considerably higher surface radon fluxes than shallower defects (Mayer and Zimmerman 1983). The probability and degree of cover failure resulting from animal burrowing depends on several site-specific features. For example, soil covers that are 1 m or more in thickness are less likely to be penetrated than shallower covers.

Methods such as those reported by Mayer and Zimmerman (1983) could be used to estimate changes in radon flux produced by cover defects due to animal burrows and other causes. It is not practical to measure the flux increases because there are no suitable techniques for measuring average fluxes due to animal burrows. Remedial action to fill in burrows, fissures, and gullies should not be required if calculations indicate that these cover defects increase the radon flux by less than a factor of two. The uncertainties in the calculated fluxes would be more than this amount even when best available diffusion coefficients are used (Kalkwarf and Meyer 1980). The flux calculations, on which the design of the cover is based, are also likely to have uncertainties that are greater than a factor of two.

DEVELOPMENT OF FISSURES IN THE MATERIAL COVERING TAILINGS PILES

Earthquakes, slumping, settling, or the drying out of the cover material could lead to the exposure of tailings or the development of fissures in the cover material that could cause increases in the radon flux. The extent of such fissures should be noted and photographed during the visual inspection of the tailings pile. Surface cracks should not be considered significant fissures. The fraction of the area covered by fissures should be estimated and used to calculate the maximum possible increase in the radon flux that could be caused by the fissures, using a method such as that described by Mayer and Zimmerman (1983). Corrective measures are probably needed only if the total increase in the radon flux due to fissures and other types of cover defects, such as animal burrows, is calculated to be a factor of two or more.

DEVELOPMENT OF SALT DEPOSITS

The evaporation of water at the surface of a covered tailings pile located in an arid region could lead to the capillary flow of water toward the surface. This process could lead to the transport of water containing dissolved radioactive and nonradioactive materials from the underlying tailings pile to the surface. These materials would be left behind on the surface if the water evaporated. It is also possible that water draining from the tailings material could lead to the contamination of the surface around the pile. Therefore, any salt deposits or standing water that developed on the surface of or around the tailings pile should be noted and photographed. Samples of any such material should be collected and analyzed to determine whether the salts contain hazardous materials from the tailings. If such hazardous material is detected, then corrective measures are needed to prevent further transport to the surface and to dispose of any material already brought to the surface.

GAMMA-RADIATION AND ^{226}Ra MEASUREMENTS

Present EPA standards set limits for ^{226}Ra concentrations in soil and for radon fluxes from covered tailings piles, but not for outdoor gamma-radiation exposure rates. It is assumed that outdoor gamma-radiation exposure rates will not reach hazardous levels if the ^{226}Ra concentrations in surface or near-surface materials do not exceed the ^{226}Ra standard. It is also assumed that a tailings pile cover of sufficient thickness to lower the radon flux below 20 pCi/m^2-s and to prevent the spread of tailings will lower the gamma-radiation exposure rate to acceptable levels. Half a meter of compacted soil will lower the gamma-radiation intensity to about 0.1% of its original value (EPA 1983a). However, gamma-radiation measurements have proved to be very useful in identifying locations where ^{226}Ra standards are exceeded because of surface or near-surface tailings material. Since it is much easier and quicker to make gamma-radiation measurements than it is to measure radon fluxes or to analyze soil or other material for ^{226}Ra, gamma-radiation measurements can be made at many more locations than is feasible for ^{226}Ra measurements. Therefore, gamma-radiation measurements should be used to identify locations where ^{226}Ra measurements should be made.

At Edgemont, South Dakota, ^{226}Ra concentrations exceeding 5 pCi/g were measured in only 2% of 951 surface soil samples collected at locations where the contact gamma-radiation exposure rate was less than 4 μR/h above the average background exposure rate. None of these soil samples contained ^{226}Ra concentrations greater than 15 pCi/g (Young, Jackson and Thomas 1983). Four μR/h corresponded to approximately twice the standard deviation of the background gamma-radiation exposure-rate measurements. At higher exposure rates the probability of ^{226}Ra concentrations greater than 5 Ci/g increased rapidly, reaching 90% for exposure rates that were 20 μR/h above background. It therefore appears that, in most cases, soil samples need to be analyzed for ^{226}Ra only at locations with gamma-radiation exposure rates greater than about 4 μR/h above background.

The procedures that are recommended for conducting gamma-radiation surveys in this report will provide data that can be used to calculate average exposure rates for individual survey units. However, the primary purpose of the surveys will be to identify locations (hot spots) having elevated levels of radioactivity. Therefore, many more measurements are recommended than would be required if the primary purpose were to determine average exposure rates with a fair degree of accuracy.

Micro-R-Meters

Gamma-radiation measurements can be made using portable, commercially available instruments, hereafter referred to as micro-R-meters, that use small (usually 2.5 x 2.5 cm) NaI(Tl) detectors to measure gamma-radiation exposure rates. They use a ratemeter and usually four different scale ranges to display exposure rates from one to a few thousand μR/h. The micro-R-meters produce audio signals that click at a rate that is proportional to the gamma-radiation exposure rate. This audio signal has a faster response than the meter, so it can be used to detect tailings material when walking between measurement points. If the audio signal shows a significant increase at any location, the exposure rate at that location should be recorded. The response of micro-R-meters to gamma-radiation is energy dependent, and the gain of the instrument tends to vary with time. Therefore, the micro-R-meter should be calibrated at least once a day with a pressurized ion chamber set up in the area to be surveyed, and only corrected readings should be recorded. The measurements should be made in dry weather, not during periods of precipitation or when the ground is wet or covered with ice or snow. These latter conditions change the degree of disequilibrium between radium and radon, thereby changing the radon daughter concentrations and the gamma-radiation activity.

Commercial micro-R-meters should be adequate for detecting surface or near-surface tailings deposits that exceed present EPA standards. However, portable gamma-ray detectors can be constructed that are considerably superior to commercial micro-R-meters for detecting smaller tailings deposits. The use of a larger NaI(Tl) crystal would significantly increase the sensitivity of the detector, considerably improving the detector's ability to detect small tailings deposits and "tip of the iceberg" cases in which large tailings deposits extend to the surface only over limited areas. The accuracy of the measurements is enhanced if a digital readout giving the average exposure rate over a selected time interval is used rather than the ratemeter used in commercial micro-R-meters. Small tailings deposits could also be detected more easily if the audible signal is set at a threshold so that it would not respond unless the exposure rate exceeds an action level (e.g., 4 μR/h above background) above which surface gamma-radiation measurements or soil ^{226}Ra measurements would be required to locate any tailings present. A portable detector system, consisting of a large NaI(Tl) detector mounted on the end of a probe and an electronics package equipped with an alarm that sounds whenever a given exposure rate is exceeded, could be used to make nearly continuous near-surface scans of even fairly large areas.

If a commercial micro-R-meter is used, gamma-radiation measurements at grid points should generally be made at an elevation of about 1 m, unless the spacing between grid points is very small (less than about 1 m). A detector placed in contact with a tailings deposit of limited area would obviously give a higher exposure rate reading than one held at a higher elevation because of the $1/r^2$ decrease in the radiation intensity with distance. However, if the detector is located an appreciable horizontal distance away from a near-surface deposit of tailings, the distance the gamma-rays have to penetrate through soil before reaching the detector is greater for lower detector elevations. According to Young, Jackson and Thomas (1983), attenuation by soil causes the exposure rate from a point source of 1.7 MeV gamma rays (^{214}Bi) located 2 cm beneath the surface to be greater at an elevation of 100 cm than at an elevation of 10 cm for horizontal distances from the source of more than 60 cm. Since the probability of detecting tailings decreases with horizontal distance between the tailings and the detector, the detector should generally be held at an elevation of 1 m to maximize the detection probability for tailings a greater horizontal distance from the detector. However, relatively small deposits of tailings an appreciable horizontal distance from the detector produce only a small increase in the detector response. Therefore, when a small increase in the exposure rate is noted at the 1-m elevation, surface measurements should be made in the surrounding area to confirm the presence of a gamma-ray source and to determine its location.

Gamma Radiation Surveys

A record of the present gamma-radiation exposure rates of a mill site, tailings pile, and surrounding areas is necessary in order to use increases in the gamma-radiation exposure rates to detect any spread of tailings material that might occur in the future. However, gamma-radiation surveys carried out during the decommissioning of the site should provide such a record. Therefore, gamma-radiation measurements of the mill site or surrounding area should not be necessary unless a serious disruption of the surface of the mill site or tailings pile occurs, such as erosion or construction activities. Without such a disruption, there would be no source of tailings to cause increases in the gamma-exposure rates of surrounding areas.

If there is any disruption of the surface of any mill site or tailings pile that could result in the exposure and spread of tailings, surface gamma-radiation measurements should be made around the area(s) of the disruptions. If significant increases (greater than about 4 μR/h) occur at any locations, ^{226}Ra concentrations should be measured in one or more soil samples at the location(s) of maximum exposure rate in each area where elevated exposure rates are detected. If ^{226}Ra concentrations greater than 5 pCi/g above background due to tailings (see page 19) are measured in any soil sample, it should be assumed that the spread of tailings could have occurred. Gamma-radiation measurements should be made in the area surrounding the disruption to determine the extent of any tailings transport.

In cases of small-scale disruption, such as animal burrowing, continuous surface gamma-radiation measurements to a distance at which exposure rates approach the background level should be adequate to determine the spread of the tailings. However, in the cases of large-scale disruption, such as water erosion, it may not be practical to make continuous surface measurements over the entire area of possible contamination. In these cases, gamma-radiation measurements could be made at grid-points over the area.

At great distances from the source of the tailings, the probability of detecting tailings would decrease and tailings would probably be spread more uniformly across the surface. Therefore, increasing the distance between measurements with distance from the source should minimize the time required to complete the survey without significantly decreasing the probability of detecting tailings. This can be done most easily by making the measurements along radials from the source. Radial measurements in each of the eight compass directions should provide adequate coverage. The distance between measurements along each radial could also be increased with distance from the source. For example, they could be made at 5 m intervals for the first 50 m from the source, and every 50 m beyond that. The measurements should be made to a distance of 50 m beyond the point at which the gamma-radiation exposure rate falls to less than 4 μR/h above the previously determined background levels.

More detailed surveys should be made of any areas where elevated gamma-radiation exposure rates are detected or where there is evidence that contamination is likely to be present. Measurements of these areas should be made at the 1-m level at the grid points of a 10-m by 10-m grid. This grid spacing should be used because the standards express the ^{226}Ra limit in terms of an average over 100 m^2. Grid spacings significantly larger than the deposit should not be used if deposits with concentrations only slightly higher than background are to be detected with a high degree of probability using micro-R-meters. If a significant increase (greater than about 2 μR/h) in the exposure rate is observed at any location, a surface search should be made for elevated readings.

The exact dimensions of a source of gamma rays can be determined more accurately if a micro-R-meter with lead-shielded sides is used. This minimizes the detection of gamma rays from other locations. Measurements of the difference between the exposure rates with and without a lead sheet between the micro-R-meter and the ground may also be used for this purpose.

Surface searches for elevated gamma-radiation exposure rates should also be made in any localized area that has a high probability of being contaminated with tailings, such as a sediment deposit produced by deep erosion of the tailings pile. The locations with the highest exposure rates should be marked, and the contact exposure rates at these locations should be recorded. If elevated exposure rates are measured at the edge of the grid, the grid should be extended until the exposure rates approach background levels.

Several processes could cause increases in the gamma-radiation exposure rates above covered tailings piles without leaving obvious visual evidence. Radium-226 in solution that diffused upward through water or was drawn upward through the cover by capillary action could later increase the gamma-radiation exposure rates. Radioactive materials transported toward the surface by burrowing animals or by vegetation could also lead to increased exposure rates. It is possible that there could be thin spots in the cover or that thin spots could develop later as a result of processes such as wind or water erosion. These thin spots might possibly lower the absorption of gamma-rays from the tailings sufficiently to increase the gamma-radiation exposure rate above the tailings. The increased radon flux through the cover at these locations would increase the concentrations of short-lived radon daughters deposited in the cover material, which could lead to an increase in the gamma-radiation exposure rate above the cover. These short-lived radon daughters are the primary source of the gamma rays emitted by tailings. Any process that led to increases in the radon flux through the cover might therefore be expected to cause increases in the gamma-radiation exposure rate above the cover.

Since it is much easier to measure gamma-radiation exposure rates than radon fluxes, gamma-radiation measurements can be made at many more locations than is practical for radon flux measurements. Therefore, gamma-radiation surveys should be carried out periodically on tailings piles to identify increases in the exposure rate caused by processes that produce little or no visual evidence. Because these processes are gradual, the surveys should be required only every 5 to 10 yr. If significant increases in the exposure rate are observed, ^{226}Ra measurements should be used to determine their cause.

The gamma-radiation measurements should be made at waist level at the grid points of a 10-m by 10-m grid on covered tailings piles. The average and the standard deviation of the measurements should be calculated. The locations of the highest contact exposure rates should be marked and the exposure rates recorded. The area around these locations should be visually inspected to determine the cause of the elevated exposure rates. Samples of soil from locations where the highest exposure rates are detected should be analyzed for ^{226}Ra.

Soil Analyses

Soil samples from the 0- to 15-cm and 15- to 30-cm depth intervals at locations with maximum exposure rates (greater than about 4 μR/h above background) should be analyzed for ^{226}Ra and other uranium daughters to determine whether tailings are present. Samples from greater depths need not be collected originally since any tailings detected using micro-R-meters would be expected to be on or near the surface. The soil samples should be homogenized and analyzed for ^{226}Ra and other radionuclides using NaI(Tl) and/or intrinsic-germanium-diode gamma-ray spectrometers to determine whether tailings are present. The greater sensitivity of the NaI(Tl) permits a considerably more rapid analysis of samples, but the resolution of the NaI(Tl) is much poorer than that of germanium diodes; it is not good enough to permit the analysis of the spectrum of uranium daughter radionuclides necessary to distinguish between tailings and natural material (Young, Jackson and Thomas 1983). If the ^{226}Ra is due to uranium mill tailings, the activity of ^{234}Th, the 24-day half-life daughter of ^{238}U, should be much lower than that of ^{230}Th, ^{226}Ra, and ^{210}Pb, which are left in the waste after most of the uranium has been extracted. If the ^{226}Ra is due to natural material, the activities of ^{234}Th, ^{230}Th, ^{226}Ra, and ^{210}Pb should be similar. Samples of natural soils from the survey area should be analyzed for these radionuclides to determine the natural variations of the ^{234}Th to ^{230}Th, ^{226}Ra and ^{210}Pb ratios in the area, so that soil samples containing mill tailings can be identified by the ratios below this range.

If the soil samples are analyzed initially with NaI(Tl) detectors, samples containing ^{226}Ra concentrations greater than the EPA standard still must be analyzed using intrinsic germanium diodes to determine whether the ^{226}Ra is due to tailings or to natural material. Therefore, it might prove practical in many cases to analyze the samples directly with intrinsic germanium diodes. Soil from locations where gamma-radiation exposure rates are greater than 20 μR/h above background is very likely to contain ^{226}Ra concentrations greater than 5 pCi/g. It should probably be analyzed directly using germanium diodes (Young, Jackson and Thomas 1983).

If it is estimated that ^{226}Ra concentrations due to tailings average greater than 5 pCi/g over any 100 m^2 area in the 0- to 15-cm layer, but do not average greater than 15 pCi/g in any deeper layer, then the contamination is likely to be confined to the surface layer. If the 15-to 30-cm layer averages greater than 15 pCi/g over any 100 m^2 area because of tailings, then the tailings may extend to greater depths. Boreholes should be logged to the depth of at least 1 m, and either NaI(Tl) or intrinsic germanium-diode gamma-ray spectrometers may be used to determine the maximum depth of the tailings. If a ^{226}Ra concentration greater than 15 pCi/g is measured at the bottom of the borehole, the borehole should be extended in 1-m increments until the ^{226}Ra concentration falls below 15 pCi/g. If it is estimated that the ^{226}Ra concentration in any 15-cm layer below a depth of 15 cm averages greater than 15 pCi/g over any 100 m^2 area, then a soil sample from that layer should be analyzed using an intrinsic germanium diode to determine whether the ^{226}Ra is due to tailings (unless borehole logging using an intrinsic germanium diode has already determined this).

The measurements described above should include any uninhabitable buildings remaining on the site. However, it might not be necessary to measure gamma-radiation in habitable buildings because any tailings that had been in and around these buildings would have been disposed of during decommissioning and any tailings that are blown or tracked in later would probably be removed during normal cleaning procedures. However, if an unusual occurrence, such as a flood, deposits a large amount of material that could contain tailings in a building, a careful search for elevated gamma-radiation exposure rates should be made on inside surfaces of the building following the initial cleanup. If any exposure rates greater than 20 μR/h are observed, additional cleanup of the contaminated material is required. The 20 μR/h limit should be used because 40 CFR 192 sets this limit for indoor gamma-radiation exposure rates.

RADON FLUX MEASUREMENTS

The EPA standard for average radon fluxes from covered tailings piles is a design standard rather than a performance standard. That is, the cover must be designed to provide reasonable assurance that it will lower the average radon flux below 20 pCi/m^2-s. It is not necessary to measure the radon flux from the covered pile to prove that the flux is, in fact, below 20 pCi/m^2-s. It might not even be possible to measure average radon fluxes from tailings piles having thick rock covers, because there are no suitable measurement techniques for surveying rock-covered surfaces at the present time. However, the flux from the covered tailings pile could increase considerably with time as a result of processes such as drying out of the pile and its cover, wind and water erosion, burrowing by animals, growth of vegetation, or upward migration of ^{226}Ra in the cover. Therefore, measurements of increases in the average radon fluxes from tailings piles that do not have thick rock covers could be used to determine whether deterioration of the cover has been extensive enough to merit remedial action. Procedures that could be used to measure average fluxes are described in the appendix.

BETA-GAMMA MEASUREMENTS

There could be some processed uranium (yellowcake) present on mill sites that was not detected during decommissioning surveys because it was buried beneath the surface. Uranium primarily emits alpha particles and low-energy gamma-rays that are rapidly attenuated by solid materials. It is also possible that some yellowcake may have been placed on the tailings pile before the stabilization of the pile. Processed uranium can produce a serious alpha particle radiation dose, particularly if it becomes inhaled or ingested. 40 CFR 192 does not specify standards for uranium. However, the principle that radiation exposure should be kept as low as reasonably achievable dictates that any processed uranium discovered should be properly disposed of.

Yellowcake cannot be detected using micro-R-meters because it does not contain significant quantities of gamma-radiation emitters. It does contain the short-lived uranium daughters, ^{234}Th and ^{234}Pa, which emit primarily beta radiation. Since thin-window GM tubes detect both beta and gamma radiation, they can be used to survey locations suspected of yellowcake contamination. If the GM tube detects a significant increase in the radiation intensity, measurements should be made with and without the GM tube being shielded from beta particles by a thin sheet of lead. This will indicate whether the radiation is primarily beta radiation. Any material that is found to emit beta radiation should be analyzed to determine whether it contains yellowcake. It is not expected that significant yellowcake will be present on the surface of open land areas of the mill sites or the tailings piles, so GM tube measurements need not be made at these locations unless visual observations detect yellow material that could be yellowcake or gullies that could expose buried yellowcake or tailings material are evident.

The most likely locations for yellowcake are in buildings in which uranium ore has been processed. However, it is expected that all such buildings will be removed during the decommissioning process. In the event that any such buildings are left standing following decommissioning, yellowcake and tailings material could be present in pipes, between walls, between ceilings and floors, or beneath the paint on painted surfaces of these buildings. Therefore, GM tube measurements should be made on the surface of any paint that has peeled off buildings on the mill site to indicate whether it contains yellowcake or tailings. If the deterioration of any buildings on the mill site exposes areas that were previously enclosed between walls or between ceilings or floors, the surface of the areas should be surveyed with shielded and unshielded GM tubes to indicate whether yellowcake or tailings are present.

CONTAMINATION OF STANDING SURFACE WATER

There should be no contaminated surface water on or around mill sites or tailings piles following closure of the sites. 40 CFR 264.228 requires that the owner or operator must "eliminate free liquids by removing liquid wastes or solidifying the remaining wastes and waste residues" during closure operations. However, contaminated surface water could accumulate following closure. Therefore, any surface water that is observed during inspections of the sites should be sampled.

The preferred method for collecting a sample of surface water is to use a small peristaltic pump to pump water through a filter and then directly into a sample container containing a preservative. Peristaltic pumps are preferred over many other types of pumps because water contacts only the inert pump tubing of these pumps, and because cross-contamination can be avoided by replacing the pump tubing. The collection of surface water samples by dipping an open container in the water can lead to difficulties (Korte and Kearl 1984). The concentrations of dissolved oxygen and carbon dioxide in samples of standing water may change rapidly if the samples are allowed to come in contact with air in open containers, especially if there is a temperature difference between the samples and the ambient air. The resulting changes in the pH and the redox potential can cause contaminants to either dissolve or precipitate. The precipitation of iron hydroxides, followed by the co-precipitation of other species, is a common occurrence.

The procedures for the analysis of surface and groundwater samples are too lengthy to be described in detail in this report. Procedures that can be used for the analysis of water samples for pH, Eh, alkalinity, specific conductance, dissolved oxygen, nitrate, and uranium are described by Korte and Ealey (1983). Trace elements can be measured using techniques such as neutron activation and x-ray fluorescence. Uranium and its daughters, including ^{226}Ra, can be measured using intrinsic-germanium-diode gamma-ray spectrometers.

CONTAMINATION OF GROUNDWATER

Groundwater contamination has been detected around tailings piles at operating mills. Operating mills are required to maintain groundwater sampling programs and to initiate corrective measures whenever groundwater contamination is detected. The fact that tailings are added to the tailings pile in the form of a slurry greatly increases the probability of groundwater contamination. It has been estimated that the probability of groundwater contamination following closure should be only 5% of that during operations because no more water would be added to the pile following closure (unless vegetation growing on the cover was irrigated). However, the percolation of precipitation, residual water remaining in the pile, or groundwater through the tailings, could still cause groundwater contamination following closure. Also, groundwater beneath the pile that became contaminated during mill operations might not reach monitoring wells until after closure. Groundwater movement can be very slow, so it could take many years for contaminated water to reach locations where it might be used for drinking or irrigation purposes. In addition, chemical changes in the pile could increase the rate of leaching contaminants several years after closure. Pyrite oxidation, for example, increases the acidity, and therefore increases the mobility of acid-soluble species. If the groundwater becomes contaminated it cannot be restored by simply eliminating the source. Therefore, groundwater should be monitored indefinitely following closure of the site.

The groundwater monitoring system should consist of a sufficient number of wells to yield groundwater samples from the uppermost aquifer that represent 1) the quality of groundwater that has not been affected by leakage from the regulated unit, 2) the quality of groundwater passing the point of compliance, and 3) the quality of water reaching locations where it might be used for drinking or agricultural purposes. All monitoring wells should be encased in a manner that maintains the integrity of the monitoring well borehole. This casing should be screened or perforated and packed with gravel or sand, where necessary, to enable the collection of groundwater samples. The annular space (i.e., the space between the borehole and the well casing) above the sampling depth should be sealed to prevent contamination of samples and the groundwater.

Federal regulations specify procedures that must be followed to monitor groundwater during the operation of uranium processing sites. It would be desirable to follow these same procedures and to measure the same constituents at the same locations following closure of the sites. Thus, data obtained during the operational phase could be used to identify trends in the contaminant concentrations following closure. Therefore, the procedures described below for monitoring groundwater following closure have been based on the procedures required during operations.

Well Locations

The network of monitoring wells should be designed to enable measurement of groundwater contamination at as many locations as is economically feasible. Monitoring wells should be placed upgradient of, within, and downgradient of tailings piles. A minimum of one upgradient well is required by the Resource Concentration and Recovery Act of 1976 (40 CFR 265).

Because measurements before and after closure will provide information on trends in contaminant concentrations, groundwater monitoring should be continued whenever possible at wells that were monitored during operation of the sites. However, there are likely to be cases where previous measurements of contaminant concentrations and studies of the hydrology and geological conditions of the site indicate that additional locations should be monitored.

Background Wells. Upgradient monitoring wells are used to determine the background concentrations of the contaminants monitored. If more than one surface water drainage system flows through the study area, monitoring wells should be placed in the alluvium underlying each drainage. Upgradient wells should also be placed below any stream confluences to ensure that the water quality of the tributary stream underflow is monitored (Korte and Kearl 1984). Upgradient wells should be placed as close to the tailings pile as possible but far enough away to ensure that water from the tailings pile is not drawn into the well during either sampling or hydrolic testing. It is necessary to know the minimum water sampling rate and the hydrolic conductivity and storativity of the formation to determine the minimum distance the wells can be placed from the pile. Background quality may be based on the sampling of wells that are not upgradient of the tailings pile in cases where 1) upgradient wells cannot be determined because of hydrologic conditions or 2) sampling at other wells will provide an indication of background groundwater quality that is as representative or more representative than that provided by upgradient wells.

It is necessary to make numerous background measurements to determine average background concentrations, variabilities, and temporal changes, because groundwater that is upgradient of the tailings pile could take years to reach downgradient wells. Therefore, a minimum of one sample should be taken from each well, and a minimum of four samples should be taken from the entire system should be used to determine the background groundwater quality each time the system is sampled.

Monitoring Wells Within the Tailings Pile. Monitoring wells should be located within and at the boundaries of the tailings disposal area to provide information on the concentrations of contaminants present in the groundwater underneath the tailings piles. This information is needed to determine the degree of saturation of individual contaminants. If the groundwater is saturated with respect to a particular constituent, the concentrations of that constituent would not be expected to decline in downgradient wells in the near future.

Downgradient Monitoring Wells. The majority of the wells in the monitoring network should be placed downgradient of the tailings pile (Korte and Kearle 1984). These wells should provide information needed to determine the approximate geometry of any contaminated zones and the potential for the advancement of the contaminated zone toward existing and potential water supplies. Several of the downgradient wells should be placed at compliance points to determine whether the site is in compliance with federal regulations. Others should be aligned parallel to the probable direction of contaminant movement near the boundary of the contaminated zone to provide information on the rate of movement of the contaminated zone.

Frequency of Measurements

Model calculations, previous measurements of contaminant concentrations, and groundwater flow rate measurements should be used to determine the frequency of the measurements required. Initially the measurements should be made at least annually. If no groundwater contamination is observed during the first several years following the closure of a site, the monitoring frequency may generally be decreased to the maximum frequency recommended in Table 1 during subsequent years. However, monitoring on a yearly, quarterly, or even monthly basis might be required indefinitely in cases where there is relatively rapid groundwater transport between monitoring wells and locations where the groundwater might be used for agricultural or drinking purposes.

Monitoring Procedures

The groundwater monitoring program should include consistent sampling and analysis procedures designed to provide a reliable indication of groundwater quality below the waste management area. There should be written procedures and techniques for sample collection, analysis, preservation, shipment, and chain of custody control. Procedures that can be used for the collection and preservation of groundwater samples are described by Korte and Kearl (1984).

Groundwater contamination resulting from tailings may consist of a wide spectrum of radioactive and nonradioactive toxic species with varying mobilities. The species having the highest mobilities reach the monitoring wells first. They provide a reliable indication of the presence of hazardous constituents in the groundwater. Therefore, it should be sufficient to analyze the groundwater for parameters such as sulfate or specific conductance with high mobilities and concentrations, as long as the concentrations of these parameters do not significantly exceed background levels. However, when concentrations of these parameters, called indicator parameters, begin to exceed background levels, the groundwater should be analyzed for the whole spectrum of possible hazardous contaminants.

The indicator parameters monitored during the operation of the facility are specified by the Regional Administrator of the EPA in the facility permit. Monitoring of these indicator parameters should continue following closure of the facility.

Procedures used for the chemical analysis of water samples are described by Korte and Ealey (1983). The elevation of the groundwater surface should be measured each time the groundwater is sampled, because groundwater surface elevations can be used to estimate groundwater flow rates.

Statistical Methods

Appropriate statistical techniques must be used to determine the precision and reproducibility of the measurements and to determine whether downgradient concentrations are significantly greater than background concentrations. The statistical techniques used should be comparable to those required during the operation of the site.

Before the closure of a site, when the level of a constituent at the compliance point is to be compared to the constituent's background value and that background value has a sample coefficient of variation less than 1.00, at least four portions must be taken from a sample at each well at the compliance point. The difference between the mean of the constituent at each well (using all portions taken) and the background value for the constituent is significant at the 0.05 level using the Cochran's Approximation to the Behrens-Fisher Student's t-test. If the test indicates that the difference is significant, the same procedure must be repeated (with at least the same number of portions as used in the first test) using a fresh sample from the monitoring well. If this second round of analyses indicates that the difference is significant, a statistically significant change has occurred. An equivalent statistical procedure may be used to determine whether a statistically significant change has occurred if the Regional Administrator finds this procedure to be satisfactory.

In all other situations in a detection or compliance monitoring program, a statistical procedure must be used that ensures that any migration of hazardous constituents from a regulated unit into and through the aquifer will be indicated. In the facility permit, the regional administrator may specify a statistical procedure that is appropriate for distribution of the data used to establish background values or concentration units. It must also balance the probability of falsely identifying a non-contaminating regulated unit and the probability of failing to identify a contaminating regulated unit. These same statistical procedures should generally be used when groundwater is monitored following the closure of the site so that pre-and post-closure data can be more readily compared to establish trends.

SECURITY MEASURES

The removal and use of tailings material from tailings piles must be prevented in order to protect the environment and public health. However, it is impractical, and probably unnecessary (at least in nonurban areas), to require that active measures, such as guards and security fences, be used to prevent the misuse of tailings material for periods as long as 1000 yr. It is unlikely that funding agencies would provide monetary support for such measures for long periods. Therefore, the use of fences and signs to prevent human intrusion into tailings piles is discussed in this section.

FENCES

Unattended, well-constructed security fences might last for a considerable time, but would surely deteriorate long before 1000 yr had elapsed. Also, such fences, constructed of valuable materials, would be subject to theft. Therefore, 40 CFR 192 recommends that passive measures be used to prevent the removal and misuse of tailings. In most cases, the thick earthen cover required to reduce radon emissions would provide adequate protection against the misuse of tailings, except by major earth-moving activities. Therefore, it generally should not be necessary to enclose tailings piles in nonurban areas within fences.

Tailings situated in urban areas, however, would be more susceptible to misuse than tailings located in nonurban areas. Also, tailings removed from a pile in an urban area present a potential for radiation exposure to a greater number of people. Therefore, tailings piles situated in urban areas should probably be enclosed and isolated by security fences. The fences should be inspected regularly to ensure that their integrity is maintained. The inspections could be carried out by local residents.

SIGNS

Signs should be placed around tailings piles warning of the dangers involved in the use of the tailings or of excavations at the site. These signs would be particularly necessary hundreds of years from now when the memory, or even the records, of the nature of the tailings material might be lost. Durable signs warning of the dangers should be placed around the tailings piles at locations that render them readily visible to individuals approaching the tailings piles from any direction. These signs would be expected to deteriorate. They should be inspected during the regular surveillance of the sites and replaced whenever necessary. However, it is not possible to guarantee that these signs would be maintained for 1000 yr. Therefore, stone markers (monuments) designed to last for as long as possible should also be placed on each side of the tailings pile to warn of the dangers of tailings misuse. The stone markers (and signs) should be placed beside any access roads.

Ideally, there should not be any uranium byproduct material remaining on the mill sites following decommissioning. However, there is always the possibility that some buried tailings material will be present that was not detected during decommissioning and post-decommissioning surveys. Therefore, stone markers should be placed around the perimeters of mill sites and near access roads. The stone markers should warn that gamma radiation measurements should be made during any future excavations on the site to determine whether tailings material has been encountered. The markers should warn that any tailings material should be buried to prevent public exposure.

DECISION TREE

A decision tree listing the observations and measurements recommended in this report is shown in Figure 1. The criteria recommended for determining what measurements should be made and whether remedial action is needed are included.

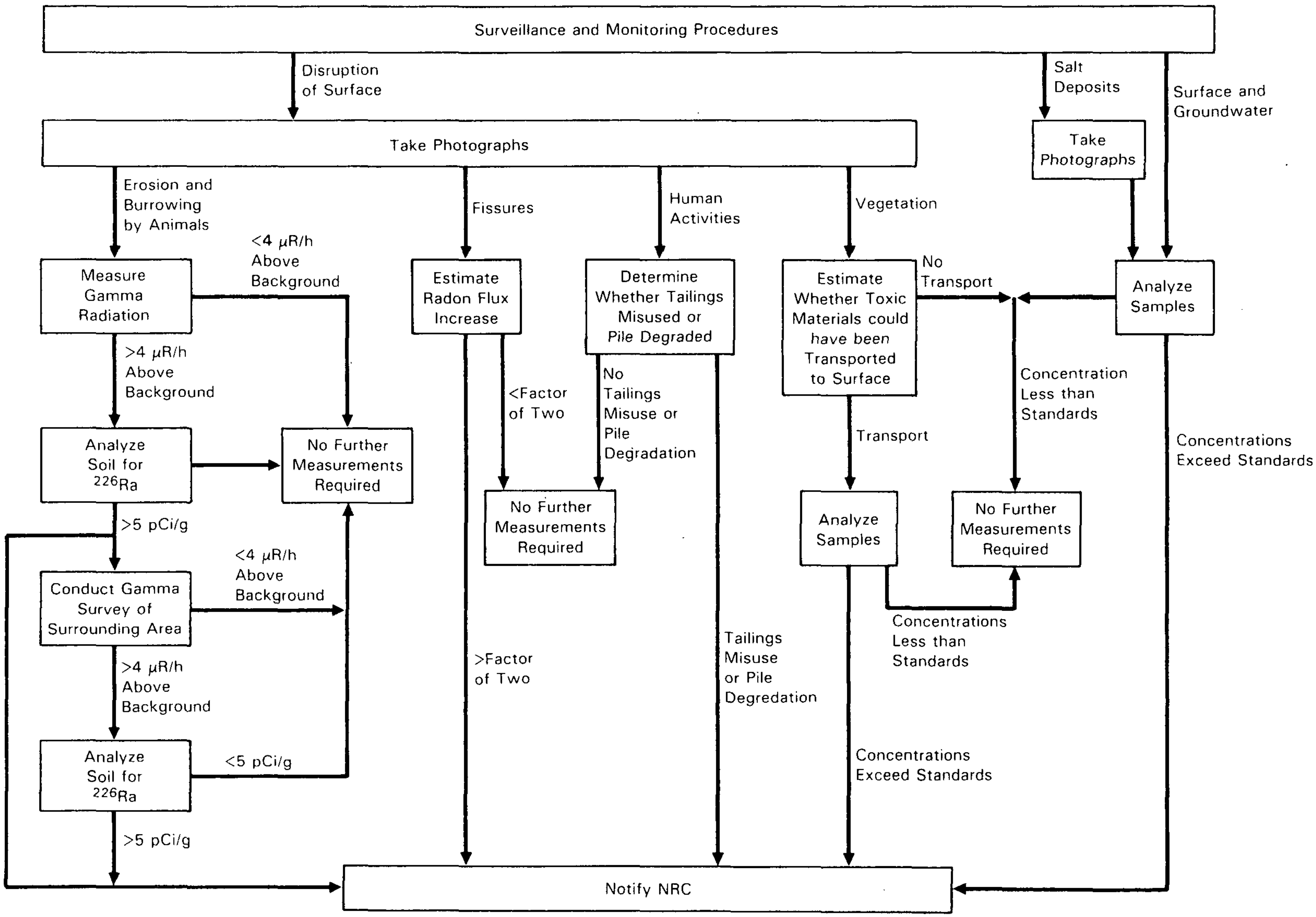

FIGURE 1. Decision Tree

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APPENDIX

RADON FLUX MEASUREMENTS

APPENDIX

RADON FLUX MEASUREMENTS

SPATIAL VARIATIONS

The determination of average radon fluxes from disposal sites is complicated by the fact that there may be large spatial and temporal variations in the flux from a given disposal site. The flux from a tailings pile can vary with location on the pile because of variations in thickness of the pile and its cover, particle size, ^{226}Ra concentration, moisture content, and emanating power of the material added to the pile (the emanating power is the fraction of the radon atoms produced by ^{226}Ra that escapes the crystal lattice and is free to diffuse). Measured radon fluxes have varied with location on tailings piles by more than an order of magnitude (Silker and Heasler 1979; Ford, Bacon and Davis Utah Inc. 1981).

According to Leggett et al. (1978), the number of locations at which a parameter must be measured to determine its average value with a precision of 25% at the 95% confidence level is given by

$$\text{Number} = 45(\text{coefficient of variation})^2 \qquad (A.1)$$

Holoway et al. (1981) give an equation specifying the number of measurements required to obtain other degrees of precision.

The coefficient of variation of the radon flux measurements made by Silker and Heasler (1979) at several locations on the Grants, New Mexico tailings pile was 0.74. Measurements by Freeman (1981) of the radon flux from the Grand Junction tailings pile showed a coefficient of variation of 0.84. The coefficients of variation of the radon flux measurements made by Ford, Bacon and Davis Utah Inc. (1981) also averaged 0.84 for several uncovered tailings piles. To determine the average flux within 25% at a 95% confidence level (according to Leggett's equation), the flux must be measured at 25 locations if the coefficient of variation is 0.74 and at 32 locations if the coefficient is 0.84.

The variation of the radon flux across a covered tailings pile could be somewhat less than that across an uncovered pile because horizontal diffusion of radon in the cover material might lower horizontal concentration gradients. However, if the cover material is not uniform, or if defects develop in it, the spatial variation of the flux from a covered tailings pile could be greater. The coefficient of variation of the radon flux measurements made by Ford, Bacon and Davis Inc. (1981) averaged 0.66 for several tailings piles covered by about 6 in. of soil. According to the equation measurements at only 20 locations would be required for this coefficient of variation. However, Leggett et al. (1978) also recommend that measurements be made at a minimum of 30 locations. It therefore appears that in most cases flux measurements should be made at 30 locations, although in some cases measurements of more locations are required because of higher variations in the radon flux.

TEMPORAL VARIATIONS

The radon flux from a given location at a disposal site also varies with time as a result of changes in meteorological conditions, moisture content of the tailings, and perhaps settling of the cover material. According to Baver (1956), the meteorological factors influencing the radon flux are, in order of decreasing importance, rainfall, variations in barometric pressure, variation of soil and atmospheric temperature, and wind speed.

The radon flux will depend greatly on the moisture content of the tailings and cover material. The fraction of radon atoms produced by ^{226}Ra decay that escape the crystal lattice increases with moisture content. When a ^{226}Ra atom decays by alpha particle emission, the radon atom that is formed recoils in a direction opposite to that taken by the alpha particle. If the recoiling atom comes to rest inside a grain of the material, it is very likely to remain entrapped. If it comes to rest in a pore it may be free to diffuse into the atmosphere. Since the pores of compacted natural materials are likely to be smaller than the recoil range of radon atoms in a gas, a recoiling atom that enters a gas-filled pore is very likely to cross the pore and become entrapped in a neighboring grain (Tanner 1980). The recoil range in water is about 100 times less than that in air. Therefore, the probability that a recoiling atom will stop in a pore is greatly enhanced if the pore is water-filled. However, since the rate of diffusion in water is much less than that in air, the rate of diffusion (into the atmosphere) of the radon atoms that have escaped the crystal lattice is lowered by increasing the moisture content of either the tailings or the cover material. Therefore, increased moisture content could either raise or lower the radon flux, depending on whether the effect of water on the emanating power or on the diffusion of radon through the pores predominates. Strong and Levins (1982) found that the radon flux from a column of mill tailings increased by a factor of 3.5 when the moisture content increased from 0.2% to 5.7% by weight. It then increased slowly with increasing moisture content until saturation was reached. Then it decreased sharply. Of course, increasing the moisture content of the tailings pile cover always decreases the flux from the pile by decreasing the rate of diffusion of radon through the cover.

The number of measurements required to determine the average flux at a given location with a precision of 25% at the 95% confidence level is given by Equation (A.1). There have been some repeated measurements at given locations on tailings piles over extended periods of time. On the average, the measurements of Silker and Heasler (1979), Marple and Clements (1977), and Clements et al. (1978) show a coefficient of variation with time of about 0.4. According to Equation (A.1), six measurements would be required if the measurements showed this coefficient of variation. Because the variation would be different for different locations, so the total number of measurements required at each location would be determined using Equation (A.1) and the coefficient of variation of the measurements at that location.

RECOMMENDED FLUX MEASUREMENT PROCEDURES

Average radon fluxes from covered tailings piles can be determined from measurements at the grid points of a rectangular grid. The first time the average radon flux is determined for a given tailings pile, the flux measurements should be made at about 30 locations on a rectangular grid. The number of locations measured during subsequent determinations of the average flux should be at least the number calculated, using Equation (A.1), from the coefficient of variation of the fluxes measured during the previous determination. The flux at each grid point should be measured approximately every other month during the course of a year. Measurements to determine the average flux should not begin until at least five years after the completion of the cover, because it could take several years for the pile and its cover to approach equilibrium moisture conditions. The time required would depend on local meteorology and the physical properties of the pile and cover material. If the coefficient of variation of the measurements at each location is so large that the average flux at each location is not determined with a satisfactory degree of precision after six measurements, then enough additional measurements to satisfy Equation (A.1) should be carried out at equally spaced time intervals during the following year.

Radon fluxes can be measured using the charcoal cannister method described by Countess (1978). (The various techniques available for measuring radon fluxes have not as yet been adequately calibrated. If calibration measurements later show that the charcoal cannister method is not sufficiently accurate, and that another method suitable for conducting surveys gives significantly better results, then this other method should be used instead of the charcoal cannister method.) When using the charcoal cannister method, care must be taken to place the cannisters as close to the ground surface as possible to minimize the buildup of radon between the cannister and the ground. Such a buildup would decrease the radon flux.

It is best to make the radon flux measurements over a period of at least one, and preferably two or three, days to minimize the effects of diurnal and other short-term variations. It is not practical to sample over much longer periods. Because radon has a 3.8-day half-life, most of the radon originally collected would decay away before measurement if longer sampling periods were used. The charcoal cannister should be checked to verify that it has 100% collection efficiency, and is not saturated during the sampling period.

Once the average flux from a covered tailings pile has been determined, it should not be necessary to measure fluxes again until other observations or measurements indicate that a serious deterioration of the cover has occurred. There is no performance standard for radon fluxes, so small increases in the flux do not merit remedial action. However, if a serious deterioration occurs, radon fluxes should be measured again to determine whether there has been a large increase in the flux. If the average flux has increased significantly, the cause of the increase should be identified.

Soil moisture contents should be measured whenever radon fluxes are measured. This helps determine whether changes in the average flux are due to degradation of the cover to changes in the moisture content resulting from short-term climactic conditions, or to the approach of the moisture content close to equilibrium values.

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(g) Mexican Hat, Utah, DOE/UMT 109, FBDU-360-03
(h) Lakeview, Oregon, DOE/UMT 110, FBDU-360-18
(i) Falls City, Texas, DOE/UMT 111, FBDU-360-16
(j) Ambrosia Lake, New Mexico, DOE/UMT 113, FBDU-360-13
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13. ABSTRACT (200 words or less)

Natural processes and human activities could expose the public to radioactive and nonradioactive toxic materials from uranium processing sites in the years following decommissioning. This report describes security, surveillance, and monitoring methods that can be used to prevent or detect the spread of these materials and to determine when cleanup or preventive maintenance is required. Visual observations carried out at least annually can be used to detect any rapidly developing conditions that could expose the public to toxic materials. If no such conditions develop during the first several years following decommissioning, then visual observations can be made at less frequent intervals to detect more gradual changes. Gamma-radiation, ^{226}Ra, and ^{238}U measurements at locations showing significant deterioration can be used to determine whether residual radioactive materials that exceed existing standards have been exposed. Measurements of contaminant concentrations in standing surface water and groundwater can detect the spread of water containing elevated contaminant concentrations. Durable signs and stone markers can be used to warn of the possible dangers associated with these sites.

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