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Determination of Compliance with Criteria for Final Tailings Disposal Site Reclamation

Prepared by P. A. Beedlow, G. W. Gee, J. F. Cline, W. H. Walters, H. D. Freeman

Pacific Northwest Laboratory
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DETERMINATION OF COMPLIANCE WITH CRITERIA FOR FINAL TAILINGS DISPOSAL SITE RECLAMATION

ABSTRACT

This report provides methods and procedures that can be used to verify compliance with Environmental Protection Agency (EPA) engineering standards for uranium mill tailings disposal sites. EPA standards for radon emissions, long-term isolation, and protection of water quality are discussed. Tailings isolation technologies are reviewed. Information the licensee needs to provide for the regulating agency to determine compliance is presented, as is the actual compliance criteria.

EXECUTIVE SUMMARY

The Environmental Protection Agency (EPA) has set standards for uranium mill tailings disposal in order to discourage future use of tailings sites, to protect people from radon, to prevent the spread of tailings, and to protect ground water. The standards for radon release are 20 picocuries per square meter per second. Radium-226 standards are 5 picocuries per gram of soil for the top 15 centimeters of soil, and 15 picocuries per gram of soil for the next 15 centimeters below the top 15 centimeters. Long-term protection standards require effective control for 1000 years to the extent reasonably achievable. Ground water protection standards require that background pollutant levels be maintained.

Tailings isolation technologies have been developed from research sponsored by the Department of Energy (DOE) and the Nuclear Regulatory Commission (NRC). Covers to reduce radon emissions are constructed, alternatively, of earth, multilayer earth, or asphalt emulsion. These protective covers are also designed to prevent erosion, biotic intrusion, and excessive water infiltration. Ground-water protection techniques prevent wastes from reaching the ground water. Liners are the basic strategy for leachate control. Protective covers control water infiltration and become the prime element for leachate control after final closure. Monitoring wells are used to assess the adequacy of the containment system.

Determination of compliance for disposal sites is based on environmental characteristics of the site and the surrounding area, tailings composition, and design and application of the containment system. Radon emission and radium concentration standards are determined by measurements of radon flux and radium concentrations in the soil. Protective covers are evaluated using site data and mathematical models. Assessments of plant and burrowing animal intrusion potential are based on site data and mathematical models. Human intrusion is evaluated from accidental intrusion scenarios as no method is felt to be capable of preventing intentional intrusion. Ground water protection is evaluated using tailings composition, climatic, and geochemical information.

Determination of compliance with EPA standards should be based on evaluation of information provided by the licensee and inspection of the sites. Compliance with the radon flux standard can be verified by either calculation or by measurement. Radium concentrations should be measured at the sites. Protective covers should be evaluated based on their ability to resist erosion, prevent biotic intrusion, and control water infiltration. Compliance with water protection standards will depend upon which standards are applicable at each site.

CONTENTS

INTRODUCTION

To reduce and control the hazards associated with uranium and thorium mill tailings, the U.S. Environmental Protection Agency (EPA) has established public health and environmental standards (40 CFR 192) under the Uranium Mill Tailings Radiation Control Act of 1978 (PL-95-604). These standards will be implemented by the U.S. Nuclear Regulatory Commission (NRC) and its Agreement States that have approval to license uranium and thorium mills.

Standards for tailings disposal are based on the following health and environmental objectives (EPA 1983):

1. To discourage future use of tailings in or near buildings.
2. To protect people from radon emanating from tailings piles.
3. To prevent the surface spread of tailings.
4. To protect groundwater.

These objectives form the basis for containment system designs. Compliance criteria will be used to ensure that containment systems meet the disposal standards. This report provides methods and procedures that can be used to verify that tailings containment systems comply with EPA engineering standards.

STANDARDS OF THE ENVIRONMENTAL PROTECTION AGENCY

STANDARDS FOR RADON-222

The EPA has set standards [40 CFR Section 192.32(b)(1)(ii)] for radon release to be applied at the end of the closure period (i.e., after the disposal site reclamation has been completed). These standards state that the radon-222 release from the surface of the disposal site cannot exceed an average flux of 20 picocuries per square meter per second (pCi/m^2s). The average is to be applied to the entire surface of each disposal area over a period of at least one year, but less than 100 years. Although the radon release from the cover material needs to be considered in the closure plan for each site, the standard applies only to the radon emissions from the uranium milling by-product materials.

STANDARDS FOR RADIUM-226

These radon standards apply only to the portion of the disposal site that has radium-226 concentrations in the soils, averaged over an area of 100 square meters. The limits are 5 picocuries per gram (pCi/g) averaged over the first 15 centimeters (cm) below the surface, and 15 pCi/g averaged over 15-cm thick layers more than 15 cm below the surface. These values are concentrations above background levels.

LONG-TERM ISOLATION OF TAILINGS

Long-term protection standards [40 CFR Section 192.32 (b)(1)(i)] require, to the the extent reasonably achievable, fully effective control for 1000 years or for 200 years minimum. The EPA (1983) investigated protection requirements for time periods from 100 to 10,000 years and concluded that existing knowledge permits the design of economically feasible control systems up to 1000 years. The time period of 200 to 1000 years was selected because it was uncertain whether some sites could endure without erosion damage for 1000 years even with the approved covers.

PROTECTION OF WATER QUALITY

The regulations specified by 40 CFR 192 for ground water protection require that background levels of pollutants be maintained or that drinking water standards be met at each tailings disposal site. The requirements are basically those specified by EPA for hazardous waste siting [Solid Waste Disposal Act (SWDA), EPA 1982b]. The EPA Regional Administrator is given authority either to enforce the standard maximum concentration limits for ground water listed in the following Table 1 or to establish alternate concentration limits if no threat to human health or environment will result from the alternate limits.

TABLE 1. Maximum Concentration Limits for Inorganic Constituents for Ground-Water Protection*

Constituent	Maximum Concentration Limit, mg/L
Arsenic	0.05
Barium	1.0
Cadmium	0.01
Chromium	0.05
Lead	0.05
Mercury	0.002
Molybdenum	0.05
Selenium	0.01
Silver	0.05
Combined Ra-226 and Ra-228	5 (pCi/L)
Gross alpha-particle activity (excluding radon and uranium)	15 (pCi/L)

*From Solid Waste Disposal Act, EPA 1982b.

In addition, the element uranium is required by the SWDA to be monitored; it is included on the list of over 300 hazardous constituents (mostly organic) which in elevated concentrations are toxic to humans (see Appendix III of CFR 260, EPA 1982b).

The standards for ground-water protection as written for the SWDA (EPA 1982b) specify the point of compliance at which ground-water protection standards apply and at which monitoring is required. This point is a vertical surface that extends down into the uppermost aquifer underlying the regulated units and is located at the downgradient limit of the waste management area (EPA 1982). The waste management area is the limit projected in the horizontal plane of the area on which waste will be placed during the active life of a regulated unit. This is basically the "edge of the pile." The waste management area includes horizontal space taken up by any liner, dike, or other barrier designed to contain waste. Therefore, no contamination should be observed beyond the edge of the pile.

The regulatory agency may establish alternate concentration limits provided that, after considering practicable corrective actions, these limits are as low as reasonably achievable. In any case, the primary standards set in Table 1 must be met at distances beyond 500 m from the edge of the disposal area or the site boundary, whichever is the shorter distance.

TAILINGS ISOLATION TECHNOLOGIES

This section discusses results of research of tailings isolation technologies on which the compliance criteria are based.

EARTHEN AND ASPHALT BARRIERS THAT LIMIT RADON EMISSION FROM TAILINGS

The NRC and DOE's Uranium Mill Tailings Remedial Action Program (UMTRAP) have sponsored research on the design of covers to reduce the release of radon from uranium tailings to the atmosphere. Earthen, multilayer, and asphalt emulsion covers were examined. These covers have been field-tested at Grand Junction, Colorado (Hartley et al. 1983) for nearly four years and all three have been shown to be effective in reducing the radon emission to below EPA standards.

Earthen covers generally consist of a layer or layers of locally available soil which has been compacted, possibly with the addition of water. This cover slows the migration of radon to the atmosphere which allows it to decay to solid daughter products that remain in the soil. The effectiveness of an earthen cover is influenced most strongly by the moisture content of the soil, and also by the soil particle size distribution. Generally soils that have small particle sizes, such as clays, are more effective covers than soils with larger particle sizes, such as sand. Diffusion coefficients for earthen cover material can range from 0.05 to 0.005 cm^2/s which means that a tailings pile with a radon emission rate of 300 pCi/m^2s would require 4.5 and 1.0 m of soil, respectively, to meet the EPA 20 pCi/m^2s limit (Gee et al. 1984). The average costs of a 3-m earthen cover have been estimated for UMTRAP sites to be approximately $27 per square meter in 1983 (Hartley et al. 1983).

Multilayer covers are earthen systems that have been engineered to optimize the radon control properties (soil moisture and compaction). The multilayer system consists of a tightly compacted clay/gravel layer that is hydraulically isolated from the surface soil by a "capillary barrier." The clay/gravel barrier is a mixture of bentonite clay, soil, and gravel chosen to minimize the void volume of the material. The clay/gravel barrier is typically 15 to 40 cm thick. The capillary barrier is a 10-cm layer of washed rock. The cover top soil is a 1-m layer of locally available soil. Diffusion coefficients for multilayer barriers can be as low as 10^{-6} cm^2/s which would result in radon fluxes substantially lower than the EPA limit. In two field tests, however, optimal multilayer barriers have not been achieved, although the barriers would still meet the EPA limit. The main disadvantage of multilayer systems is cost, which varies according to material availability. For the inactive tailings site at Durango, Wyoming, costs were estimated at $35.00 per square meter. Costs for the Grand Junction field test (UMTRAP), however, were $57 per square meter (Baker and Hartley 1982).

The asphalt-emulsion admix seal is a radon-gas barrier consisting of an 8-cm-thick asphalt-emulsion admix that is covered by 1 m of soil. The asphalt-emulsion admix layer acts as a gas-tight diffusion barrier, and the

soil protects the admix seal from weathering and stabilizes the admix. The admix is a mixture of asphalt emulsion and fine concrete sand. After curing, the admix contains about 22 wt% asphalt on a dry aggregate basis and less than 1 wt% residual water. Although the admix has greater structural strength than pure asphalt, it is fairly ductile and will cold flow over a period of time. The sand is much finer aggregate than is usually used in asphalt road pavements. Therefore, the admix has a higher asphalt-aggregate bonding surface area per unit volume than normal road pavements. The very high asphalt content, coupled with the fine aggregate, gives the admix seal a low void volume resulting in a very tight radon barrier. Soil protects the asphalt from ultraviolet light which is detrimental to the longevity of the seal. The asphalt-emulsion admix typically has a diffusion coefficient for radon which is less than 10^{-5} cm^2/s. Only a very thin layer of admix would be needed to reduce the radon emissions from a tailings pile to the EPA limit. However, a thicker barrier is used to provide better mechanical stability. The cost of the Grand Junction field-tested asphalt-emulsion/soil barrier is approximately $27 per square meter; similar to the cost of a 3-m earthen cover (Baker and Hartley 1982).

MEASURES TO MAINTAIN EFFECTIVENESS OF THE CONTAINMENT SYSTEM

A single tailings pile could conceivably require several different types of protective covers depending on the expected erosive forces, biotic intrusion potential, and soil moisture dynamics. Sloped areas that are subject to higher erosion rates may require different treatments from those that are level. Where stream erosion is expected, relatively massive rock riprap may be required. Portions of the tailings above the projected flood level will require protection from wind and overland flow. Plant and animal intrusion potential will vary from site to site and from place to place on a single pile. Soil moisture requirements and designs to control infiltration will depend on the type of radon barrier and the surface cover.

Erosion

Erosion protection requirements will vary according to expected erosion stresses. The degree of protection ranges from that provided by established vegetation to that of heavy-duty rock riprap. Rock riprap is placed on the slopes and around the base of the impoundment to prevent flood damage and gully encroachment. Rock riprap is also used on slopes that are susceptible to gullying from impoundment run-off. Piles or portions of piles not exposed to flooding will not need as much protection. Where riprap is used, filter layers of rock and gravel are necessary to prevent leaching of the soil cover through the interstitial openings in the riprap.

Slopes greater than approximately 10% are particularly vulnerable to erosion (Beedlow 1984). Stabilizing these slopes is critical in preventing both wind and water damage to the entire pile. Such slopes above the

design flood level may be protected by light-duty rock riprap consisting of gravel and cobble-sized material (Beedlow and Hartley 1984).

On flat and gently sloped (up to 10%) portions of the tailings pile, vegetation, a combination of vegetation and surface rock (rock mulch), or rocky soil can be used (Beedlow 1984). The potential vegetative cover at a particular site can be used for determining the potential composition of the surface cover. For example, rock mulch would be used at sites that are not likely to support enough vegetation to stabilize the soil.

Plant and Animal Intrusion

Two types of biological barriers have been developed for use on uranium mill tailings piles (Cline et al. 1982): 1) physical barriers to prevent animal burrowing and root growth, consisting of cobble placed over the radon barrier, and 2) polymeric carrier/biocide delivery systems to provide controlled release of a herbicide. Laboratory tests show that the chemical barriers can be effective for up to 200 years. Cobble barriers have been shown to be most effective when fine soil particles are prevented from filtering into the spaces between the stones. Cline et al. (1982) suggest additional guidelines for ensuring the effectiveness of biobarriers: 1) the zone beneath the barrier should be kept as dry as possible; 2) enough soil or other earthen material should be placed on top of the barrier to store annual precipitation; and 3) plant covers should be established, or other means provided, to remove excess water. The guidelines emphasize water control because plants and some animals (such as ants) tend to seek soil water, especially in arid areas. Thus, a zone of relatively high soil moisture in a cover or in the tailings is likely to attract plant roots and animals. The chances of successful exclusion are increased by efforts to ensure that soil moisture does not accumulate below the biotic barrier.

Human Intrusion

Three approaches to prevent human intrusion into repositories have been suggested: 1) isolate the site in a remote area, 2) construct adequate physical barriers, and 3) mark the site and attempt to convey information about the repository location, contents and associated risks to future generations (Adams et al. 1981). However, it is considered nearly impossible to prevent human intrusion over a 1000-year period (Kaplan 1982, Adams et al. 1981). Thus, it appears important that uranium mill tailings disposal sites be marked with structures that will survive and be visible for 1000 years (EPA-40 1983). Symbols and/or written language may be used to project the message comprehensibly to future generations (Kaplan 1982).

GROUND-WATER PROTECTION METHODOLOGIES

Liners

Containment is the basic strategy to protect ground water from hazardous liquid wastes. Since virtually all of the mill tailings disposal sites are in the western United States where evaporation can be used to reduce

contaminant volumes, synthetically-lined evaporation ponds are the recommended method for liquid disposal (EPA 1982b). Liner technology can be used to facilitate removal of liquids from a tailings site during its active life (including the closure period), thereby providing a greater assurance of long-term protection at the facility.

Protective Covers

After closure, a protective cover becomes the prime element for liquid effluent management strategy (Beedlow and Hartley 1984). A well-designed and maintained cover can be reasonably effective in reducing infiltration of liquids into the tailings, particularly at relatively dry sites. There is, however, considerable uncertainty regarding the long-term effectiveness of earth caps which may subside, crack or erode. Protection of the cover system against natural disruptive events for 200 to 1000 years cannot be guaranteed. For sites where considerable water infiltrates into the soil on an annual basis and the water table is shallow, considerable effort may be needed to design an adequate cover system.

Monitoring

Both up-gradient and down-gradient monitoring wells are needed to assess the adequacy of the tailings disposal design. Up-gradient monitoring wells located adjacent to the tailings pile are used to compile data on predisposal ground water, and down-gradient monitoring wells are used to assess the compliance of the tailings pile to the ground water quality standards.

INFORMATION NEEDED ABOUT THE SITE AND CONTAINMENT SYSTEM TO DETERMINE COMPLIANCE

Determination of compliance for tailings disposal sites is based on the following types of information: environmental characteristics of the site and the surrounding area, tailings composition, and design and application of the containment system. This section discusses the factors that affect radon emissions, erosion and leachate movement. Information needed to determined compliance is presented. The intent is to provide a basis for the compliance criteria presented in the last section of this report.

RADON EMISSION AND RADIUM CONCENTRATION

The compliance of a disposal site can be determined by calculating the radon flux from cover and tailings properties and measuring the radium concentrations, or by measuring the radon flux and radium soil concentrations at the site. The types of calculations and measurements needed to determine compliance follow.

Calculation of Radon Flux From the Disposal Site

The radon emissions from a tailings disposal site can be calculated from the physical and radiological properties of the tailings and cover materials. Methods for calculating radon emissions have been developed as part of the NRC regulatory guide on radon cover design (NRC 1984). Part of this regulatory guide is a handbook on calculating radon flux entitled "Radon Attenuation Handbook for Uranium Mill Tailings Cover Design" (Rogers et al. 1983a). The handbook describes how to calculate the radon emissions from bare and covered uranium mill tailings piles using the diffusion theory of radon migration. The calculations can be made either with a hand calculator or with more complex computer models.

To successfully use the handbook to calculate radon emissions from covered tailings, key properties of the cover and the tailings are needed. The most important parameters are the radon diffusion coefficient, bulk density, and porosity of the cover and tailings material. Also, the emanating power of the tailings must be determined.

The diffusion coefficient is by far the most important parameter in calculating the radon flux from the cover. The diffusion coefficient is a function of moisture content and compaction of the cover. These two parameters can be combined into a parameter known as moisture saturation which is the fraction of the void space of the soil filled with water. A data base of diffusion coefficients for a wide range of soil types has been accumulated over the last several years as part of UMTRAP-and NRC-sponsored research on radon diffusion through earthen covers. A correlation of this data base has been proposed by Rogers et al. (1983a). The diffusion coefficient for a cover can be estimated by:

$$D = 0.07 \exp -4m(1-P^2+m^4) \quad (1)$$

where

D = diffusion coefficient, cm^2/s

m = moisture saturation, cm^3 water/cm^3 soil

P = porosity.

This correlation has a geometrical standard deviation of 2.0. However, individual estimates for a particular soil at a given moisture may be in error by as much as an order of magnitude, especially at higher values of m.

Calculation of the radon emission from a disposal site is subject to uncertainties associated with the estimation of the diffusion coefficient, source term and spatial variations in the properties of the cover material. In addition to the errors introduced by using the correlation above, spatial variability of the moisture content and compaction of the soil across the disposal site could result in insufficient cover to meet the standard. Moreover, the soil used as the cover could vary significantly, especially if there was more than one source of material used for the cover. The large uncertainties that may be encountered must be considered when determining compliance by calculated methods. The careful implementation of a good quality control program during cover placement can minimize the uncertainties associated with variations in soil type, moisture and compaction.

Measurement of Radon Flux From the Cover

An alternative to calculating the flux from a disposal site to determine compliance is to measure the radon flux from the cover. Several techniques have been used in the past to measure radon flux including the accumulator can method, activated carbon canisters, and flow-through techniques. Each of these techniques have been described in detail (Rogers et al. 1983a; Freeman 1981; Hartley et al. 1983). Comparisons of these techniques on a homogenized dried tailings source have been reported by Rogers et al. (1983a) and Hartley et al. (1983). The cross comparison showed that reliable values could be obtained from any one of the techniques as long as the limitations of each technique were recognized and incorporated into the measurement procedure. As long as the limitations of each technique were not exceeded, radon fluxes were measured to within 10% of the theoretical flux calculated from the radium concentration, emanating power, and tailings depth. This is an ideal case and may not be representative of the performance under other conditions (e.g., moist tailings, large change in barometric pressure, etc.).

Another problem associated with measurement of radon flux is that the techniques are only valid for short measurement times (usually less than 48 h). These short measurement times may not be representative of the annual average radon flux due to the large temporal fluctuations in radon flux over the year. This drawback can be overcome by making several sets of measurements during the year. A quantitative understanding of how radon

flux is affected by meteorological parameters would allow short-term radon flux measurements to be used to estimate the annual average.

Measurement of Radium in the Soil

Because EPA standards do not apply to areas of the disposal site that have low radium concentrations (5 pCi/g or less in the top 15 cm of soil; 15 pCi/g or less in the next 15 cm of soil), it is important that these areas be defined so unnecessary efforts for containment are avoided. Some areas adjacent to the tailings pile may be contaminated with windblown or spilled tailings that could easily be moved to the tailings pile to reduce the area to be contained.

Identification of areas that will exceed the 5 or 15 pCi/g standards can be done using a variety of techniques including gamma spectroscopy of cored soil samples and gamma-radiation exposure rates. The exposure rates will not directly give the activity of radium-226 in the soil, but they are very useful in locating "hot" spots which can be further analyzed by gamma spectroscopy.

The gamma spectroscopy method of radium analysis is fairly straightforward. The equipment and procedures that can be used are widely documented in the literature (Adams and Dams 1970). Either NaI (Tl) or germanium detectors can be used along with single or multichannel analyzers. The soil is usually sealed in an airtight container and allowed to reach secular equilibrium (about 30 days) between the radon and radium. The radon daughters (usually 609 keV peak of Bi-214) are used to quantify the radium in the soil. This method can be relatively costly to perform on a great number of samples due to the extensive amount of time needed for sample preparation and counting. Therefore, it is desirable to have a screening tool for identifying contaminated areas. The most suitable tool for this purpose is the portable NaI(Tl) gamma radiation detector (also known as a micro-R-meter).

The micro-R-meter responds to a wide range of gamma radiation. This can be a detriment if materials other than radium-226 are present. However, for normal tailings pile situations, the meter can be calibrated and adjusted so that it responds only to radiation in the energy range of radium or its daughters. The micro-R-meter can be used to make many more measurements than would be possible with gamma spectroscopy alone. The areas that show radiation exposure rates greater than 20 μR/hr will be very likely to contain Ra-226 concentrations greater than 5 pCi/g, and should probably be analyzed with germanium diodes so that the nature of the contamination (tailings or ore) can be identified (Young 1983b).

LONG-TERM PROTECTION FROM EROSION AND BIOTIC INTRUSION

Evaluating protective covers for uranium mill tailings requires information gathered directly from a particular site and from mathematical models (Beedlow and Hartley 1984). Methodologies for evaluating protective covers are discussed in the following sections.

Erosion

The location of an impoundment in a watershed drainage system will largely determine the type of erosion to be considered in design. All above-ground tailings impoundments will be subjected to overland erosion processes from rainfall runoff. Those located in the lowland watershed areas or flood plains may also be subjected to flood erosion.

Overland erosion involves the processes of sheet and rill erosion. These processes begin with the wetting and detachment of the soil by rain- drops which break down soil aggregates for the transport of particles. This leads to sheet erosion that moves fine soil particles, such as clays and silts, in a uniform manner over an exposed slope with the surface runoff. As the surface runoff concentrates in depressions, soil may be removed to form small well-defined channels called rills. These usually are closely spaced and nearly parallel. As more flow concentrates in the larger depressions, the erosive power increases and gullies can develop. The steeper the impoundment side slopes, the more the gullies tend to increase and the more severe the erosion damage.

The erosion of the land surface surrounding the tailings impoundment could involve all of the above processes. This would merely be the ongoing natural watershed or flood plain erosion as modified by the presence of the tailings impoundment. The occurrence and extent of the erosion are site specific.

Flooding presents the most critical design condition because of the high-velocity flows and hydrodynamic forces on the impoundment. Each structure exposed to flooding requires riprap protection depending on the depth and flow characteristics of the design flood.

To design rock riprap protection for worst-case flood conditions, the procedure is to determine the peak discharge of the design flood at the site and the hydraulic design criteria. These data, together with the identification of a rock source and its properties, are used to determine the rock size needed to resist the flood forces. The rock size is calculated by using the selected riprap design method (Walters 1982). Once the rock size is known, the gradation of rock sizes for the armor layer, the layer thickness, and foundation requirements is determined using written specifications and engineering judgment.

A probable maximum flood is used for the design of rock riprap protection. Probable maximum flood discharges and water surface elevations can result from various combinations of sequential precipitation, centering, time and areal distribution, storm duration, seasonal variations of precipitation, antecedent snowpack and related meteorological parameters, antecedent soil moisture, reservoir elevations in regulated watersheds, flood-caused dam failures, ice jams, and superimposed wind waves.

The report "American National Standard for Determining Design Basis Flooding at Power Reactor Sites" (American Nuclear Society 1981) presents

methods for determining and/or evaluating the probable maximum flood and the probable maximum precipitation. The report also discusses runoff and streamflow models that can be used to develop flood hydrographs and compute hydraulic design data for riprap. Unsteady flow models that compute simultaneously the time sequence of both flow and water surface elevation over the selected stream length should be used. However, steady flow models that consider only a peak discharge and that are simpler to use should be sufficient for uranium tailings sites. The most well-documented steady flow model for flood studies is the "HEC-2 Water Surface Profiles" model developed by the U.S. Army Corps of Engineers (1976). This model calculates average velocities for the channel and overbank areas, depths, water surface elevations, energy grade lines, and channel geometry data.

The median rock diameter for the riprap layer can be calculated by several available methods. Walters (1982) identified the Safety Factor Method [Stevens, Simons, and Lewis (1976)] as perhaps the best method for uranium tailings impoundments based on versatility. There are also two other methods available that can be utilized for riprap design: The Caltrans Method (California Highway Department 1970) and the U.S. Corps of Engineers method (1970). These three riprap design procedures were evaluated and compared by Walters and Skaggs (1984). The study results indicated that both the Caltrans and Corps of Engineers methods were more conservative than the Safety Factor Method with the Corps of Engineers method being the most conservative. All three methods compute the median rock diameter for the riprap gradation. The gradation and layer thickness are derived from this value. Table 2 summarizes the basic input data required for the three procedures. Once the design of the rock layer has been determined the underlying filter material can be designed using the procedures presented in various textbooks (Sherard et al. 1963; Simons and Senturk 1977).

Local flooding, due to intense rainfall, can be estimated using the probable maximum precipitation. Estimates for the probable maximum precipitation are available in generalized studies prepared by the National Weather Service (American Nuclear Society 1981). Drainage systems designed to accommodate the probable maximum precipitation may be located on or adjacent to the impoundment and can be evaluated for discharge capacity and resistance to erosion. Drainage channels can be armored with rock riprap for long-term protection. Initial hydraulic evaluation of the drainage channels can be accomplished using the analysis techniques of Chow (1959) and Henderson (1966) prior to any modeling effort.

Since overland erosion does not generate high shear stresses relative to flood flows, the armor protection requirements are much less. Usually some type of rock mulch and/or vegetation is sufficient. Rock used for protection is usually material such as gravels and cobbles.

Computational models for overland erosion can provide estimates of soil loss rates and/or sediment yield. Although they were primarily developed for agricultural erosion, they can be used for evaluating protective vegetative covers on tailings impoundments (Beedlow 1984). For unprotected areas of the impoundment cover and the adjacent watershed, the models can

Table 2. Summary of Variables Required for Riprap Design Methods

Variable	Caltrans	Corps of Engineers	Safety Factor Method
Discharge velocity	Average cross-sectional velocity, ∇ (2/3 ∇ for impinging flow).	Average cross-sectional velocity	Average cross-sectional velocity optional
Shear stress	Not required	Compares local and design shear stress	Required
Angle of velocity vector	Not required	Not required	Assumed to be zero for natural streamflow (water surface slope is small).
Specific	Recommends 2.5 or greater to minimize rock layer thickness	Required	Required
Angle of repose	Not identified. Uses 70° for randomly-placed rock (value reduced by side slope in method)	Uses a constant value of 40°C	Determined from graph of empirical data
Hydraulic radius	Not directly used in method. May be required in hydraulic calculations.	Used to compute local shear stress	Not directly used in method. May be required for hydraulic calculations
Side slope	Required	Required	Reqired

estimate rates of soil losses and determine the potential severity of long-term overland erosion. Walters (1983) discusses the more well-accepted models for overland erosion. A brief summary is provided below:

The computational methods for overland flow and erosion include both regression and physical process simulation models. Two examples of regression models are the Universal Soil Loss Equation (USLE) and the Modified Universal Soil Loss Equation (MUSLE). The USLE estimates soil losses on an annual basis and is the most widely accepted; whereas the MUSLE model estimates sediment yield. Soil loss is the gross amount of potential erosion computed for conditions specified in the model. Sediment yield is defined as the total sediment outflow from a watershed and implies a net loss of soil. The physical process simulation models are based on mathematical simulations of the overland erosion processes such as raindrop splash, surface runoff, overland flow, and interflow beneath the soil surface. Three of the more widely accepted models are the CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) model, the ARM (Agricultural Runoff Management) model, and the MULTSED (Multiple Watershed and Sediment Routing) model. These models are able to output other parameters such as particle size distribution of the eroded soil and drainage channel erosion. A summary of the above models is provided in Table 3.

Another erosional process that may have a long-term effect on tailings impoundments is wind erosion. Bander (1982) states that the most appropriate computational model for wind erosion of tailings impoundments is the equation developed by Chepil. (This equation, compared to others, includes more factors describing the variables that influence wind erosion from a tailings pile.)

Gully erosion can be expected to develop on any unprotected areas of the earthern cover primarily as a result of overland erosion processes. Gullies tend to develop headward due to increasing concentrations of runoff water and may eventually lead to a breach in the impoundment. According to the American Society of Civil Engineers (1975), methods are not available for any given locality and under any set of existing or assumed conditions for accurately predicting rates of gully erosion or gully advance. Gully erosion at uranium tailings impoundments may have to be prevented by the use of riprap and taken into account when designing the erosion protection.

Biotic Intrusion

Site-specific assessments of the biotic intrusion problems are required to evaluate methods to exclude plants and animals from tailings. Biotic intrusion facilitates the release of contaminants in three ways:

- Active transport of tailings and contaminants to the surface by physically moving tailings or incorporating contaminants into tissues

Table 3. Summary of Selected Models for Evaluating Erosion of Uranium Tailings Impoundments

Model	Hydrologic Component	Sediment Component	Results
USLE[(a)]	Annual rainfall erosivity factor	Soil erodibility factor; sediment delivery ratio	Soil loss; sediment yield (with sediment delivery ratio)
MUSLE[(b)]	Peak discharge and runoff volume for single event; annual storm-weighted water yield	Uses USLE	Sediment yield
CREAMS[(c)]	SCS curve number; infiltration	Overland flow; channel flow; impoundment (pond) deposition	Sediment yield; particle size distribution
ARM[(d)]	Runoff simulation; infiltration; interflow	Raindrop impact; overland flow; (clay/silt-sizes only) groundwater flow	Sediment yield based on overland flow simulation
MULTSED[(e)]	Infiltration; kinematic flow; channel routing	Raindrop impact; overland flow; channel flow	Sediment yield based on overland flow simulation; channel erosion, transport and deposition; particle size distribution

(a) USLE = Universal Soil Loss Equation
(b) MUSLE = Modificed Universal Soil Loss Equation
(c) CREAMS = Chemicals, Runoff, and Erosion from Agricultural Management Systems
(d) ARM = Agricultural Runoff Management
(e) MULTSED = Multiple Watershed and Sediment Routing

- Transport enhancement where radon emission and water movement are increased by burrowing and root growth, or where burrowing activity increases erosion of the cover material

- Secondary transport where contaminants are spread by plants and animals after reaching the surface by active transport or as the result of transport enhancement.

Active transport can be evaluated by computer programs such as BIOPORT (McKenzie et al. 1982), which takes both plants and animals into consideration, and is flexible enough to account for various plant and animal communities, plant succession and animal activity over time. Secondary transport must be qualitatively evaluated as no computational models yet exist.

Transport enhancement due to biotic intrusion can be evaluated using existing erosion, soil moisture, and radon flux models. The effect that burrowing animals have on soil loss is related to the amount of soil they bring to the surface. Water infiltration is related to both burrowing activity and root distribution. Radon flux is related to the extent of burrowing, the type of animals burrowing (hole depth and size), and plant root distribution.

The major obstacle to using existing models for quantitative analyses of the effects of biotic intrusion is the gathering of necessary input data. Data bases characterizing burrows are presented by Gano and States (1982) and Cline et al. (1982). No comprehensive data base is available for rooting characteristics of plant species, although a significant amount of rooting literature exists. Collecting site-specific data may be necessary to fully evaluate biotic intrusion.

Human Intrusion

As human populations increase, disposal sites could become urbanized to the extent that houses, roads, etc., may be built over the tailings. These activities would place increased pressures on the containment system. Future uses of the site will depend on the extent of institutional control and the nature of human resources in the area. In most of the arid and semi-arid regions of the United States, the tailings sites will be revegetated with plant species similar to those growing in the area. Through time, these revegetated areas may be grazed by sheep, cattle, and wildlife. In areas with enough moisture to support crops, the land may be used for farming.

Mining and drilling to recycle or remove the materials within the tailings pile would be drastic intrusions. These actions would subject intrusion barriers to extreme pressures, and in advanced stages would completely nullify the effectiveness of any intrusion barriers.

GROUND-WATER CONTAMINATION

Causes

Uranium tailings are crushed ore materials which have been leached with strong acid or alkaline solutions. When discharged from the mill, tailings have both solid and liquid components that contain soluble contaminants generally far in excess of permissible standards. Within the tailings, the acid or alkaline solutions contain high concentrations of soluble radionuclides and heavy metals. Radioactive constituents in high concentrations include Th-230, Ra-226, Rn-222, Po-210, and Pb-210. In addition, inorganic constituents including arsenic, chromium, lead, selenium, molybdenum, and vanadium have been found in elevated concentrations at some tailing sites in near-surface ground water (EPA 1982). In general, however, the mill tailings sites in the western United States have shown little evidence of contaminant migration away from the tailings. Contamination of deep aquifers near mill tailings sites has not been observed (University of Idaho 1980).

Climatic Controls

Most of the uranium mill tailings sites are located in the western United States. The climatic conditions are semi-arid or arid for the majority of the sites. Continual leaching of the tailings by infiltrating water is unlikely for all but the wettest sites (e.g., those on the Texas Coastal Plain and in high mountain areas). Some infiltration occurs at all sites but rates are generally quite small. At a few sites, where the water table is shallow (0 to 2 m deep) surface evaporites (salt deposits) have been observed (Markos 1979). Surface evaporites, typical of western alkali flats, result from evaporation of interstitial tailings water. This upward migration of salt is readily eliminated by lowering the water table or covering the pile with an appropriate cover system (asphalt or thick soil layers). Typical tailings piles found in the arid west have relatively deep water tables with little or no annual recharge evident.

Simmons and Gee (1981) have modeled the hydrology of the Grand Junction, Colorado tailings pile and have shown that the amount of water infiltration into the tailings depends upon the climatic variables (rainfall, evaporation, etc.) as well as the hydrologic properties of the tailings and the cover systems. Several years of observations at this pile indicate that no recharge has occurred through 3 m-thick covers placed on the tailings pile (Gee, Nielson, and Rogers 1984).

Geochemical Controls

The chemistry of the tailings and of the underlying soils and sediments plays a major role in determining the extent of contaminant migration at a tailings site. Attenuation mechanisms that tend to retard the contaminant migration from tailings include chemical precipitation, coprecipitation, adsorption/exchange, convective dispersion, and

radioactive decay. For acid-leached tailings, the natural buffer capacity of alkaline soils and sediments found at western tailings sites is generally large enough to adequately neutralize the tailings seepage waters (Shepherd and Cherry 1980; Gee et al. 1980). The neutralization process is an effective geochemical control and causes the precipitation of most of the radionuclides and heavy metals that are soluble under acidic conditions. In addition, amorphous iron and aluminum oxides precipitate out of solution when tailings solution contacts alkaline sediment and act as scavengers for trace metals, further reducing the contaminant concentrations (Markos and Bush 1981; Peterson et al. 1983). Contaminants which are either anionic or less sensitive to pH (such as nitrate and molybdenum) tend to migrate unimpeded through the alkaline sediments. Sulfate, also anionic, interacts with calcium carbonate in the soil to form slightly soluble gypsum, but for typical tailings treated with sulfuric acid, the concentrations of sulfate are so large (10,000 to 30,000 mg/L) that the seepage water generally contains sulfate levels well above permissible standards (Peterson et al. 1981).

Soil Moisture Models

Assessment of water flow in the unsaturated zone may be required at arid sites. Computer modeling using both simplified and detailed unsaturated water flow codes has been used in UMTRAP research and provides a useful tool for predicting water movement and storage in soils (McWhorter and Nelson 1978, 1979; Simmons and Gee 1981; Mayer et al. 1981). The use of such codes as UNSATID and TRUST require detailed input data, often difficult to obtain without careful planning. While these codes may require information too detailed for developing conceptual designs, they certainly could be applied in evaluating final designs. Information such as soil water retention characteristics, and unsaturated hydraulic properties for local soil or facility materials are often not available from preliminary site reports (e.g., environmental assessments or environmental impact statements).

Groundwater Models

Ground-water modeling has developed to a point of sophistication where water flow descriptions can be realized with considerable accuracy. (Prickett 1975; Reisenauer et al. 1982; Yen and Ward 1980; Narasimhan and Witherspoon 1978; Nelson et al. 1983). However the transport processes are still poorly understood (Bear 1972; Dagan 1979) and groundwater monitoring will be required to assist in validation efforts for computer models designed to quantitatively describe migration from tailings impoundments.

CRITERIA FOR DETERMINING COMPLIANCE

This section gives criteria for evaluating tailings disposal sites to determine compliance with EPA standards (40 CFR 192). Compliance should be based on evaluation of the information provided by the licensee and on inspection of the site. Therefore, quality assurance procedures are necessary throughout closure that provide for documentation of data collection methods, operation and calibration of equipment, traceability of samples and associated data from the beginning of closure to the verification of compliance.

RADIOLOGICAL EVALUATIONS OF COVER MATERIAL

Radon Flux

Compliance with the radon flux standard can be verified either by calculation or measurements. However, certain conditions must be met to use either procedure.

If compliance is to be verified by calculational methods, it must be demonstrated that the cover placed on the disposal site has indeed met the specifications outlined in the radon attenuation cover design*. The most important parameters to verify are the radon diffusion coefficients and cover thickness. The radon diffusion coefficients should be determined by using a documented and standardized procedure (Rogers et al. 1983b) on a statistically significant number of cover samples taken at regular intervals during cover construction. The parameters that should be measured at the time of the diffusion measurements are moisture content, particle size distribution,and proctor densities. Documentation should be available on equipment used, method of collection, and personnel training. Changes in soil texture should be tested to determine whether the radon attenuation properties of the material are adequate. The soil samples should be placed in airtight containers to preserve the field moisture values and the radon diffusion coefficients should be determined at field moisture contents. Weather conditions during sample collection should be documented. Sampling of soils should be avoided during any unusual weather conditions such as rainstorms or severe drought.

The thickness of the cover should be verified at the time compliance is to be determined. Because the measurement of cover thickness should be made after a period of time has elapsed to allow for cover settlement, compliance should be determined after no less than one year following completion of the containment system.

The data obtained from the sampling program should be input into the equations described in the radon attenuation design guide to verify that

*Radon Attenuation Handbook for Uranium Mill Tailings Cover Design. (Rogers et al. 1983b).

the cover will meet the pCi/m^2s standard (e.g., Rogers et al. 1983b). The specific equations used, input values, results, personnel making the calculations, and dates the calculations were made should be documented.

An alternative to calculating the radon flux from the cover is to measure the radon flux from the cover. Because of the temporal changes in radon flux, the measurements should be repeated a minimum of 4 times during the year (quarterly) at the same locations. A measurement procedure used is outlined by Young et al. (1983). The radon flux should be measured at a minimum of 30 locations on a rectangular grid. The number of flux locations to be measured during subsequent determinations of the average flux should be calculated from the coefficient of variation of the fluxes measured during the first determination (Leggett et al. 1978). According to Leggett, a parameter should be measured at a number of locations equal to 45 times the square of the coefficient of variation of the measurements to determine the average value with a precision of 25% at the 95% confidence level. He also recommended that measurements be made at a minimum of 30 locations regardless of the coefficient of variation.

Radium-226 in Soil

Any area of the disposal site that will not be contained must be shown to be below the EPA limits for radium-226. The EPA standards do not set limits for gamma radiation exposure rates, but gamma radiation measurements should be used for identifying locations where surface or near-surface tailings material is likely to be present. Documentation of gamma radiation measurement locations on the site should be provided. It is much easier to make gamma radiation measurements than it is to analyze soil or other material for radium-226; so gamma radiation measurements can be made at many more locations than is feasible for radium-226 measurements. Radium-226 measurements should be made on soil core samples at locations where elevated exposure rates indicate that radium-226 is present.

The gamma radiation measurements on the tailings and in the surrounding area should be made at an elevation of approximately one meter above the cover using a micro-R-meter. 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 according to written procedure, against an NBS traceable standard, by trained personnel, in a controlled environment. Weather conditions at the time of measurement should be documented. 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.

Additional detailed surveys should be made of any areas showing elevated gamma radiation exposure rates. Measurements of these areas should be

made at the one-meter level at the grid points of a 10-m x 10-m grid. If an exposure rate above 4 μR/h is observed at any location, soil samples should be collected for radium-226 analysis. 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. Samples of soil from the 0 to 15 cm depth should be collected at several of the locations showing the highest gamma radiation exposure rate. The soil samples should be analyzed for radium-226 and other radionuclides using NaI(Tl) and/or intrinsic-germanium-diode gamma-ray spectrometers.

Copies of the records of the gamma exposure and radium-226 surveys should be provided to the parties responsible for the long-term surveillance of the site so that a baseline is available for future measurements, if needed.

LONG-TERM EFFECTIVENESS OF THE COVER

The long-term effectiveness of the cover on evaluation of several factors: resistance to erosion, rate of soil loss by overland flow, gully erosion, plant and animal intrusion, and human intrusion. The following sections give compliance criteria for each.

Resistance to Erosion

Each impoundment will be subjected to overland erosion from the rainfall-runoff process and some may have to resist erosion from flood. Engineered rock riprap covers are perhaps the only one feasible for protection against flooding. However, for overland erosion rock may be used in conjunction with vegetation. In either case the rock used must be durable enough to resist to a reasonable degree the hydraulic forces of water erosion for periods of time upward of 1000 years. The structural integrity of rock armor protection depends on the following characteristics:

- Quality of the rock. The rock should be hard, dense, and durable in order to resist dislodgement by the flow of water and long exposure to weathering. There are currently no procedures, laboratory or others, that will determine if rock material will last upwards of 1000 years. However, there are laboratory tests that do indicate by their results the relative durability of various rock samples.

- Rock weight and size and layer thickness. The thickness of the riprap should be sufficient to accommodate the weight and size of the rock necessary to resist dislodgement.

- Rock shape. The shape of individual rock fragments influences the ability of riprap to resist displacement. Angular fragments tend to interlock and resist displacement better than the more rounded fragments.

- Embankment slopes. Safe embankment slopes on which the riprap is placed is determined during the design process. The slope angle is one of the input variables in the riprap design methods discussed in the erosion section of this report. The slope angle can be varied until an optimum design is determined.

- Stability and effectiveness of the filter. Layers of crushed rock, gravel, or coarse sand are placed beneath the rock layer to prevent the washing out of cover soil particles.

The competency and quality of rock for riprap are judged by geologic field conditions, physical properties tests, petrographic examination, and service record of the material. Representative samples of each type of material in a proposed source must be collected. When there is more than one type of material at a source, separate samples should be obtained representing each material proposed for use. Other material at the source not suitable for riprap, such as intervening layers of soil, shale, or other soft material, should not be sampled but should appear in the site investigation report.

Large boulder fields and talus slopes are sometimes proposed as sources of riprap. Field boulders should be avoided, if possible, for use as riprap because of their more rounded shape. They usually do not have the angularity and interlocking properties of quarried rock. Talus should be sampled only if it is proposed for use as riprap. Talus material has usually been weathered, altered, or case-hardened and would provide misleading laboratory test results (compared to quarried rock) for the source.

The two primary objectives in the construction of a rock armor layer are to obtain a well-graded rock mixture from the source (quarry or other) and to place the rock in a well-keyed, uniform blanket without segregation. Inspection may be necessary both at the rock source and on the impoundment. Inspection of riprap placement consists of visual observation of the operation and of the completed structure to ensure that a dense, rough surface of well-keyed, graded rock fragments of the specified quality and sizes is obtained.

The best time to inspect the gradation of the mixture is during the quarrying. The gradation can be verified by dumping one or two truckloads on a flat area for sorting. The rocks can then be segregated into fragments of approximately equal sizes for actual measurement. The gradation of the material for the filter underlying the riprap will usually be small enough to be verified by sieving. The angularity of the rock should be verified at this time.

The verification of the layer thickness both for the filter and riprap and that they were placed to the lines and dimensions shown on the construction drawings can be accomplished by field measurements at the impoundment. The thickness should conform to the design specifications and verified during initial construction and after completion. During

the inspection, the quantity of fines in the riprap layer should be determined. Too many fines can eventually lead to enlarged holes in the layer because they can be washed out. Likewise, an absence of the smaller rock sizes, which can be used for filling large interstitial areas, can also leave enlarged in the layer. The embankment slopes can be verified prior to the placement of the riprap and filter by either field surveying techniques or aerial photo mapping.

The durability of the rock material cannot be adequately determined. There are, however, several engineering laboratory tests that can be used to determine the relative durability of a suite of samples. The California Highway Department (1970) reported on their testing program which used both laboratory tests and field examinations in an attempt to determine rock durability. Of the tests run they recommended the following for better control over the quality of rock used for riprap.

1) Absorption - A general correlation exists between percent of absorption and degree of weathering. The more weathered specimens have a higher absorption due to a greater porosity.

2) Soundness - The application of sodium sulphate acts as an accelerated mechanical weathering test which is assumed similar to frost action. This test does not simulate chemical weathering.

3) Wetting and Drying - This test meausres the percent loss of sample weight after cyclic wetting and drying. It is helpful in eliminating rocks with readily soluble material.

While these tests may improve the quality of the rock selected for riprap they do not in any way provide an estimate of the time the rock will remain effective. Other discussions of rock durability test procedures with respect to riprap can be found in textbooks and design manuals (e.g., U. S. Bureau of Reclamation 1977).

Rate of Soil Loss by Overland Flow

Calculated soil loss should not exceed the depth of the protective cover over the design life of the containment system. Long-term average erosion and probable maximum precipitation (PMP) events should be used to calculate soil loss. Survey cover data (vegetation, soil, rock cover) should be considered in the calculations. The erosion model version of the model, input variables, and results should be documented.

Gully Erosion

Compliance should be determined by inspection of the tailings cover. Riprap should be placed around the base of the tailings to prevent gully encroachment. Slopes greater than 10% should be covered with riprap to prevent gully formation from runoff. Drainage structures should be lined with riprap.

Plant and Animal Intrusion

The types and densities of animals and plants that inhabit the site should be documented. This documentation must contain enough data to determine a statistically significant estimate of the species present and their densities. Soil structure and climatic conditions affect burrowing and rooting depths in the various areas; depths for these areas should be determined from literature and field data.

If a physical barrier is used, construction should be documented to verify that adequate measures to deter plant root and burrowing animal intrusions into tailings are provided. Documentation should include application rates, gradations and thicknesses for the installed barrier.

If chemical barriers are used either alone or in conjunction with rock barriers to prevent root growth into tailings, documentation of laboratory tests to show their effectiveness in prohibiting root growth and their longevity must be provided by the licensee. The effectiveness of the chemical barriers must meet the specifications and standards as outlined by the U.S. EPA (1982b).

If earthen covers are used without biobarriers, the thickness should exceed the maximum expected root or burrow depths. Specifications and construction methods for the application of the cover should be documented.

Human Intrusion

Markers should be massive and the materials used in their construction should be long-lasting and resistant to weathering and human interferences. The markers should have a low center of gravity, protrude above ground at least twice the height of the average man, and extend underground to a depth of at least five feet. The marker should be tapered to create a broad base for stability, to reduce wind resistance, and to allow rain run-off. Single-piece construction should be used to eliminate joints which tend to weaken and present areas for increased weathering with time.

The materials used for marker construction should be very hard, dense, nonporous, rock-like, and non-metallic. Metals should not be used because they deteriorate and are susceptible to recycling due to their value. Adams et al. (1981) recommended markers made from granite shaped as an obelisk; or basalt shaped as a monolith with basalt cobble piled and cemented around the base for stability.

The messages should be inscribed into the stone depth that will be legible up to 1000 years. For example, basalt can weather 9.1 x 10^{-4} cm/yr. Therefore, for a 1000-yr life span, the depth of the scribes into basalt or granite should be 0.9 cm (Adams et al. 1981). The message should include a radiation symbol, "Radioactive Waste", and "Do Not Dig." Each of these groups of inscriptions should be located at

three locations on the outboard side of the marker. One of the three groups should be located under-ground. The number of markers placed around the burial site will vary with site size; however, the distance between markers should be dictated by visibility so that when a person is standing by one marker, another marker is visible with the unaided eye in each direction from that location and so on as he progresses around the site.

COMPLIANCE WITH WATER PROTECTION STANDARDS

Water protection standards vary from site to site; however, consideration must be given to surface waters, ground waters, and the effect of remedial action on contaminant migration. In all cases, the standards must be satisfied at all points at greater distances than 500 meters from the edge of the disposal area or outside the site boundary.

Surface-Water Standards

No release to surface waters is allowed unless the released water meets appropriate state and federal water standards. The surface water standards for potentially harmful contaminated water from the tailings require the contaminated water to be chemically treated to below the concentration levels found in the surface water where it will be discharged. This concept of nondegradation is designed to prevent increases in concentration of any toxic substance in surface waters. Periodic monitoring of on-site waters and adjacent, down-gradient surface waters are required to assure that there is no contamination resulting from direct discharge or erosion of the waste pile. Appropriate measures, proper engineering of evaporation ponds, and surface stabilization of tailings piles must be employed in order to assure that surface waters remain uncontaminated.

Ground-Water Standards

The EPA regulations indicate that uranium tailings are to be treated as hazardous wastes. In addition to requiring an impermeable liner for protection against liquid migration, compliance with EPA standards requires the following:

- Free liquids must be removed from the tailings.
- The pile must be stabilized to a bearing capacity sufficient to support a final cover.
- The surface impoundment must be covered with a final cover which will:
  - Provide long-term minimization of migration of liquids through the impoundment.

- Function with minimum maintenance.

- Promote drainage and minimize erosion or abrasion of the final cover.

- Accommodate settling and subsidence.

- Have a permeability less than or equal to the permeability of any bottom liner system or natural subsoil present.

The system operation and design as indicated above will minimize leachate losses and provide long-term protection against seepage from tailings resulting from rainfall infiltrations. In summary, compliance to EPA standards requires that the tailings must be drained, stabilized, and covered. The uranium tailings system must comply with conditions specified in the facility permit. These conditions should be designed to ensure that hazardous constituents from the tailings, which enter the uppermost aquifer underlying the tailings, do not exceed concentration limits at any point between the specified point of compliance (generally the edge of the tailings pile). Hazardous constituents cannot exceed concentration levels as specified in Table 1 unless the uppermost aquifer already exceeds these limits for some of the constituents, in which case the compliance limits are those of non-degradation (i.e., no contaminants can enter the aquifer which exceed the levels already present). Alternate concentration limits may be established at existing sites if after considering practicable corrective actions these limits are as low as reasonably achievable.

Ground-Water Monitoring

Monitoring wells at the edge of the pile and downgradient from the pile are necessary for evaluation of compliance and to assure that the water quality standards are met. Detailed procedures for the installation and monitoring of wells and for the collection and preservation of ground-water and surface water samples have been established by the EPA, the U.S. Geological Survey (USGS), and the DOE (EPA 1975, 1979a, b, 1980a, b, c; USGS 1977; Korte and Kearl 1984). When these monitoring and measurement procedures are properly followed, an adequate representation of ground- water quality at the tailings site can be obtained. After the site has been determined to be in compliance, the site owners must maintain compliance by continuing a long-term monitoring effort for ground-water contaminants (40 CFR, Part 264, U.S. EPA 1982b). Ongoing monitoring is necessary because at present, there are no geochemical transport codes that can adequately predict the contaminant migration from uranium tailings piles (Peterson et al. 1983). This monitoring program must contain the following elements:

1) Development of an adequate data base for background levels of contaminants in ground water.

2) Determination of what would be a statistically significant increase in contaminant levels.

3) Quarterly monitoring of hazardous constituents in all monitoring wells.

4) Annual determination of flow rate and direction of uppermost aquifer.

5) Determination of any statistically significant increases of hazardous constituents occurring at compliance points. (Procedures of Nelson and Ward 1982 and Rothrock 1982 are recommended.)

If significant increases of ground-water contaminants are found, corrective action must be taken, such as reverse gradient pumping (pump back) wells, grout curtains and in-place chemical grouting. As a last resort, the tailings pile may require relocation. The required system will be site-specific and depend on the nature and extent of the contamination. After corrective action has been taken, it must be determined if the action was successful (i.e., it reduced contaminants to acceptable levels).

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This report provides methods and procedures that can be used to verify compliance with Environmental Protection Agency (EPA) engineering standards for uranium mill tailings disposal sites. EPA standards for radon emissions, long-term isolation, and protection of water quality are discussed. Tailings isolation technologies are reviewed. Information the licensee needs to provide for the regulating agency to determine compliance is presented, as is the actual compliance criteria.

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