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Designing Protective Covers for Uranium Mill Tailings Piles: A Review

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Pacific Northwest Laboratory

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Commission

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ABSTRACT

This report reviews design considerations for protective covers for uranium mill tailings impoundments. The role of protective covers in tailings containment systems is discussed. Factors affecting the long-term stabilization of tailings (erosion, biotic intrusion, and soil moisture) are summarized. Basic elements to be considered in design of all uranium tailings covers are presented, and then quantitative techniques for designing site-specific covers are reviewed.

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EXECUTIVE SUMMARY

Uranium mill tailings contain material that is potentially hazardous to humans and the environment. The Environmental Protection Agency has established standards to provide for safe, environmentally sound disposal of these tailings. Technologies have been developed in compliance with these standards to construct containment systems that will control the escape of toxic materials from tailings piles. This report reviews the existing technology for protective covers for containment systems.

The basic elements of a containment system are radon barriers, liners, biotic barriers, systems to control water infiltration, and surface covers to prevent erosion damage. Protective covers, which can include several of these elements, ensure the sustained functioning of the containment system by controlling erosion, biotic intrusion, and water infiltration for the design life of the impoundment.

Erosional forces likely to affect a tailings pile include surface runoff, flooding, wind, and long-term changes in surrounding landforms. Plant and animal activity in and on a covered tailings pile could compromise the effectiveness of the containment system. Uncontrolled infiltration of water into tailings could lead to leaching of toxic compounds and destabilization of tailings and cover materials.

Site-specific designs for protective covers are necessary because site conditions and availability of cover materials differ greatly between the regions of the country where tailings piles exist. Despite potentially large differences in site conditions, the use of a systematic approach for designing protective covers can result in more efficient designs.

Protective covers have several basic design elements. Heavy rock riprap prevents flood and gully erosion. Primary protection against runoff erosion on steeper slopes is provided by light riprap of gravel and cobble-sized rock. Vegetation on these steeper slopes can provide additional protection while also serving to anchor the riprap. On flat and gently sloping portions of the pile, vegetation or combinations of vegetation and rock protect against runoff and wind erosion. Vegetation prevents accumulation of water in the tailings. Rock and chemical barriers prevent intrusion of tailings from plant roots and burrowing animals.

To design protective covers, specific site data on meteorology, hydrology, and location and geometry of the pile must be applied to quantitative models. Existing quantitative models can estimate erosion stresses, biotic transport of contaminants, and moisture dynamics in tailings and cover material.

INTRODUCTION

Uranium by-products are potentially hazardous to public health and safety and to the environment. Therefore, tailings are impounded under an earthen dam during the operating life of the mill and for a period of time after operations have ceased. To provide for safe, environmentally sound disposal and control of uranium milltailings, the 95th Congress of the United States enacted the Uranium Mill Tailings Radiation Control Act of 1978 (Public Law 95-604, 42USC7901). The Environmental Protection Agency (EPA) has subsequently established standards for disposal of these tailings (40 CFR Part 192). These standards establish the design life of the containment system to "... be effective for 1,000 years, to extent reasonably achievable, and in any case, for at least 200 years." [40CFR192.32(b)(1)(i)]. Average annual radon emissions into the air are limited to 20 pCi/m^2. Ground water standards require that background levels of pollutants be maintained or that drinking water standards be met at each tailings disposal site (40 CFR Part 192).

Since the passage of the Uranium Mill Tailings Control Act, a considerable amount of research has been conducted on disposal of uranium mill tailings. Technology applicable to tailings disposal has been developed from research on the disposal of low-level radioactive waste. This report reviews the current state of technology for providing long-term protection of uranium mill tailings by use of protective covers.

THE CONTAINMENT SYSTEM

Containment systems control the release of toxic materials from tailings into the environment. The basic elements of containment systems are:

- liners to control leaching
- radon barriers to control radon emissions
- biological barriers to control animal burrowing and plant root growth into tailings
- soil layers and vegetation to control infiltration of precipitation
- protective covers.

Protective covers ensure the sustained functioning of containment systems by controlling erosion, biotic intrusion, and water infiltration for the design life of a tailings impoundment.

The components of a containment system do not function independently (Beedlow 1984b; Beedlow and Hartley 1984). Each component of a system affects the others and is affected by the surrounding environment. A crucial factor is soil moisture. Once precipitation infiltrates, it becomes soil moisture. The interaction between soil moisture and system components must be well-characterized for systems to meet requirements for radon control, prevention of leaching, and long-term stability. Control of soil moisture can be achieved by a site-determined mix of rock and vegetation in protective covers. The depth to which roots penetrate a cover can be controlled through placement of root barriers. For example, maximum soil moisture (to prevent radon release) could be achieved by placing a root barrier close to the surface and placing a permeable cover over it. In this way, precipitation quickly infiltrates beyond the rooting zone. Minimal soil moisture could be achieved by maximizing root development and the surface of the vegetative cover.

The method of disposing tailings (above or below ground), the geographic location of tailings piles, local climatology and the physical and chemical processes that occur within tailings and between tailings and containment systems make each tailings impoundment unique. Consequently, each tailings containment system must be designed to fit site-specific conditions.

FACTORS AFFECTING LONG-TERM STABILIZATION

The three major factors that protective covers control--erosion, biotic instrusion, and soil moisture--are discussed in the following sections. However, cover designs to control these factors must be tailored to specific conditions at each site. While generic requirements and solutions need to be systematically applied to each site, a single standard design is not appropriate at each site. Final designs will depend primarily on site-specific conditions and the local availability of suitable cover materials.

EROSION

The primary role of protective covers is to control potentially disruptive erosive forces: surface run-off and rain impact, flooding, wind, mass wasting and settlement, and geomorphic hazards. To protect against erosion, varying amounts of rock and/or vegetation, depending on individual site conditions (tailings geometry, expected type and severity of erosion, climate), can be placed on the cover surface. Details of these erosive forces as they affect uranium mill tailings piles have been reported elsewhere; summaries of these forces based on referenced publications are presented in the following paragraphs. (For further discussion, see also Voorhees et al. 1983.)

Surface Runoff/Rain Impact

The major factors affecting the erosive force of raindrops are drop mass, size, size distribution, direction, terminal velocity, and rainfall intensity. The detachability and transportability of the soil and the amount of vegetation determine the ease of soil movement by raindrop impact.

Water transports soil by raindrop impact, surface flow, and flow within the upper soil layer, and by forming and enlarging networks of rills and gullies (Walters 1983). Raindrops detach soil particles and initiate downhill movement of material. Soil material in solution and suspension within the upper soil layer(s) is transported by a process termed through-flow. Water flowing over the soil surface is called overland flow, which causes three types of erosion: sheet, rill, and gully erosion. Sheet erosion is the removal of thin layers of soil from slopes; rill erosion is erosion caused by the convergence of water into channels. Continued development of rill erosion leads to the formation of gullies, which are relatively deep channels recently formed where no well-defined channel previously existed.

Soil particles set in motion by raindrop impact can be carried downhill by thin films of water. Sheet erosion is usually minor because the water generally does not develop erosive velocities. Water flowing at a sufficient velocity initiates the movement of soil particles by concentrating flow into rills. The rills must form at a certain distance from the top of a slope for the water to achieve enough velocity to

initiate particle movement. The development of this velocity is also controlled by the surface roughness, flow intensity, and vegetation.

When the eroding force exerted by concentrated flowing water exceeds the resistance of the earth material over which it is flowing, gully formation occurs (see also Schumm and Chorley 1983). Gully formation is rapid (sometimes within hours) and progressively severe. Sloped portions of tailings piles are particularly susceptible to gully formation.

Gullies can be formed by either saturation overland flow or Horton overland flow. Saturation overland flow results from lateral deflection of percolating water due to decreasing permeability with depth. If rainfall exceeds infiltration for a sufficient length of time, the soil layers become saturated and the lateral subsurface flow is deflected toward the surface. When the soil becomes saturated to the surface, overland flow occurs. Saturation overland flow can occur under lower rainfall intensities than those required for Horton overland flow if the rainfall is sustained. Saturation overland flow generally forms gullies that are extensions in existing channel systems and can therefore be expected to encroach on tailings piles from downstream drainage* or from established drainage on the impoundments.

Horton overland flow begins at a critical distance from slope crests or inflection points in the profile. The critical distance is that at which the hydraulic power of the flow exceeds the strength of the soil and vegetation to resist particle movement. The greatest erosive force from this type of overland flow occurs at the inflection point between convex/upward and concave/upward slopes. Horton overland flow can initiate gullies separate from established drainage systems.

Major factors influencing gully formation are topographical features such as slope angle and slope length, the existence of stable base levels on or near the site, the erodibility of the soil, and the flow velocity. Specific geomorphic and hydrologic conditions that increase the potential for gullying include steep slopes, narrow flow width, and large run-off volume in the drainage area.

Flooding

Tailings piles located on flood plains of rivers could experience erosion stress resulting from floodwater (Walters 1982). Hydrologic and hydraulic characteristics of the river systems affect the potential for flood erosion. The stability of a tailings pile during a flood is primarily influenced by the quantities and flow velocities of the floodwater in the immediate vicinity of the site. These factors depend, in turn, on the location of the impoundment within the flood plain and the magnitude and duration of the flood.

*Downstream drainage refers to portions of the watershed that are downstream from the pile. Gullies that are initiated in existing drainages can move upstream as they develop.

Flood protection methods have been based on concepts of initiating movement of single particles. Water flow over a layer of particles initiates movement when it approaches a velocity sufficient to momentarily entrain individual particles. The entrained particles generally bounce back and forth without net displacement. A slight increase in velocity removes some particles and destroys the integrity of the layer.

The forces acting on a particle under flowing water are gravity, lift, and drag. Under critical or threshold conditions, the hydrodynamic forces acting on a particle are balanced by resisting forces. When in this balanced condition, the particle is considered to be at the point of incipient motion, which is the point at which erosion begins.

Wind

The potential for soil loss due to wind erosion appears to be minor compared to water erosion over the long term. If tailings are adequately protected against water erosion, wind erosion should be minimal in most cases.

Surface wind velocity, soil particle size, soil conditions, surface roughness, and tailings shape are the primary factors affecting wind erosion (Bander 1982). Particle size determines if and how the particle can be moved. Soil conditions that affect wind erosion are soil moisture, organic material, and cloddiness or cohesiveness. The primary configuration factors influencing wind erosion on a tailings pile are (1) length of the pile along the prevailing wind erosion direction, (2) height of the pile above the existing terrain, and (3) length and steepness of the pile slope.

Vegetation and surface rock greatly reduce wind erosion. Organic material resulting from the decomposition of plants imparts shear strength and resistance to soil movement. The extent to which soil loss is reduced by vegetation depends on the height of the vegetation. Surface particles that are greater than 0.8 mm in diameter are generally resistant to movement by wind (Cooke and Warren 1973). Consequently, a continuous layer of gravel would reduce soil loss even in the absence of vegetation.

Mass Wasting and Settlement

Mass wasting is the en masse downslope movement of soil or rock in response to gravity. Mass wasting can range from slow (creep) to rapid movement (debris avalanches). On tailings piles, mass wasting may result from differential settlement of the tailings or failure of the cover material on the steeper slopes of the impoundment (Young, Long and Reils 1982). Slope failure could directly expose tailings or damage the radon barrier. The types of mass wasting most likely to occur in the cover material are slumps and earth flows that are related to moisture conditions in the earthen cover (Zellmer 1981). Cover systems that tend to confine water movement into a saturated zone, thereby reducing friction (e.g., those using asphalt or relatively impermeable clay as radon barriers), would be most susceptible to mass wasting.

The prediction and mitigation of differential settlement are discussed by Nelson et al. (1983). Prediction is based on materials engineering and stress analysis. Common engineering methods such as surcharging and surface grading are suggested to mitigate adverse effects of differential settlement. The use of sandy materials that are self-healing minimizes cracking of the protective cover.

Geomorphic Hazards

A geomorphic hazard is defined by Schumm et al. (1982) as "any landform change, natural or otherwise, that may adversely affect the geomorphic stability of a disposal site." In order to assess the long-term stability of a tailings containment system, the geomorphic processes that could influence the disposal site must be considered: climate change, tectonic activity, base level change, and vegetation and land form change by man (Schumm and Chorley 1983; Beedlow and Hartley 1984). These processes affect the land form in the area surrounding the disposal site, and a change in any or all could create geomorphic hazards by influencing run-off, soil transport, river behavior, and slope erosion.

The disposal site should be located on a relatively stable geomorphic surface. For each site, potential changes in hillslope erosion rates and accompanying stream behavior must be evaluated against potential changes in climate, base level, and tectonic activity. If the required geomorphic, climate, tectonic and hydrologic data are not available for the disposal site, a geomorphic evaluation of the site is necessary.

BIOTIC INTRUSION

Plant and animal activity (biota) in and on covered tailings can affect the stability of the impoundment and the performance of the containment system (Beedlow and Hartley 1984). Biological factors other than those resulting from human activity are long-term problems because the establishment and development of plant and animal communities are relatively slow.

Biota may be involved in contaminant escape through transport enhancement, active transport, and secondary transport (Beedlow and Hartley 1984). (These types of transport are discussed in more detail in a later section of this report, "Biotic Intrusion.") Active transport (the direct penetration of wastes by burrowing animals and plant roots) is considered to be the most significant in the transport of uranium mill tailings.

The composition of the surface cover can affect the degree of biotic intrusion. Properties of the cover material can affect the species composition of the vegetation covering the surface (Beedlow and Carlile 1984), and rooting depth (Brady 1974). Vegetation type and soil properties affect the species of burrowing animal in an area (Beedlow and Hartley 1984).

SOIL MOISTURE

Uranium mill tailings usually occupy an unsaturated flow zone in the transition region between the atmosphere and a ground water system. An unsaturated zone gains moisture from precipitation, agricultural irrigation, and seepage from rivers and lakes. Moisture is lost by evaporation, plant transpiration, and drainage. Soil moisture moves in an unsaturated zone under the influences of gravity, Darcian flow and vapor diffusion.

If the water infiltrating the cover-tailings profile exceeds its water holding capacity, drainage will occur. Except in cases where the ground water level lies within the tailings, soil moisture dynamics result from input from precipitation and are regulated by surface conditions. Expected surface conditions of tailings piles range from covers where vegetation is predominant, to rock/vegetation mixtures, to covers of total rock. Rock covers generally increase infiltration and decrease evaporation (Mayer, Beedlow and Cadwell 1981; Kirkham, Beedlow and Gee 1982). Thus, areas covered with rock can effectively capture more precipitation than the adjacent areas without rock. Thick rock covers are capable of excluding plant growth for a number of years and can cause water to accumulate in, and percolate through, the tailings cover system. Thin rock covers can promote plant growth. Transpiration by vegetation growing in a rock cover can prevent water accumulation if enough vegetation is present (Beedlow and Carlile 1984).

PROTECTIVE COVER DESIGNS

The wide range of site conditions and availability of cover materials complicates the design of appropriate protective covers. At each site, environmental conditions must be considered in conjunction with the characteristics of the tailings pile and the availability of materials. Beedlow and Hartley (1984) present a systematic approach to designing long-term protective covers based on site conditions and containment objectives. They divide the process of designing protective covers into three phases. In the first, or assessment phase, the appropriate site information is collected. Second, a preliminary plan is developed that describes the general characteristics of the protective cover and presents alternatives. The preliminary plan is used in conjunction with preliminary designs for the other components of the containment system to produce a conceptual site design. In the third phase, a detailed site-specific design of the protective cover is formulated. The detailed design is evaluated with respect to the entire containment system to produce a finalized design.

BASIC DESIGNS FOR PROTECTIVE COVERS

Erosion protection requirements will vary according to expected erosion stresses. The degree of protection ranges from that provided by established vegetation (Beedlow 1984a) to that of heavy-duty rock riprap (Walters 1982). Rock riprap is placed on the slopes and around the base of the impoundment to prevent flood damage and gully encroachment. Riprap is also used on slopes that are susceptible to gullying from impoundment run-off. Slopes above the design flood level may be protected by light-duty rock riprap consisting of gravel and cobble-sized material. On flat and gently sloped portions of the tailings pile above the design flood level, vegetation, a combination of vegetation and surface rock (rock mulch) or rocky soil can be used.

Vegetation should be established at all sites to prevent the accumulation of excess soil moisture when rock covers are used for stabilization (Beedlow 1984a). However, as an alternative to vegetation, rock covers can be engineered to drain laterally. Engineering such drain systems is certainly feasible; however, they must remain functional for the design life of the impoundment, which means they must allow for climate change and, inevitably, vegetation growth that could damage the drainage characteristics. In contrast, a plant community consisting of species adapted to the local environment is dynamic; it is capable of responding to changes in climate. By increasing and decreasing in response to available soil moisture, vegetation can be an effective and reliable "pump" for removing excess soil moisture. Vegetation alone will probably not be able to remove all of the excess moisture in areas of high rainfall or where deep snowpacks develop; additional preventive measures for these areas may be necessary, such as impermeable layers or drain fields.

Two types of biological barriers have been developed for use on uranium mill tailings piles (Cline et al. 1982). Physical barriers to animal

burrowing and root growth consist of cobble placed over the radon barrier. Cobble barriers have been shown to be most effective when fine soil particles are prevented from filtering into the spaces between the stones. A polymeric carrier/biocide delivery (PCD) system has been developed to provide controlled release of a herbicide (Cline et al. 1982).

MATERIAL SELECTION

Materials for an erosion protection system should be selected using the best available materials that can withstand physical and chemical decomposition, temperature and water fluctuations, and water and wind erosion for the design life of the protection system.

Field investigations and laboratory testing should be used for determining suitability of rock for use as riprap and filter material (Nelson et al. 1983; Walters 1982; Simons and Associates 1982; Lindsey et al. 1982). However, most existing tests are based on much shorter life-span requirements for the riprap than those required for mill tailings protection. Therefore, the final selection of riprap materials should also rely to a large extent on good engineering judgment and should be based on economic and environmental impact considerations.

The availability of soil that can be used for erosion protection should also be determined from site-specific data. Soil suitability can be determined by analyzing chemical and physical properties and estimating the potential for vegetative growth (Walters 1983; Brady 1974; Beedlow, McShane and Cadwell 1982; Whicker 1982; Mayer and Zimmerman 1981). Burrowing animals occupying the soil at the borrow site should be noted and factored into the determination of soil suitability (Beedlow, McShane and Cadwell 1982; Cline et al. 1982). Final selection of soil must also consider economics, accessibility, and environmental impact.

The availability of vegetation for use as an erosion protection material is determined from the site data. The suitability of vegetation for erosion protection should be based on the ability of the established vegetation to resist expected erosion stresses (Beedlow 1984a), and on whether deep-rooted plants would comprise the integrity of the radon barrier. The same species of plants on the site should be used for the cover.

USING QUANTITATIVE MODELS FOR SITE CHARACTERIZATION AND ANALYSES

Designing protective covers for uranium mill tailings requires information gathered directly from a particular site. The following sections present quantitative methods for designing protective covers that control erosion, biotic intrusion, and soil moisture.

EROSION

Systems to protect stabilized uranium mill tailings impoundments from erosion are generally designed on a site-specific basis because of the wide range of site conditions and available cover materials. Climate, surface drainage, soil type, and topography, as well as revegetation potential and the availability of cover materials are considered for each site. The initial step in designing erosion protection systems is to evaluate regional and site data on climate, hydrology, soils, vegetation, impoundment geometry, and topography/geomorphology (discussed in the following sections).

Design parameters and erosion protection measures rely heavily on existing regional and site data. Sources of these data include environmental impact statements for individual sites and more generic ones from the NRC (Lindsey, Long and Begej 1982). Inspection of the tailings impoundment and surrounding landforms provides information on the prevalent erosion processes. For impoundments located on flood plains or low terraces, potential river or stream channel alterations are also evaluated. Even though the impoundment may be located some distance from the river or stream, shifts in the river channel may result in direct river impingement on the tailings pile. River channel morphology investigations include an evaluation of the river system upstream and downstream of the impoundment. Nelson et al. (1983) discuss river channel morphology considerations in the evaluation of long-term stabilization of uranium mill tailings impoundments.

Meteorological Data

Climatic conditions and regional meteorological patterns are used in the design of erosion protection measures for impoundments. Meteorological conditions such as types of air masses, synoptic features, airflow patterns, temperature, humidity, precipitation, and relationships between synoptic-scale atmospheric processes and local meteorological conditions can be found in climatological summaries by the National Oceanic and Atmospheric Administration (NOAA) (U.S. Department of Commerce 1968a,b). Severe weather phenomena can be identified from standard meteorological records at representative National Weather Service (NWS) stations, military stations, or other recognized stations with extensive records (U.S. Department of Commerce b,c).

Hydrological Data

Hydrological data include a description of all streams (including intermittent streams), lakes, and shore regions that could significantly affect the stabilized uranium mill tailings impoundment. The hydrologic and climatological data are used as the basis for determining the design flood. Pertinent hydrological data include facts on drainage areas, lengths and slopes of the drainage area, average, minimum, and maximum discharges of all major and minor watercourses, and flood history of these watercourses (including upstream, man-made changes). Flood history includes dates of occurrence, observations stations, peak daily discharges, and crest elevations. Flood histories may not exist for smaller streams and may have to be estimated (Chow 1964; U.S. Army Corps of Engineers 1969, 1973).

Characteristics of the soils in the watershed where a tailings impoundment is located affect the surface and ground-water hydrology and are pertinent to the design flood. For this application, soil is considered to be the weathered upper zone in the unconsolidated material overlying bedrock (Brady 1974). Soil characteristics will affect the cover's susceptibility to erosion. Soil erodibility is determined by its infiltration capacity, surface roughness, and its resistance to detachment and transport by rainfall and runoff. Necessary soil data include particle size distribution, organic matter content, structure, porosity, permeability, bulk density, and moisture characteristics (Walters 1983).

Vegetation protects the surface from raindrop impact and reduces the amount and velocity of runoff water by improving infiltration. Vegetation increases surface roughness which decreases soil loss. Plant roots help keep the soil in place by binding the particles together. Vegetation data are used to calculate runoff from the watersheds in which tailings are located and to calculate the potential for wind and precipitation erosion of cover materials caused by runoff. Some vegetation data are available from soil surveys, impact statements, range surveys and aerial photographs. However, unless this information is recent and site-specific, field samples are needed.

Vegetation can be sampled on the soils being considered for cover material and on the surrounding watershed area to determine the species composition and canopy coverage. Vegetation existing on relatively undisturbed soil can be assumed to represent that expected over several hundred years (Beedlow, McShane and Cadwell 1982). Sampling in areas as free as possible from recent disturbance (e.g., farming and fires) will yield the most useful information. A vegetation cover is generally measured by calculating how much area each species covers. Existing vegetation cover should be measured at maximum growth and while dormant. Information on the identity and growth requirements of plant species is available from local Soil Conservation Service or Bureau of Land Management personnel.

Location and Geometry Data

The impoundment location and geometry are considered in the reclamation plans before milling operations are begun. The location of a tailings impoundment within the watershed and the geometry of the impoundment influences the design of the erosion protection system. Above-grade tailings impoundments located within flood plains can produce large-scale irregularities in the topography which may alter flood flow characteristics. Localized increases in flow velocities from these irregularities may induce scour of flood-plain soils adjacent to the impoundment, possibly undermining portions of the impoundment. High flow velocities impinging directly on the tailings pile may also breach the radon barrier. Steep side slopes may induce erosion of the radon barrier by precipitation runoff. Inundation of the impoundment by flood flows may cause differential settling, leading to rupture of the radon barrier.

To determine the extent of erosion protection necessary, watershed characteristics (e.g., size of drainage area, slope surfaces and lengths and surface roughness) are used to evaluate potential flood flows, flow velocities, and depths. The tailings impoundment geometry can be evaluated in terms of the potential flood flows that may impinge on the tailings pile. The erosive forces from the potential flows are determined and erosion protection measures are designed accordingly.

QUANTIFYING EROSION RATES

The development of design specifications for covers depends on estimates of erosion rates, as does the selection and justification of particular cover schemes. Existing erosion models, which have been used primarily for agriculture, have only recently been adapted to erosion models for long-term stabilization of waste sites (e.g., Nyhan and Lane 1982).

Models by themselves cannot be relied upon as the sole answer for predicting erosion at a certain site. Model implementation and interpretation of results must be guided by a thorough knowledge of geomorphological processes at that site. In addition, during site selection, a qualitative analysis of prevailing and potential types of erosion should be made by inspecting the pile and surrounding landforms. Because all erosion models are highly sensitive to climatic variables, criteria for estimating future climatic conditions need to be defined. Designing a cover to resist the average amount of precipitation falling in 1000 years is quite different from designing a cover to withstand a 1000-year storm. Current methods of predicting erosion are not capable of analyzing all of the possible combinations of events that can occur. Over time periods in which climatic data have been recorded (10 to 100 years), event sequences can be estimated on a statistical basis with some confidence. However, climatic conditions for periods longer than 100 years must take long-term climatic changes into account or rely on "worst-case" scenarios (Chow 1964; U.S. Army Corps of Engineers 1969). "Probable maximum" events have been prescribed by the NRC for determining worst-case erosion stresses at new and existing mills (NRC 1982).

The geometry of the impoundment, particularly the base and crest elevations and side slopes, is considered in the design of an erosion protection cover. Flatter side slopes will generally require less protection, but they will increase the area of the protective cover. The configuration of the impoundment in relation to the direction of the design flood flows is important because localized areas of high erosive forces due to irregularities may increase potential scour of the impoundment. The soil quality and grain-size characteristics of the radon barrier will directly affect the design of the erosion protection system.

The capability of the tailings impoundment and radon barrier to support loads during construction, as well as the erosion protection cover itself, are evaluated during the design stage of the protective cover. Stability analysis can be performed using engineering manuals published by the U.S. Army Corps of Engineers (Simons, Li and Associates 1982) and in accordance with guidance provided by the NRC (1977).

Flood Erosion: Quantitatively Designing Riprap Covers

The tailings impoundment may be protected from flood erosion by a rock cover (riprap). The design flood flows and the geometry of the impoundment generally dictate the riprap size. However, in some cases surface drainage features extending below the flood elevation may carry flows at higher velocities and may require larger riprap sizes than are needed for just the incipient flood flows.

Design methods for riprap covers are discussed by Walters (1982). The methods provide an analytical framework for computing rock size as a function of the tractive stress on rock particles and can be applied to any channel side slope, flow direction, and velocity.

The size of the riprap required for a given set of design stresses is determined by calculating the effective size of the rock, which represents the roughness of the channel in the hydraulic analysis of the flow. Once this size is determined, the gradation of the riprap and riprap layer thickness is determined from empirical relationships such as those recommended by the U.S. Army Corps of Engineers (1970).

The hydraulic calculations required to determine the design velocity, water surface elevation, energy slope, and tractive force exerted on the rock can be determined through the use of an accepted technique for back-water computations. The best available approach may be the computer program HEC-2, which describes the flow field (U.S. Army Corps of Engineers 1976). Local scour conditions and flow patterns around an impoundment are important when designing flood protection, but existing computer models do not provide adequate means to calculate localized flow forces.

Wind Erosion: Using Chepil's Equation

A document prepared for the NRC (Bander 1982) reviews the mechanics of wind erosion and predictive models. The model that best describes the wind erosion of a tailings pile is the equation developed by Chepil (Skidmore

1974). Chepil's equation contains more factors describing the variables that influence wind erosion from a tailings pile than any other model reviewed. The equation is fairly easy to use because there are charts and graphs for obtaining the various factors in the equation, and an existing computerized program for using it.

The wind erosion equation gives the amount of soil lost from a covered tailings pile over many years. A caution in using this equation: For any particular year, the amount of soil lost can vary, depending on the wind and precipitation for any particular location. Considered on a seasonal basis, the variations from average values would be even greater. One way to improve the accuracy of the equation and to estimate the variability of the annual values predicted would be to incorporate probability functions for some of the dynamic variables (Skidmore 1974).

Overland Flow: The Regression Model and the Process Model

Walters (1983) discusses the processes involved in overland erosion and appropriate models for evaluating this form of erosion on tailings piles. The models are of two basic types:

(1) Regression models, such as the Universal Soil Loss Equation, and the Modified Universal Soil Loss Equation. These are derived from empirical data and interpret input-output relations using simplified forms that may or may not reflect actual physical conditions.

(2) Physical process simulation models, such as the Agricultural Runoff Model, the CREAMS model (Chemical, Run-off, and Erosion from Agricultural Management Systems), and the MULTSED model (Multiple Watershed Water and Sediment Routing). These models formulate the processes controlling erosion.

Both types of models can be used for cover design. Regression models are simple to use and can accommodate regional data. The primary limitation of regression models is that they are empirical, in that they are most accurate for the specific locations where soils and climate data used to construct the models were collected. As a result, significant errors may occur when regression models are used for sites where no empirical data exist. Whenever empirically derived factors are used, the relevance to a particular site is highly dependent on the experience and skill of the model user.

While process models are more accurate than regression models for specific sites, they require computers and use more detailed input data than regression models do. In addition, some process models use empirically derived relationships in some portions of their sediment yield calculations.

Regression models can be used to quickly assess the erosion potential of the impoundment by providing relative estimates of erosion on various parts of the tailings (e.g., slopes and tops) and for various segments of the

watershed. For tailings located on hydrologically simple landscapes such as plains, the regression models may suffice. Regression models are also appropriate for selecting materials for erosion protection. The relative erosion rates of different soil materials and slopes can be evaluated quickly with simple regression models.

Complex hydrologic landscapes are common at tailings sites in the western United States. Design of these protective covers must consider runoff from the tailings themselves, runoff from the surrounding watershed, and any nearby streams that present potential flood danger. Under flooding conditions, a regression model is not appropriate, so hydraulic and process models should be used for designing protective covers (Walters 1983).

Gully Erosion: The Empirical Method and the Tractive Force Method

Currently, there are two techniques generally used to determine gully erosion potential: (1) empirical observation and (2) the tractive force method (Nelson et al. 1983).

In the following descriptions of these two methods, keep in mind that the empirical observation and tractive force methods can be used to identify where gully erosion might occur; they do not predict the magnitude of erosion.

The empirical method involves identifying critical locations in drainage areas that may be subject to gullying. Measurements of drainage areas above gullies and of slopes at the point of existing gullies are compared with similar measurements of ungullied areas. Such comparisons result in threshold relationships of drainage areas and slopes that indicate potential gullying.

The tractive force is the force exerted by moving water over the wetted perimeter of the channel that causes sediment transport. The tractive force method involves selecting the average shear stress exerted by flow as a threshold parameter related to gully incision. Gullying potential is calculated using the frictional forces at the soil/water interface and comparing the results to an allowable tractive force determined by an empirical evaluation of the local geomorphology.

BIOTIC INTRUSION

Biotic intrusion facilitates the release of contaminants by

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

- 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.

Before methods to exclude plants and animals from tailings are designed, the extent of the intrusion problem must be determined at each disposal site. 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, because no computational models exist yet.

Transport enhancement can be evaluated using existing erosion, soil moisture, and radon flux models (Mayer and Zimmerman 1981). 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, and the 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 will in any case be necessary.

Because the extent of damage caused by biotic intrusion is unknown, preliminary assessment followed by quantitative analyses is suggested before developing design specifications. Assessment of plant and animal species that could cause intrusion problems can be made from the literature and from site visits. If potential problems exist, a preliminary modeling study can be made using existing data. If the preliminary modeling study suggests that precautions must be taken to prevent biotic intrusion, detailed site data can be collected to produce design specifications. Site-specific evaluation by experts should coincide with modeling efforts to avoid costly misinterpretations.

SOIL MOISTURE

For conceptual designs, simplified calculations of long-term soil moisture (Gee, Nielson, and Rogers 1984) are appropriate. These calculations are based upon empirical relationships between soil and climate characteristics.

Computer modeling using the UNSAT water flow code has been used in UMTRAP research and provides a useful tool for predicting water movement and storage in soils (Simmons and Gee 1981; Mayer et al. 1981). However, detailed input data are required for operation of UNSAT. While UNSAT may require information too detailed for developing conceptual designs, it will certainly be applicable for final design plans.

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This report reviews design considerations for protective covers for uranium mill tailings impoundments. The role of protective covers in tailings containment systems is discussed. Factors affecting the long-term stabilization of tailings (erosion, biotic intrusion, and soil moisture) are summarized. Basic elements to be considered in design of all uranium tailings covers are presented, and then quantitative techniques for designing site-specific covers are reviewed.

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