Revegetation and Rock Cover for Stabilization of Inactive Uranium Mill Tailings Disposal Sites: Final Report

P. A. Beedlow

May 1984

**Prepared for the U.S. Department of Energy
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**Pacific Northwest Laboratory
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ABSTRACT

Guidelines for using vegetation and rock to protect inactive uranium mill tailings from erosion were developed by Pacific Northwest Laboratory as part of the Department of Energy's Uranium Mill Tailings Remedial Action Project (UMTRAP) Technology Development program. Information on soils, climate, and vegetation were collected for 20 inactive tailings sites in the western United States. Sites were grouped according to similarities in climate and vegetation. Soil loss for those sites was characterized using the Universal Soil Loss Equation. Test plots were used to evaluate 1) the interaction between vegetation and sealant barrier systems and 2) the effects of surface rock on soil water and vegetation. Lysimeter and simulation studies were used to direct and support field experiments.

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CONCLUSIONS

The author wishes to thank the many individuals who have helped him in the preparation of this report. He is particularly indebted to Mr. J. H. Smith, Jr., for his help in the design and construction of the test apparatus, and to Mr. J. H. Smith, Jr., for his help in the design and construction of the test apparatus. He is also indebted to Mr. J. H. Smith, Jr., for his help in the design and construction of the test apparatus.

With the assistance of Mr. J. H. Smith, Jr., the author has been able to obtain the results of the tests. The results of the tests are given in the following table. The results of the tests are given in the following table. The results of the tests are given in the following table.

SUMMARY

The Pacific Northwest Laboratory (PNL), under contract to the U.S. Department of Energy's Uranium Mill Tailings Remedial Action Project (UMTRAP) Office, conducted research on the use of rock and vegetative materials to protect inactive uranium mill tailings from long-term erosion stresses. The overall objective of the research was to develop guidelines for the use of vegetation and rock material for surface stabilization. The research effort centered on developing generic solutions to the problem of surface erosion.

Covered tailings are made up of components that function together as a system. Surface covers protect this system from erosion that could damage its integrity. Surface covers interact with other system components through soil moisture, plant root growth, and burrowing activities of animals.

Although each tailings pile will require an individual design, three basic cover designs involving vegetation were identified: 1) vegetation alone, 2) vegetation with surface rock, and 3) vegetation with subsurface rock. One or any combination of these may be used on a given tailings pile, and if gully or channel erosion is probable, rock riprap may be added. The vegetation material consists of various combinations of perennial plant types (grasses, forbs, and shrubs) that are adapted to the conditions at a particular site. Rock material can range from pit-run to sorted material. Engineered rock armor designs were not considered in UMTRAP research but are part of an ongoing project sponsored by the U.S. Nuclear Regulatory Commission (NRC).

The inactive tailings sites in the western United States were grouped into three major geoclimatic regions to evaluate the adequacy of vegetation for long-term stabilization: the Colorado Plateau, the West Slope of the Rocky Mountains, and the Northern Great Plains. Four general vegetation types were found at western sites: grasslands, woodlands shrub steppe, and salt shrub. Soil loss rates calculated using the Universal Soil Loss Equation were variable within geoclimatic regions and vegetation types, but trends were apparent. Vegetation or vegetation plus a layer of surface rock provides adequate stabilization against long-term average soil loss for slopes less than 10% at the UMTRAP

sites evaluated. However, detailed analyses of erosion due to severe storm events, gully formation, and channel cutting is necessary for each site.

Radon barriers and an herbicide used as a root barrier had no significant effects on vegetative cover or soil moisture. Root distributions were not significantly affected by the asphalt seal or by the herbicide. No damage to the asphalt seal due to root penetration was detected. Root penetration into tailings occurred in an area without asphalt seal.

The effects of surface rock on vegetation and soil moisture were determined by: 1) simulation modeling, 2) a lysimeter experiment, and 3) field-scale studies. Results indicate that care must be taken when designing surface covers. The moisture dynamics of the tailings pile can be altered significantly by surface treatment. Vegetation and vegetation-and-rock covers can result in a relatively stable moisture content. Rock covers that exclude plant growth, even for short time periods, can increase the moisture content of the tailings pile and cover, which may lead to drainage or destabilization of the cover.

Surface rock affected vegetation structure by favoring the establishment of weeds, shrubs, and forb plant species. Grass cover was highest on soil without surface rock. The most successful seed mixture was predominantly shrub and forb species that have adapted to the local environment. Surface rock with vegetation had no significant effect on soil moisture relative to soil without surface rock.

Regardless of the surface cover design used, efforts to establish vegetation are necessary, especially in the West. Establishment of vegetation in arid areas is typically episodic, depending on favorable soil moisture conditions. The more arid the site, the more infrequently that favorable conditions occur naturally. By seeding and irrigating properly during the first growing season, favorable conditions for plant establishment can be created. Relying on natural succession to establish vegetation could leave the surface without a perennial plant cover for considerable lengths of time (conceivably tens of years).

A means to quantify erosion stresses likely to impact a tailings pile is critical in designing long-term protective covers. A survey of available erosion models was conducted; and various models and approaches to using them were suggested. However, regardless of the model used to predict erosion, implementation and interpretation of results must be based on a thorough knowledge of geomorphological processes. Criteria for estimating future climatic conditions need to be defined because all erosion models are highly sensitive to climatic variables.

An approach to designing surface covers, presented in the form of a decision tree, outlines the process of gathering information and evaluating the effects of the surface cover on the containment system. Three phases are recognized: assessment, preliminary design, and final design. The benefit of such an approach is the flexibility it allows in the design of covers.

A review of published research suggests that the following are the most effective methods for designing long-term behavior change. A review of research in the field of health communication and behavior change suggests that the following are the most effective methods for designing long-term behavior change. A review of research in the field of health communication and behavior change suggests that the following are the most effective methods for designing long-term behavior change. A review of research in the field of health communication and behavior change suggests that the following are the most effective methods for designing long-term behavior change.

An approach to designing behavior change is presented in the form of a cycle. The cycle consists of the phases of behavior identification and evaluation, the selection of behavior change strategies, the development of behavior change strategies, the implementation of behavior change strategies, and the evaluation of behavior change strategies. The cycle is presented in the form of a cycle.

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INTRODUCTION

Uranium mill tailings are waste products of the uranium extraction process. The tailings contain hazardous compounds that may become a biohazard if released into the atmosphere and groundwater (NRC 1980). To provide for safe, environmentally sound disposal and control of uranium mill tailings, Congress enacted the Uranium Mill Tailings Radiation Control Act of 1978 (Public Law 95-604). The U.S. Environmental Protection Agency (EPA) subsequently established standards for disposal of these tailings (EPA 1983), limiting radon emissions into the air to $20 \text{ pCi m}^{-2} \text{ s}^{-1}$ on an annual average basis. The design life of the impoundment is to be 1000 years where practicable, but 200 years at least. Groundwater protection is based on state and local standards.

To facilitate the design of containment systems that will meet the EPA standards, the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) have sponsored research to develop the necessary technology (O'Brien 1981; Foley 1983). Asphalt and earthen materials have been evaluated for use as radon barriers (Hartley et al. 1983) and as liners to minimize leaching (Buelt et al. 1981). Herbicide and rock barriers to biological intrusion have been evaluated (Cline et al. 1982). To maintain long-term effectiveness, a containment system must be protected from wind and water erosion, chemical and physical degradation, and biologic disturbance by a protective surface cover. Research under the DOE Uranium Mill Tailings Remedial Action Project (UMTRAP) has addressed problems related to surface stabilization of covered tailings piles.

The Pacific Northwest Laboratory (PNL)^(a) has developed guidelines for the use of vegetation and gravel or earth/rock material to protect inactive uranium mill tailings impoundments from long-term erosion stresses. The research effort centered on developing generic solutions to the problem of surface erosion. The results of this research have provided a range of alternatives to be evaluated for site-specific remedial action designs.

(a) Operated by the DOE for Battelle Memorial Institute.

Vegetation can effectively control erosion. However, in some areas where vegetation is sparse, or under particular erosion stresses (i.e., flooding and gullyng), vegetative cover may not provide adequate protection. Additional protection can be gained by using vegetation in combination with gravel or other rock material. In some cases, engineered rock riprap may be required, however, riprap protection was beyond the scope of this program. A prerequisite for designing protective covers using vegetation is an understanding of the relationships between plants, the containment system, and the environment. This knowledge can then be used to determine the sites where vegetation can be used and how it interacts with other system components.

The research reported here examined the suitability of vegetation and rock covers for stabilizing the surfaces of radon covers on uranium mill tailings. The erosion potential of soils under existing conditions at western tailings sites was calculated to determine whether vegetation alone could stabilize the tailings for long periods of time. The interactions between surface treatments and barriers are critical to the proper functioning of the entire impoundment system. Penetration of radon barriers by plant roots could decrease their effectiveness. Changes in the soil water balance resulting from surface treatments could also affect barrier performance or contribute to decreased groundwater quality by accelerating leaching. Therefore, learning how surface treatments affect soil water and vegetation was the primary objective. Test plots were used to evaluate: 1) the interactions between vegetation and barrier systems (radon and biological) and 2) the effects of rock covers on soil water and vegetation. Plant types and planting methods for particular surface treatments were studied, including combinations of rock and vegetative covers.

This report summarizes the research on surface stabilization, beginning with a conceptual discussion that presents decommissioned tailings piles as dynamic systems. Three basic design schemes for vegetative covers are described. The applicability of vegetative covers in western uranium milling regions is evaluated. Because the use of vegetation in combination with gravel or rocky soil is considered for surface covers, experimental results of the effects of rock materials on vegetation are presented. A systematic procedure for designing surface covers is outlined.

CONCLUSIONS AND RECOMMENDATIONS

Vegetation and rock are suitable surface covers for protecting covered uranium mill tailings. Basic designs include vegetative covers, rock covers, and combinations of vegetation and surface rock. Subsurface rock can be used for additional erosion protection, soil moisture control, or biological barriers. The following general guidelines relate to the formulation of site designs:

- Covered tailings consist of components that function as a system. Surface covers interact with other components to regulate soil moisture, plant root growth, and biointrusion. Designs for protective covers should consider these interactions.
- Inactive tailings sites in the West were grouped into three major geoclimatic regions. Soil loss was calculated with the Universal Soil Loss Equation. At the sites evaluated, vegetation or vegetation plus a layer of surface rock provided adequate stabilization against long-term average soil loss for slopes less than 10%. These results indicate that vegetation or vegetation-plus-surface rock should be considered for protective covers on portions of the piles not exposed to gully or flood erosion.
- Vegetation had no significant effects on and was not significantly affected by radon barriers or the Treflan® herbicide used as a root barrier.
- Surface rock without vegetation increased soil moisture in lysimeter and field experiments. Simulation modeling suggested that drainage from tailings could occur within three years if rock covers thick enough to prevent growth of vegetation are applied. High moisture contents in cover materials could also lead to destabilization. The use of rock covers that limit vegetation growth should be minimized to avoid increasing moisture within tailings and covers.

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- Surface rock favored different plant species than did bare soil. Shrubs, forbs, and weeds were favored where surface rock was applied. Grasses were favored on soil without surface rock. Shrubs, forbs, and weeds typically have deeper root systems than do grasses. Cover designs must accommodate the increased risk of root intrusion when rock covers are used.
- Efforts should be made to establish vegetation on tailings covers. Relying on natural colonization to establish vegetation could leave the surface without a perennial plant cover for tens of years in the West. Supplemental irrigation during the first year after planting can expedite plant establishment.
- Erosion stresses impacting a site should be evaluated with appropriate mathematical models in conjunction with a geomorphological survey.
- Surface covers should be designed on a site-specific basis and in a systematic manner. The method used should be flexible enough to allow for differences in materials availability, climate, topography, erosion stresses, plant and animal use, and tailings characteristics.

COVERED TAILINGS PILES AS DYNAMIC SYSTEMS

The goal of a tailings containment system is to minimize the escape of hazardous materials. Pollutants can escape through leaching, surface run-off, gaseous diffusion, biotic transport, or any combination of these mechanisms. Each component of the containment system is designed to minimize one or more of these factors. Leaching is controlled by liners, by the inherent buffering properties of underlying soils, or by minimizing water infiltration. Radon barriers are designed to limit gaseous diffusion. Chemical and physical barriers prevent intrusion of plants and animals into tailings. Surface covers protect the impoundment from erosion that could render barriers inoperable or lead to direct transport of tailings material.

The components of a containment system do not function independently, however. The control of soil moisture is the common link between them. The amount of moisture in the soil affects radon attenuation by earthen materials because radon release is inversely related to soil moisture content (Mayer et al. 1981; Hartley et al. 1983). The design of an effective liner must allow for the amount and rate of water passing through the tailings (Buelte et al. 1981). The amount and depth of soil moisture affects the growth of plant roots, and influences the need for animal intrusion barriers.

The type of surface cover will affect the moisture balance of the containment system. Except in cases where the groundwater level lies within the tailings, soil moisture dynamics are driven by input from precipitation and regulated by surface conditions. Expected surface conditions on tailings range from covers where vegetation predominates, to rock/vegetation combinations, to rock covers. At most western sites, potential evapotranspiration equals or exceeds precipitation. Under these conditions no appreciable accumulation of moisture in the soil-tailings profile is expected because, normally, evaporation from the soil surface and transpiration by plants removes the water that enters the soil as precipitation. Rock covers cause increased infiltration and decreased evaporation (Mayer, Beedlow, and Cadwell 1981; Kirkham, Beedlow, and Gee 1982). Areas covered with rock effectively capture more precipitation than do adjacent areas without rocks. Thick rock covers that exclude plant growth

for a number of years contribute further to water accumulation in, and percolation through, the tailings cover system. Thin rock covers (rock mulches) that permit plant growth, increase infiltration, and decrease evaporation make additional moisture available to plants and thereby support more vegetative cover than would otherwise thrive.

The effectiveness of radon barriers constructed of earthen materials and the percolation of water into tailings may be affected by plant growth and animal activity in and on the pile. The penetration of plant roots through radon barriers can increase radon flux by providing channels for gas escape. Burrowing activity of mammals and invertebrates in the overburden results in a series of tunnels and chambers that can promote the escape of radon gas. Hakonson, Martinez, and White (1982) discovered up to two miles of pocket gopher tunnels over a low-level waste burial site at Los Alamos National Laboratory. Vogel, Ellington, and Kilgore (1973) reported that prairie dogs construct their mounds in a way that promotes wind-induced ventilation through their tunnels. Tunnel systems created by small mammals, ants and decomposing plant roots may also enhance the passage of surface water through earthen covers and into tailings. Burrowing mammals may bring about increased erosion of cover materials (Winsor and Whicker 1980). For example, pocket gophers accelerate the loss of soil by continually bringing soil to the surface in the process of tunneling.

The surface cover can affect the kinds of plants and animals that occupy a tailings site. The species of plants growing on covered tailings is influenced by soil characteristics (e.g., texture and amount of rock) and by the amounts of soil water available to plants (Douglas 1972; Barbour and Diaz 1973; Harner and Harper 1976). Rooting depth is largely a function of plant type and soil moisture dynamics (Grime 1979). To prevent root growth into tailings, both soil moisture dynamics and plant type (species) must be considered. Vegetation type and soil characteristics affect the kinds of burrowing animals that inhabit an area (McCloskey 1976; Price 1978; O'Farrell 1980; Gano and States 1982). Observations at Hanford suggest that the species of grass influences the species of burrowing animals at low-level waste sites. Conversely, animal activity can change the vegetation (Coppock et al. 1983).

Decommissioned tailings piles should be viewed as dynamic systems--each component affects the others and responds to the surrounding environment. Components should therefore be designed in an integrated manner that minimizes the release of toxic elements. Containment system designs will involve a number of trade-offs: increase the amount of soil moisture to reduce radon flux and increase the chance of biotic intrusion or erosion; reduce the erosion potential by thickening rock covers and increase the amount of water in the system--and so on. Optimization of system components is a vital part of containment design.

Because soil moisture is a factor in the functioning of all components, the ability to regulate the amount of moisture in the system allows a greater range of design options. Soil moisture control can be achieved by a proper mix of rock and vegetation in the protective cover. The depth to which roots penetrate a cover can be controlled through proper placement of root barriers. For example, maximal soil moisture could be achieved by placing thick rock covers on the surface to reduce evapotranspiration and by placing a root barrier close to the surface. In this way, precipitation quickly infiltrates beyond the rooting zone. Minimal soil moisture could be achieved by maximizing vegetative cover and root development to extract the water.

BASIC SURFACE STABILIZATION DESIGNS USING VEGETATION

A single tailings impoundment could conceivably require several different types of protective covers depending upon the potential erosive forces, biotic intrusion, 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 riprap may be required. Portions of the tailings above the projected flood level will require protection from wind and overland flow. For those sites where soil and climatic conditions permit, vegetation alone may be adequate to protect the portions of the impoundments above the flood level. Sites which are not capable of supporting enough vegetation to control erosion can be stabilized with combinations of rock and vegetation. 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 radion barrier and surface cover.

Although each site will require an individual design, three basic cover types involving vegetation (Figure 1) are identified for use above the flood level: 1) vegetation alone, 2) vegetation in combination with surface rock, and 3) vegetation in combination with subsurface rock. The vegetation consists of various combinations of plant types (grasses, forbs, and shrubs) that are adapted to the conditions at a given site. The rock material can range from pit-run to sorted material depending on the design requirements. Engineered riprap covers can protect against gully and channel erosion (Walters 1982).

VEGETATION

The simplest and probably the least expensive way to protect impoundments is to establish vegetation (Figure 1a). This design involves seeding selected plant species directly into overburden material or placing topsoil over the radon barrier or overburden^(a) and then seeding.

(a) For discussion purposes, no differentiation is made between overburden and earthen radon barriers in this report.

VEGETATION AND SURFACE ROCK

Under arid conditions, where poor quality soil is used, or on steep slopes, vegetation may not provide enough cover to adequately stabilize the surface. Additional protection can be afforded by applying a thin layer of rock or rocky soil to the surface (Figure 1b). Vegetation is seeded into the rock. This combination can be applied over topsoil or suitable overburden. The rock is likely to affect the types of plants that will become established. Because the rock acts like a mulch, more water can be available for plant growth.

VEGETATION AND SUBSURFACE ROCK

Where vegetation alone provides adequate protection except against a rare but severe storm event, and where aesthetic designs are necessary, subsurface rock can provide the additional protection (Figure 1c). Subsurface rock can also be used when barriers are needed to prevent plant and animal intrusion (Cline et al. 1982). Maximal water accumulation can be expected if the rock is placed near the surface, because extraction of water by plant roots is limited to the soil above the rock barrier. Any water percolating through the barrier will be stored or lost by drainage. The amount of water passing through the barrier will depend upon the climatic conditions, the properties of the topsoil, and the transpiration rates of the plants.

FIGURE 1. Basic Cover Designs Using Vegetation

Figure 1. Three types of landfill cells.

EFFECTIVENESS OF VEGETATION FOR EROSION CONTROL--REGIONAL ANALYSIS

The inactive uranium mills are located throughout the Rocky Mountain West, the Texas Gulf Coast, western Pennsylvania, and the western Dakotas. The western sites are shown in Figure 2. Large-scale differences in climate, vegetation, and land form were used to identify broad geoclimatic regions. The effectiveness of vegetative covers for stabilizing tailings within the major geoclimatic regions was evaluated using the Universal Soil Loss Equation (USLE) described by Wischmeier and Smith (1978). The USLE is somewhat limited in its application (Walters 1983), but it was chosen for this study because it is well suited for regional data, it is widely recognized, and the calculations are relatively simple.

Evaluating the effectiveness of vegetation for tailings stabilization involved sampling undisturbed soils of the type likely to be used as the top layer on tailings covers. It was assumed that over long time periods (>100 yr) vegetation growing on the tailings cover would be similar to that existing on that soil type, provided that: 1) the microclimate at the soil site is similar to that at the tailings site, 2) the slope and aspect are similar between the soil and tailings sites, and 3) the dominant species of plants growing on the undisturbed soil are reestablished on the tailings cover. Long-term climatic change was not considered. The data on soils, climate, and vegetation were used to 1) group sites into geoclimatic regions, 2) characterize the vegetation found in those regions, and 3) calculate soil loss by the USLE. Evaluations of erosion losses due to wind, intense storm events, gullying, and flooding were beyond the scope of this work.

Only sites in the arid and semi-arid West were evaluated. The use of vegetation for stabilization on the Texas Coastal Plain and in Pennsylvania is assumed because those areas support high vegetative cover, and because revegetation practices are well established in these areas.

Data on soils, climate, and vegetation were collected from 40 undeveloped sites close to 20 of the 23 tailings piles shown in Figure 2. At a chosen sampling location, the line-intercept and plot-frame methods (Daubenmire 1968) were used to estimate shrub cover. All cover measurements were taken by

FIGURE 2. Location of Western Inactive Uranium Mill Tailings Piles

species. A surface soil sample for pH measurement was taken every 50 m along the 500 m line. Soil cores were analyzed using standard procedures for Washington State (Moodie and Kochler 1975) for texture, organic matter content, particle size, electrical conductivity, and macronutrients (nitrogen, soluble sodium, exchangeable sodium, magnesium, calcium, potassium, and phosphorous).

Information on the climate of the sampling sites was obtained from published National Oceanic and Atmospheric Administration (NOAA) reports. Average

monthly temperatures, monthly precipitation, numbers of consecutive frost-free days, and annual maximum and minimum temperatures are listed for a network of stations throughout each state. Specific climatic data were not available for the individual sampling sites.

Sites were grouped based on similarities in vegetation and climate using multivariate analyses (Beedlow, McShane, and Cadwell 1982). The data used to group the sites are shown in Tables 1 and 2. The soils chosen for sampling in the vicinity of each tailings pile were the best available for use as topsoil, and were, consequently, fairly similar. Because of this similarity, soil factors accounted for very little of the variability in vegetative cover between sites and were therefore not used to group sites.

CLIMATIC ANALYSIS

The western tailings sites can be grouped into three general regions based on climate and geographical location: the Colorado Plateau, the West Slope of the Rocky Mountains, and the Northern Great Plains.

The climate of the Colorado Plateau is characterized by cold winters, hot summers, and low amounts of precipitation (Bailey 1978). The inactive tailings piles located within the region include Monument Valley and Tuba City, Arizona; Grand Junction and Slick Rock, Colorado; Ambrosia Lake and Shiprock, New Mexico; and Green River and Mexican Hat, Utah. Annual precipitation at these sites ranges from a low of 19.4 cm at Monument Valley to a high of 28.3 cm at Slick Rock. Within the Colorado Plateau region, however, considerable variation may be found in the pattern of precipitation, and this variation can affect surface stabilization requirements. At the Mexican Hat and Shiprock sites, for example, less than 40% of the annual precipitation falls during the growing season (April to September), while the Grand Junction and Green River tailings sites receive at least half their annual precipitation during this period. The sites at Monument Valley and Ambrosia Lake, on the other hand, have frequent summer thunderstorms during late spring and summer, and these contribute 70% of the annual precipitation.

Moderate amounts of precipitation, warm summers, and cold winters are the predominant climate characteristics of the West Slope (Bailey 1978). Inactive

TABLE 1. Location, Soil Type, and Mean Percent Cover for the Vegetative Cover Variables Used to Classify Vegetation at Sites Sampled in the Vicinity of 20 Western Uranium Mill Tailings Piles

Tailings Piles	Site Code	Soil Type and Texture	Cover, %						
			Perennial Grass	Annual Grass	Shrub	Salt Shrub	Forb	Tree	Total
Grand Junction	GJ-1	Glenburg sandy loam	9.6	36.3	0.1	2.8	2.95	0.0	51.3
	GJ-2	Avalon loam	12.4	40.3	0.0	1.1	6.1	0.0	59.8
	GJ-3	Fruita loam	4.7	28.5	1.1	0.0	6.8	0.0	41.1
	GJ-4	Billings silty clay loam	1.0	7.1	4.1	17.0	2.5	0.0	29.4
Naturita	NA-1	Clovis-Progresso fine loam	20.0	1.0	26.3	0.0	8.5	0.0	48.2
Slick Rock, 1 and 2	Sl-1	Minchy fine sandy loam	17.1	5.0	1.0	1.1	0.6	0.0	25.0
Rifle, 1 and 2	RF-1	Potts loam	26.4	0.4	1.4	0.0	1.9	0.0	29.9
	RF-2	Kim loam	1.0	0.5	42.4	0.0	0.19	0.2	46.2
Maybell	MB-1	Rock river loam	17.8	18.0	30.0	0.0	11.4	0.0	78.7
Gunnison	GU-1	Duffason-Copering loam	14.4	0.0	27.5	0.0	8.2	0.0	48.6
	GU-2	Evanston loam	12.4	0.0	33.8	0.0	3.0	0.0	49.1
Durango	DU-1	Jordero loam	40.0	0.5	0.0	0.0	36.3	0.0	76.8
	OU-2	Sili clay loam	3.2	0.0	57.0	0.0	14.4	0.4	75.0
	DU-3	Falfa clay loam	3.6	1.6	23.7	0.0	10.2	28.3	67.4
Shiprock	SR-1	Los sandy loam	0.5	0.0	0.7	6.8	0.3	0.0	8.3
	SR-2	C-18 sandy loam	9.8	0.0	0.0	9.3	1.0	0.0	20.1
	RM-1	Aneth-Sheppard loamy fine sand	17.2	1.5	4.2	0.0	2.4	0.0	25.2
	FA-1	Fruitland sandy loam	13.5	0.6	3.0	1.4	15.3	0.0	40.0
Ambrosia Lake	GR-1	Penistaja sandy loam	32.1	0.0	0.7	0.0	3.7	0.0	36.9
	GR-2	Dioxic loam	29.7	0.0	0.2	0.0	1.8	0.0	31.7
Monument Valley	KA-1	Palma Colvis sandy loam	8.9	0.0	18.0	0.0	0.5	0.0	27.3
	KA-2	Tours-Navajo-Trial	6.5	0.0	2.9	0.0	16.4	0.0	26.3
Mexican Hat	MV-1	Monue-Sheppard loamy fine sand	3.7	0.0	13.4	0.0	0.4	0.0	18.0
	MV-2	Nakai very fine sand loam	3.8	0.0	8.0	0.0	5.4	0.0	17.1

TABLE 1. (contd)

Tailings Piles	Site Code	Soil Type and Texture	Cover, %						
			Perennial Grass	Annual Grass	Shrub	Salt Shrub	Forb	Tree	Total
Green River	MO-1	Sager silt loam	0.5	0.4	0.1	5.8	11.3	0.0	18.2
	MO-2	Typic Torrifluvents silt loam	10.0	7.5	0.8	6.7	2.9	0.0	25.5
Baggs	BG-1	Camborthids loam	48.7	11.6	0.5	4.3	27.3	0.0	92.5
	BG-2	Floutsch-Cushool fine sand loam	33.1	1.8	9.3	0.5	20.2	0.0	66.7
	BG-3	Ryan Park-Elk Mt. loamy fine sand	50.0	4.2	2.9	1.4	12.5	0.0	71.3
Spook	SP-1	Fort Collins loam	35.1	0.1	13.7	0.0	0.4	0.0	55.5
	SP-2	Stoneham-Cusham sandy loam	41.9	1.1	9.3	0.0	6.8	0.0	59.3
	SP-3	Olney sandy loam	47.0	0.1	7.9	0.0	5.8	0.0	61.0
Riverton	RI-1	Griffy loam	23.9	0.0	20.3	0.0	1.8	0.0	46.3
	RI-2	Trook sandy loam	29.6	0.0	4.9	0.0	2.6	0.0	37.5
	RI-3	Apron sandy loam	24.4	0.0	1.7	0.0	0.9	0.0	28.1
Bowman/Belfield	BO-1	Sandy loam	61.2	0.5	0.4	0.0	8.8	0.0	71.0
	BO-2	Grassna silt loam	73.2	0.1	0.8	0.0	7.8	0.0	82.0
	BO-3	Chjama silt loam	91.0	0.0	0.0	0.0	3.7	0.0	95.7
Lowman	LO-1	Coski complex	7.2	0.1	47.9	0.0	34.3	34.3	105.3

TABLE 2. Mean Values for Each of the 10 Climatic Variables Used to Group Western Tailings Sites

Tailings Piles	Site Code	Temperature, °C				Precipitation, cm					Consecutive Frost-Free Days
		Jan	Apr	Jul	Annual	Jan	Apr	Jul	Oct	Annual	
Grand Junction	GJ-1	-3.8	10.3	23.9	10.3	1.73	1.96	1.47	2.13	21.08	137
	GJ-2	"	"	"	"	"	"	"	"	"	"
	GJ-3	"	"	"	"	"	"	"	"	"	"
	GJ-4	"	"	"	"	"	"	"	"	"	"
Naturita	NA-1	-5.0	6.3	20.1	7.3	2.24	2.79	2.95	4.04	32.18	116
Slick Rock	SL-1	-3.2	9.8	25.3	11.1	2.67	2.72	3.99	1.63	28.30	150
Rifle, 1 and 2	RF-1	4.9	8.4	21.2	8.4	2.34	2.36	2.08	3.15	28.55	111
	RF-1	"	"	"	"	"	"	"	"	"	"
Maybell	MB-1	-8.9	6.8	19.1	5.6	3.71	4.93	1.85	3.89	47.40	79
Gunnison	GU-1	-11.9	8.7	16.6	3.2	2.54	1.98	3.58	2.26	28.55	14
	GU-2	"	"	"	"	"	"	"	"	"	"
Durango	DU-1	-3.6	7.3	19.7	8.0	4.32	3.45	4.70	4.93	47.22	130
	DU-2	"	"	"	"	"	"	"	"	"	"
	DU-3	"	"	"	"	"	"	"	"	"	"
Shiprock	SR-1	-8.2	10.3	23.3	10.3	1.17	5.33	2.08	1.40	15.37	124
	SR-2	"	"	"	"	"	"	"	"	"	"
	RM-1	-2.8	11.9	28.3	1.3	1.45	1.12	2.18	2.67	21.36	120
	FA-1	-1.5	10.8	24.6	11.5	1.29	1.45	2.11	2.74	20.55	166
Grants	GR-1	-2.4	8.7	21.1	9.5	1.50	0.53	3.84	1.29	22.89	118
	GR-2	"	"	"	"	"	"	"	"	"	"
Monument Valley	KA-1	1.1	10.7	24.6	11.7	1.37	1.04	2.79	2.62	19.38	160
	KA-2	"	"	"	"	"	"	"	"	"	"
Mexican Hat	MV-1	-1.3	6.7	27.2	12.9	2.44	0.61	1.80	1.35	14.73	170
	MV-2	"	"	"	"	"	"	"	"	"	"
Green River	MO-1	-0.8	13.6	27.3	13.5	1.22	2.16	1.19	2.67	20.17	174
	MO-2	-2.7	11.1	25.8	11.7	1.65	2.06	1.55	2.82	22.66	179

TABLE 2. (contd)

Tailings Piles	Site Code	Temperature, °C				Precipitation, cm					Consecutive Frost-Free Days
		Jan	Apr	Jul	Annual	Jan	Apr	Jul	Oct	Annual	
Baggs	BG-1	-7.9	5.3	18.3	5.2	2.21	3.12	2.69	3.23	31.65	73
	BG-2	"	"	"	"	"	"	"	"	"	"
	BG-3	"	"	"	"	"	"	"	"	"	"
Spook	SP-1	-3.4	7.3	22.3	8.6	1.27	3.99	2.67	2.59	32.79	139
	SP-2	"	"	"	"	"	"	"	"	"	"
	SP-3	"	"	"	"	"	"	"	"	"	"
Riverton	RI-1	-9.4	6.6	21.1	6.2	0.48	2.97	1.55	1.96	21.74	100
	RI-2	"	"	"	"	"	"	"	"	"	"
	RI-3	"	"	"	"	"	"	"	"	"	"
Bowman/ Belfield	BO-1	-10.1	5.3	21.3	5.7	1.07	3.66	6.10	2.06	41.68	142
	BO-2	"	"	"	"	"	"	"	"	"	"
	BO-3	"	"	"	"	"	"	"	"	"	"
Lowman	LO-1	-4.8	6.7	19.6	7.2	7.06	3.84	2.16	2.57	56.54	65

tailings piles in this area include: Durango, Gunnison, Maybell, Naturita, and Rifle, Colorado; Lowman, Idaho; Lakeview, Oregon; Salt Lake City, Utah, and Baggs,^(a) Wyoming. Annual precipitation ranges from 28.6 cm at the Gunnison and Rifle sites to 47.4 cm at Maybell and Durango to 56.5 cm at Lowman. With the exception of Lowman, all of the West Slope sites receive approximately half their annual precipitation between April and September. The Lowman site is unique: located in Idaho on the western side of a different range of the Rockies, it is considerably further north than the rest of the West Slope sites. It receives higher annual precipitation, with more falling as snow, than do the other West Slope sites. The Gunnison site (elevation ~8000 ft) has a climatic pattern similar to the other West Slope areas, but is significantly cooler and has a very short growing season.

Four of the inactive tailings piles are in the Northern Great Plains: Riverton and Spook, Wyoming; and Bowman and Belfield, North Dakota. This region is characterized by cold dry winters and hot summers; most of the precipitation falls during the summer. Total precipitation is variable throughout the region, ranging from 21.7 cm at Riverton to double that amount at the Bowman and Belfield sites. The Wyoming sites receive approximately 70% of their annual precipitation between April and September. Over 80% of the yearly precipitation falls during this time period at the Bowman and Belfield tailings piles.

VEGETATION ANALYSIS

Based upon multivariate analyses of the vegetative cover data, six plant community types were identified at the 40 sites sampled (Table 3). The species composition of a particular community type varies between locations, but the basic structure is the same.

One of the most widespread community types is the perennial grassland. The vegetation of this community consists primarily of short bunchgrasses. Scattered shrubs and small trees are also represented, along with occasional forbs and cacti. All sites sampled in the vicinity of the Bowman, Belfield,

(a) Formerly included in UMTRAP.

TABLE 3. The Six Plant Community Types Identified Within the Three Climate Zones Represented by Sites Sampled in the Vicinity of 20 Uranium Tailings Piles

Region	Perennial Grass	Shrub	Forb/ Perennial Grass	Annual Grass	Salt-Tolerant Shrub	Woodland
Northern Great Plains	X	X	X			
West Slope	X	X	X			X
Colorado Plateau	X	X	X	X	X	

Spook, Ambrosia Lake, and Slick Rock tailings piles, and at least one of the sites sampled near the Rifle, Baggs, Shiprock, and Riverton piles, consist of perennial grassland vegetation.

Three of the four sites sampled in the vicinity of the Grand Junction tailings pile also had a dominant grass cover, though these were annual rather than perennial grasslands. As in the perennial grassland, there are scattered trees and shrubs with occasional forbs, but the dominant vegetative cover consists mainly of annual grasses in the genus Bromus.

Areas covered predominantly by shrubs were also common. In this community small shrubs, mainly sagebrush (Artemisia tridentata) or blackbush (Coleogyne ramosissima) are dominant. Bunchgrasses and forbs are present in the understory. Sampling locations with shrub-dominated communities include all those in the vicinity of Gunnison, Mexican Hat, Naturita, and Maybell, and one each near the Rifle, Durango, Monument Valley, and Riverton sites.

The vegetation at areas near Lowman and at one location near Durango was classified as woodland. At Lowman, the tree canopy was composed mainly of ponderosa pine (Pinus ponderosa) and Douglas fir (Pseudotsuga menziesii). In the Durango area, pinyon pine (Pinus edulis), juniper (Juniperous osteosperma), and gamble oak (Quercus gambelii) were codominant with ponderosa pine. Both of these sites had a moderate to heavy understory of shrubs, grasses, and forbs, and the tree canopy was not closed.

Some areas of the Colorado Plateau, particularly bottomlands from which soil is likely to be borrowed for tailings, have soils with relatively high concentrations of salt. The plant communities in these areas are distinctive; often saltbrush (Atriplex spp.) and greasewood (Sarcobatus vermiculatus) are the dominant shrubs. A sparse to moderate cover of forbs (often in the genus Atriplex) and salt-tolerant grasses is usually present. Sites with a salt-tolerant plant community include those sampled near Green River, one near Grand Junction, and two in the vicinity of Shiprock.

Six of the sampled sites are of a mixed plant community type that can best be described as forb-dominated. In two of the areas sampled near the Baggs tailings piles, and in one each near Shiprock, Durango, and Monument Valley, forbs comprise greater than 30% of the total cover. Shrubs are generally sparse and grass cover is moderate to high (10% to 50% of the total cover) in all these areas.

The six plant community types were grouped into four general vegetation types for calculating soil loss: grassland, shrub steppe, woodland, and salt shrub. The perennial grass, forb/perennial grass and annual grass types were combined because the differences in effects on soil loss were negligible between types of grassland.

The relationship between annual precipitation and percent total vegetative cover is shown in Figure 3. The Colorado Plateau sites, which receive less precipitation than those on the West Slope or in the Great Plains, have lower total vegetative cover values. However, variability between sites due to soil factors was reduced by sampling only those soils that could be used for topsoil. Thus, the relationship illustrated in Figure 3 is not applicable to poor-quality or rocky soils. Also, the total percent cover values used to generate the graph were obtained in the summer of 1981 but are plotted against average annual precipitation values. Total precipitation fluctuates from one year to the next; consequently, vegetative cover can be expected to change somewhat from year to year.

At a particular location, the species composition and cover of the plant community is determined not only by climatic and edaphic factors, but also by

FIGURE 3. Relationships Between Percent Vegetative Cover and Mean Annual Precipitation at Sites Sampled in the Vicinity of the Western Inactive Tailings Piles (site codes are defined in Table 1)

the degree of disturbance to which the vegetation has been subjected. In the West, grazing deserves particular attention when analyzing any vegetation data that could be used in a decision-making process.

SOIL LOSS ANALYSIS

Soil loss was calculated using the USLE (Wischmeier and Smith 1978) for each soil type sampled at the inactive tailings sites. The USLE is an erosion model designed to predict the long-term average soil losses in run-off within

limitations.^(a) Despite such limitations, the USLE was considered adequate for comparing the relative effects of vegetation, climate, soils, and slope. The USLE is thought to provide conservative estimates of soil loss, especially in the West (Hart 1982).

The soil loss equation is

$$A = R \cdot K \cdot LS \cdot C \cdot P$$

where A = average annual soil loss (weight/unit area)

R = rainfall erosivity factor

K = soil erodibility factor (weight/unit area per unit of rainfall factor, R)

LS = topographic factor (length and steepness of slope)

C = cropping factor

P = erosion control practice factor (e.g., contouring or terracing).

The terms LS, C, and P are dimensionless. Soil loss, A, has the time period of R and the soil loss dimensions of K.

Values for R were taken from the isoerodent map by Wischmeier and Smith (1978) for each county containing a tailings site. R was corrected for snow-melt for sites receiving snow, following Wischmeier and Smith; this procedure was as follows:

$$R = R_i + 1.5 \text{ (precipitation December through March)}$$

where R = the erosion index used in the USLE

R_i = the R value as read from the isoerodent map.

Values for K were calculated from the Wischmeier and Smith soil erodibility nomograph using the soils data obtained at each site and information provided by the Soil Conservation Service Soil Surveys.

Several slopes and lengths were used in this study: LS-1 = 3% for 30 m, LS-2 = 3% for 183 m; LS-3 = 10% for 30 m, LS-4 = 10% for 183 m, and LS-5 = 2% for 305 m. These slopes were considered to be representative of slopes likely to be vegetated on stabilized tailings. Slopes in excess of 10% are generally

(a) See Walters (1983) for a discussion of the model and the limitations of its applicability to tailings.

considered too steep for successful revegetation although conclusive proof of this "rule of thumb" is not documented. However, riprap is likely to be used on tailings slopes greater than 10%. Slope lengths of 30 m, 183 m, and 305 m are reasonable considering the size of most tailings (15 to 40 ha and 7 to 30 m high).

The cover factor (C) can be divided into three types of effects (subfactors): Type I--effects of canopy cover; Type II--effects of mulch or close-growing vegetation directly contacting the soil (e.g., grass); and Type III--tillage and residual effects (in this study these were the effects of roots). The cover factor is the product of these subfactors. In this study the subfactors were calculated using vegetation data collected at each site. Calculations considered undisturbed land (see Wischmeier and Smith 1978, Dissmeyer and Foster 1981, and Wischmeier 1972 for procedures).

- Type I (canopy effect)--determined by examining the plant species present to estimate canopy height; effective canopy (used in the calculation) = total canopy cover x (% bare ground/100).
- Type II (mulch and ground cover effect)--calculated as $100 - \% \text{ bare ground}$. This method includes the least amount of overlap and represents the amount of ground with no litter, rock, moss, algae crust or ground plants such as grass, forbs, and cacti.
- Type III (root network effect)--% mulch (litter) and ground cover were used. These values were weighted by the type of cover (e.g., living plants, especially grass, are more effective at reducing runoff).

The support practice factor, P, was not included in this study because these control practices are not likely to be maintained over long time periods.

A bulk density of 1.5 g/cm^3 was used for all calculations. This value is representative of the soil types sampled (Brady 1974). Soil loss was represented on a 1000-yr basis to correspond with the EPA regulations on the design life of the impoundment structures (EPA 1983).

Geoclimatic Regions

The median and the range for soil loss in the three major geoclimatic regions are shown in Table 4. The trend is a reduction in loss rates from the Northern Great Plains to the West Slope to the Colorado Plateau. However, the range in each region is quite high, indicating that other factors are more likely to influence soil loss rates.

Vegetation Types

The variability in erosion rates within vegetation types is greater than that between types. A trend of increasing soil loss rates can be observed from grassland to salt shrub (Table 5). Grass is more effective at stabilizing soil than are canopy plants because it eliminates raindrop impact and reduces the velocity of run-off (Wischmeier 1972). Shrub steppe generally has more vegetative cover than salt shrub, and thus provides more protection. Woodlands are often open under the tree canopy, with bare ground common, especially in the pinyon-juniper woodlands in the Southwest (e.g., Durango).

TABLE 4. Soil Loss Calculated with the USLE for Inactive Tailings Sites in Three Geoclimatic Regions of the Western United States^(a)

Region	Soil Loss, cm/1000 yr				
	LS-1	LS-2	LS-3	LS-4	LS-5
Colorado Plateau					
Median	1.52	2.62	7.32	17.93	0.69
Range	18.80	32.21	89.71	220.64	8.26
West Slope					
Median	1.02	1.73	4.80	11.79	0.43
Range	9.45	16.21	45.11	110.64	4.14
Northern Great Plains					
Median	0.76	1.32	3.63	8.94	0.33
Range	1.17	2.01	5.61	13.77	0.51

(a) LS-1 = 3% slope for 100 ft, LS-2 = 3% for 600 ft, LS-3 = 10% for 100 ft, LS-4 = 10% for 600 ft, LS-5 = 2% for 1000 ft.

TABLE 5. Soil Loss Calculated with the USLE for Inactive Testings Sites in the Western United States, Comparing Common Vegetation Types^(a)

Vegetation Type	Soil Loss, cm/1000 yr				
	LS-1	LS-2	LS-3	LS-4	LS-5
Grassland					
Median	0.84	1.42	3.99	9.45	0.36
Range	9.78	16.76	46.69	114.48	4.29
Shrub Steppe					
Median	1.30	2.24	6.20	15.16	0.56
Range	3.30	5.64	15.72	38.56	1.45
Woodland ^(b)					
Median	1.73	2.97	8.31	20.35	0.76
Range	2.59	4.42	12.34	30.28	1.14
Salt Shrub					
Median	2.06	3.53	9.80	24.03	0.91
Range	18.42	31.60	87.96	215.70	8.10

(a) See Table 4 for LS values.

(b) Woodland sites included only Lowman and Durango.

Slope Effects

Despite the wide range in soil loss rates, vegetation allows less than approximately 30 cm of soil loss on slopes of 2% to 3% (LS-1, LS-2, LS-5) over a 1000-yr period. The typical depth of topsoil placed on overburden for revegetation is 20 to 35 cm. For low-angle slopes, soil loss due to run-off is not likely to damage the long-term (>1000 yr) integrity of an impoundment system stabilized with vegetation. The USLE does not predict erosion due to gully or channel erosion, however. Those portions of the tailings subject to these types of erosion must be protected by other means.

In many cases, slopes of 10% can be adequately stabilized (if 30 cm of soil loss after 1000 yr is used as the limit). The choice of whether or not to use vegetation on slopes 10% or steeper then becomes a site-specific question.

Based on this analysis, vegetation should not be discounted as a stabilization technique simply because of geographic area, vegetation likely to exist on the cover, or degree of slope (up to 10%).

Effect of Additional Rock Cover

Soil has been stabilized at construction sites and highway cuts by dumping and spreading crushed stone or gravel over the surface. Table 6 shows the decrease in soil loss when 0.64- to 1.27-cm-dia. crushed stone is applied at 539 MT/ha (calculations based on Wischmeier and Smith 1978). The sites shown are those with the highest soil loss rates; a 10% slope for 30.5 m is used for comparison. The soil loss rates are drastically reduced because the rock eliminates raindrop impact and reduces overland flow. The vegetation in this example was not altered; however, experimental evidence^(a) suggests that rock-covered soil may support different vegetation types from those without rock.

This exercise suggests that at sites where soil loss may be excessive when protected by a vegetative cover only, surface stone may be used in combination with vegetation to provide adequate stabilization. Other erosion factors such as flooding or gullying may necessitate the use of riprap on some portions of the pile.

TABLE 6. Soil Loss as Reduced by Applying Rock to the Soil Surface

Site ^(a)	Soil Loss, cm/1000 yr	
	LS-3	LS-3 + 539MT/ha Crushed Rock
SR-1	90.27	1.93
RF-1	47.24	1.68
MV-2	18.42	0.43
DU-3	14.45	1.92
FA-1	14.33	0.49

(a) Site codes are identified in Table 1.

(a) See section on Vegetation and Vegetation/Rock Covers in this report.

EFFECTS OF BIOLOGICAL AND RADON BARRIERS ON VEGETATION

A test plot was constructed during November 1980 in conjunction with other UMTRAP projects on the inactive tailings pile at Grand Junction, Colorado. Studies conducted at this site focused on: 1) the relationship between vegetation and radon barriers, 2) the interaction between vegetation and the herbicide barriers intended to limit plant root penetration, 3) the effect of soil depth on vegetation, and 4) soil moisture responses to plant cover. These phenomena were evaluated using the parameters of soil moisture, vegetative cover, and root distribution.

A primary objective was to evaluate the influence of asphalt emulsion, multilayer earth, and root barrier herbicide treatments on the establishment of a stabilizing vegetative cover. Soil moisture is critical to the establishment and maintenance of vegetation on disturbed sites in arid and semi-arid regions, and it is influenced by tailings cover treatments.

The soil moisture experimental design included soil over tailings, soil over asphalt, soil over asphalt plus herbicide, soil over multilayer earth, and soil over multilayer earth plus herbicide. The asphalt and plain soil treatment consisted of a mounded soil cover ranging in depth from 0.3 to 1.4 m. The soil over the multilayer earth plot was 0.74 m deep. Soil preparation and seeding were the same for all cover treatments. No significant differences in soil moisture were detected among treatments during three years of study.

Vegetative cover was estimated by species in May, July, and September 1981; and August 1982 and 1983. The percentage of ground covered by each species was estimated during the sampling periods using the Daubenmire cover scale (Daubenmire 1968). September samples were analyzed to identify differences in vegetative cover among the types of barrier treatments. We assumed that the September data would be most indicative of vegetative establishment and growth. No significant treatment-related differences were found.

Root distribution studies were conducted at the Grand Junction test plot in late October 1981. Trenches in the overburden were dug on the asphalt seal portion of the plot and over one location above the tailings. Root distributions were estimated by sampling root frequency at increments of 20 cm in

depth. Root distributions were not significantly affected by the asphalt seal or depths of the overburden. However, roots had penetrated into the surface of the tailings in areas without asphalt. No damage to the asphalt seal by root penetration was apparent. The frequency of roots below the 60-cm depth over asphalt and asphalt with herbicide was noticeably lower than that at shallower depths.

No significant effects were detected on vegetation or soil moisture from the multilayer or asphalt seals. Depth of overburden ranging from 0.5 to 1.0 m had no significant effect on vegetation or soil moisture. The Treflan herbicide used to stop root penetration had no significant effect on vegetation or soil moisture. Plant roots grew throughout the overburden within a year, and penetrated the tailings where there was no asphalt seal. Plant roots did not noticeably damage the asphalt seal.

EFFECTS OF ROCK MATERIAL ON VEGETATION AND SOIL MOISTURE

In extremely arid climates or where poor-quality soil is used, the attainable vegetative cover may not adequately stabilize the surface. Rock material applied over the surface cover can provide the additional protection needed. If applied to a depth that limits evapotranspiration, rock covers may cause the moisture content of the tailings to increase. An advantage of maintaining elevated moisture contents in tailings cover systems is reduced emission of radon (Nelson, Gee, and Oster 1980; Mayer et al. 1981). Excessive moisture accumulation, however, may result in drainage through the tailings pile and may increase the potential for groundwater contamination. Increased moisture in tailings may also decrease the stability of the pile (Zellmer 1981).

The objective of studies on rock and vegetative covers was to examine the effects of surface rock on vegetation and soil moisture. Four separate investigations were conducted: 1) model simulations comparing the effects of vegetation and rock covers on soil and tailings moisture, 2) a lysimeter study of the effects of rock and vegetation surface covers on soil water loss, 3) a field-scale study comparing the effects of rock cover on soil moisture, and 4) a field-scale study of vegetation and vegetation plus rock covers focusing on interactions between vegetation and rock, and soil moisture effects.

SIMULATION MODEL OF EFFECTS OF ROCK AND VEGETATION COVERS ON TAILINGS MOISTURE

Unsaturated zone modeling was used to examine the effects of rock and vegetation covers on moisture within the tailings-cover system (Mayer et al. 1981). Most tailings occupy an unsaturated flow zone which constitutes the transition between the atmosphere and the groundwater. The unsaturated flow zone in a tailings pile gains moisture from precipitation, irrigation if used, and seepage from nearby rivers. 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. Gravity causes downward movement of soil water until the restraining force due to capillary hydraulic potential (matric potential) is in balance with the gravity force. If the capillary action is stronger than the gravity force, upward moisture

movement may occur. The movement by capillary action is called Darcian flow and is described by the hydraulic conductivity and the matric potential gradient, both of which are strongly dependent on the moisture content.

Movement of soil moisture by vapor diffusion is significant near the soil surface and is the primary mechanism controlling moisture loss by surface evaporation. Potential evaporation rates are the highest when the soil near the surface is nearly saturated; otherwise, a dry layer of soil limits evaporation. Moisture is also lost by plant transpiration. To model this mechanism, the relationship between the potential transpiration and the climatic conditions must be specified. Root zone extraction behavior must also be described, since plant roots remove moisture at different rates at different depths.

If the water infiltrating the soil profile exceeds the capability of the soil to store moisture, drainage will occur. This drainage may enter the groundwater system, depending on the depth of the water table.

The presence of soil layers complicates unsaturated flow modeling. Clay, silt, sand, and gravel layers affect the movement of soil water differently. Certain layers rapidly transmit soil moisture, while others impede its movement. The computer code, UNSAT (Gupta et al. 1978), was developed to solve the one-dimensional unsaturated flow equation. The code accounts for the important factors influencing the unsaturated zone:

- water infiltration from precipitation or irrigation
- evaporation
- transpiration
- run-off
- drainage.

A modified version of UNSAT called UNSATV (developed by Simmons and Gee 1981) was used for this study because it is capable of modeling the effects of water vapor diffusion.

Model Setup

The multilayer cover system at the Grand Junction site was simulated because the water content in the seal affects its performance as a radon barrier (Hartley et al. 1983). The multilayer cover system consists of a layer of

wet clay/gravel mix followed by a capillary barrier of washed rock and a surface layer of soil.

Simulations were run for one year using the climatic data for 1979 (wettest year on record). The purpose of this one-year simulation was to allow the moisture content in the soil to adjust to the actual climate. Since this is simply an initialization procedure, the results for this year are not discussed here. The moisture content profile at the end of the one-year simulation was next used as the initial condition for a two-year simulation using repeated 1979 climate data and for a two-year simulation using repeated 1976 climate data (driest year on record). This approach provided two dry years and two wet years for comparison of the effects of climate on each surface treatment. The surface treatments were compared with each other to illustrate the effects of vegetation and rock covers.

Vegetation Cover Simulation

The purpose of this simulation was to examine how vegetation influences the moisture content of a covered uranium mill tailings pile. A plant community typical of the Grand Junction area that consisted of the following plant species (percentages are cover values) was modeled:

- 29% Artemisia tridentata (big sagebrush)
- 2% Atriplex confertifolia (four-wing saltbush)
- 2.5% Agropyron (wheatgrass)
- 2.5% Bromus tectorum (cheatgrass).

Thus, the plant community consisted of 36% plants and 64% bare soil.

Figure 4 is a plot of the moisture contents for selected days from the third wet year simulated. Figure 5 presents data for the third dry year simulated. The multilayer radon barrier appears as a uniformly dry layer over a uniformly wet layer beginning at 100 cm and extending to about 150 cm. An important feature is that, although the moisture content in the surface layer varied dramatically, the lower layers exhibited very little change in moisture content. Comparing Figure 4 with Figure 5 reveals that the dry climate resulted in drying of the upper layer and less variation of the moisture content throughout the year. The moisture content in the upper layer was generally smaller and the moisture content profiles did not change as much in Figures 5.4

FIGURE 4. Moisture Content Distribution for Vegetated Cover for Wet Year (1979) Climate Data

FIGURE 5. Moisture Content Distribution for Vegetated Cover for Dry Year (1976) Climate Data

The water balance for the wet years is summarized in Table 7; that for the dry years in Table 8. The initial storage values represent the amount of water stored in all four layers on day one for each year. The rainfall value is the amount of water from precipitation that was available for infiltration. The run-off values indicate the amount of precipitation that did not infiltrate but that flowed over the soil surface and eventually entered a stream or lake. The total amount of water lost by evaporation from the soil surface and the amount lost by transpiration are also given. The water that drained through the soil profile and out the bottom is listed. The final storage values indicate the amount of moisture stored in all four layers on the last day of each year. The mass balance error, a measure of the accuracy of the model results, can be computed by comparing the difference in the change in water storage computed as the difference in initial and final water storage or by combining the rainfall, run-off, evaporation, transpiration, and drainage values (values must be added or subtracted as appropriate).

Storage during the wet years changed negligibly. The two dry years resulted in slight drying of the soil profile. Note that no run-off or drainage occurred for either the wet or the dry years.

TABLE 7. Water Balance for Two Wet Years, Vegetated Cover System

Water, cm	Simulation Year	
	2	3
Initial storage	139.3	139.2
Rainfall	22.6	22.6
Run-off	0.0	0.0
Evaporation	5.8	5.8
Transpiration	16.2	16.3
Drainage	0.0	0.0
Final storage	139.2	139.1
Mass balance error	0.6	0.6

TABLE 8. Water Balance for Two Dry Years,
Vegetated Cover System

Water, cm	Simulation Year	
	2	3
Initial storage	139.3	137.1
Rainfall	13.4	13.4
Run-off	0.0	0.0
Evaporation	6.0	5.1
Transpiration	8.8	7.5
Drainage	0.0	0.0
Final storage	137.1	137.1
Mass balance error	0.8	0.9

Rock Cover Simulation

This simulation examined the effect of surface rock on moisture storage in covered uranium mill tailings. The analysis was essentially identical to that for the vegetated cover except that the plants were removed and 50 cm of rock (washed 5-cm-dia. cobble) was added to the top of the tailings pile.

Moisture moves through the rock primarily by a vapor diffusion process. UNSATV solves the unsaturated flow equation for liquid water movement and can simulate vapor diffusion through a thin mulch layer. To model the movement of water vapor through the relatively thick rock layer considered here, it was necessary to slightly modify UNSATV (Mayer et al. 1981).

The resulting moisture content profiles are shown in Figure 6 for the third wet year and in Figure 7 for the third dry year. Again the radon barrier began at 100 cm and extended to about 150 cm. Note that the rock cover is not shown on these plots, because the liquid water movement was not modeled for the rock cover. It is apparent from these plots that the rock cover had a significant effect on the moisture content in the tailings pile in comparison to vegetation cover treatments. The moisture content in the soil layer was much higher, and the seasonal variation in moisture content was not as great (compare with Figures 4 and 5). The major difference, however, was that the tailings layer became wetter, meaning that water was draining from the upper

FIGURE 6. Moisture Content Distribution for Rock Cover for Wet Year (1979) Climate Data

FIGURE 7. Moisture Content Distribution for Rock Cover for Dry Year (1976) Climate Data

layers. The moisture content throughout the tailings pile was also affected by the climatic conditions (i.e., the moisture content was changed in the vapor barrier rock, clay/gravel, and tailings layers).

Tables 9 and 10 summarize the water balance for the wet and dry years, respectively. The rock cover caused a greater increase in the moisture storage than did vegetation, because the evaporation from the rock cover was significantly lower than for the vegetated cover. The moisture loss from the combined run-off and evaporation for the rock cover was on the order of 1 cm of water per year. The moisture loss due to evapotranspiration from the vegetated cover was between 10 cm and 20 cm of water per year. The moisture input to a tailings pile with a rock cover in a setting similar to Grand Junction (i.e., arid) can therefore exceed the moisture input with a vegetated cover by more than 10 cm of water. Significantly, the moisture input for the rock cover exceeded the ability of the soil to store water, and drainage from the system occurred.

Conclusions

Care must be taken when selecting a surface stabilization system for a tailings pile. The moisture content response of the tailings pile and cover system can be radically altered by different surface treatments. The two cases

TABLE 9. Water Balance for Two Wet Years;
Rock Cover System

Water, cm	Simulation Year	
	2	3
Initial storage	167.5	185.8
Rainfall	22.6	22.6
Run-off	0.8	0.8
Evaporation	0.2	0.2
Transpiration	0.0	0.0
Drainage	0.4	15.1
Final storage	185.8	189.4
Mass balance error	2.8	2.8

TABLE 10. Water Balance for Two Dry Years;
Rock Cover System

Water, cm	Simulation Year	
	2	3
Initial storage	167.5	179.9
Rainfall	13.4	13.4
Run-off	0.4	0.4
Evaporation	0.2	0.2
Transpiration	0.0	0.0
Drainage	0.1	5.4
Final storage	179.9	186.8
Mass balance error	0.4	0.4

considered in this study indicate that, under the arid climatic conditions occurring at Grand Junction, the evapotranspiration from a vegetated cover can result in a relatively stable moisture content. A rock cover, however, may increase the moisture content of the tailings pile by significantly reducing evaporation. In fact, moisture storage may increase to the point that drainage occurs.

Once a cover system is selected, the modeling effort should also include an assessment of how the cover system affects radon gas emissions. This capability is developed and can be directly coupled to the unsaturated flow analysis presented in this study (Nelson, Gee, and Oster 1980; Mayer et al. 1981). It is important to consider the effects of atmospheric contamination from uranium mill tailings, as well as the potential for groundwater contamination.

LYSIMETER STUDY OF THE EFFECTS OF SURFACE COVERS ON SOIL MOISTURE

The purpose of this investigation was to empirically examine the effects of surface covers on soil water loss. Water loss from lysimeters covered with various types and amounts of rock, vegetation, and vegetation/rock was compared to water loss from bare soil.

Lysimeters were constructed of 10-gal galvanized steel cans set into 20-gal galvanized steel cans and filled with Ritzville silt loam. At the start

of each experiment enough water was added to each lysimeter to equalize the water contents. Percentage of vegetative cover was occularly estimated and the leaf area was determined by an automatic area meter for vegetation treatments.

The following are descriptions of the surface treatments for each experiment:

Experiment 1 (16-21 July 1981)--the effect of stone size on soil water loss. Treatments included: 1) bare soil with water added to the lysimeter to maintain the moisture content, 2) 2-cm-dia. crushed rock completely covering the surface, 3) pea gravel completely covering the surface, 4) sand, and 5) bare soil without addition of water.

Experiment 2 (25 July - 25 August 1981)--the effect of stone depth on water loss. Three-cm-diameter crushed stone was applied in the following rates: 0 (bare soil), 225 MT/ha, 450 MT/ha, 675 MT/ha, and 900 MT/ha.

Experiment 3 (23 April - 10 May 1982)--the effects of rock and vegetative covers on soil water loss. Treatments included: 1) bare soil, 2) 2-cm-dia. crushed rock applied at a rate of 900 MT/ha, 3) vegetated cover consisting of cheatgrass (Bromus tectorum; cover ranged from 50% to 90%), 4) vegetation mixed with 2-cm-dia. crushed rock; vegetation cover was about 25% and rock was applied at 900 MT/ha. Cheatgrass was planted in September 1981.

Experiment 4 (28 June - 9 July, 13-20 July, 3-9 August 1982)--treatments were the same as in Experiment 3 except that sunflowers (Helianthus annuus) were used instead of cheatgrass. This experiment was repeated three times: (a) three plants/lysimeter, (b) two plants/lysimeter, and (c) one plant/lysimeter.

Treatments were replicated five times in Experiments 1 and 2, and six times in Experiments 3 and 4.

Results

In Experiment 1 the sand cover had significantly less water loss than did bare soil (Table 11). Pea gravel and crushed rock treatments were not significantly different from bare soil although they tended to lose less water.

TABLE 11. Cumulative Water Loss From Lysimeters in Experiment 1, Comparing the Effects of Rock Size on Soil Water Loss

<u>Treatment</u>	<u>Mean Water Loss, lb</u>
Sand	2.60 (a)
Pea gravel	4.65 (a,b)
2-cm-dia. rock	5.00 (a,b)
Bare soil	6.80 (b)
Bare soil (water added)	7.50 (b)

(a,b) Treatments with common letters are not significantly different ($\alpha \leq 0.05$).

No significant differences were found in net water loss between bare ground and the various application rates of 2-cm-dia. crushed rock (Experiment 2).

The experiments comparing bare soil, rock cover, vegetation cover, and rock plus vegetation cover (Experiments 3 and 4) had similar results even though cheatgrass was used in Experiment 3 and sunflowers were used in Experiment 4 (Table 12). No significant differences in net water loss were found between vegetation treatments and vegetation-plus-rock treatments, except in Experiment 4b. Experiment 4b was shorter than Experiments 3 and 4a and the plants were younger than those in 4c. Bare soil lost significantly less water than vegetation and vegetation/rock treatments in all cases except one (Experiment 3), but the loss from bare soil was consistently greater than for rock cover treatments. Water loss from rock treatments was always significantly far less than from the other treatments.

Conclusions

The results of this study support the findings of simulation studies on the effects of rock and vegetative covers on uranium mill tailings (Mayer et al. 1981). Rock covers reduce soil water loss dramatically and could lead to water accumulation and drainage from a tailings site.

Rock covers that are revegetated appear to facilitate rates of water loss similar to those of vegetation covers. Tailings covered with vegetation/rock are not likely to accumulate more moisture than the surrounding soil.

TABLE 12. Cumulative Water Loss from Lysimeter in Experiments 3 and 4 Comparing the Effects of Rock and Vegetative Covers on Soil Water Loss

Treatment	Mean Water Loss, 1b			
	3	4a	4b	4c
Bare soil	13.38(a)	9.29(a)	8.79(a)	9.25(a)
Rock cover	2.83(b)	1.96(b)	1.79(b)	3.08(b)
Vegetation	18.50(a,c)	12.00(c)	12.75(c)	13.9(c)
Vegetation and rock	15.71(c)	11.83(c)	11.04(d)	14.49(c)

(a,b,c,d) Treatments with common letters do not differ significantly ($\alpha < 0.05$).

The implication for tailings site management is that in areas where vegetation is too sparse (extremely arid regions) to stabilize the cover material, vegetation/rock covers will provide additional erosion protection while preventing moisture accumulation. In some areas, rock covers may enhance vegetation establishment and growth. The rough surface of the rock cover may benefit seed germination by providing favorable microsites. Rock covers can reduce evaporation and consequently make more water available for plant growth.

FIELD-SCALE STUDY OF THE EFFECT OF VEGETATION/ROCK COVERS ON SOIL MOISTURE

A field study was conducted to evaluate the effect of vegetation/rock covers on soil moisture (Kirkham, Beedlow, and Gee 1982). The cover system used in this study, the multilayer radon barrier, consists of a layer of wet clay/gravel mix covered by a capillary barrier of washed rock and a surface layer of fill soil (Gee et al. 1981). However, the results of this study are also applicable to cover designs using stabilized earth fill.

Site Preparation and Data Collection

In November 1981 a soil sterilant, Ureabor®, was added to the FY 1980 multilayer field study site at Grand Junction, and rock cover was applied to half of the field plot surface. A 15-m by 76-m central section of the plot

(a) Registered trademark of the Occidental Chemical Company, Houston, Texas.

received the soil sterilant and rock treatment. Ureabor was hand-broadcast onto the soil surface at 100 g/m². Rock (4-cm-dia. washed) was then trucked to the site and spread to a thickness of ~15 cm.

Measurements of water content and soil matric (capillary) pressure were taken on the cover. A down-well neutron moisture meter (Gardner 1965) was calibrated to measure volumetric water content changes in the cover system. Gypsum moisture blocks (Jones et al. 1982) were used to measure soil matric potential. Surface soil samples were collected at selected vegetation and cobbled sites. Soil samples were oven dried to determine gravimetric moisture content. Figure 8 shows a cross section of the FY 1980 multilayer site after rock addition. Figure 9 shows the location of the rock cover, neutron moisture probes, and gypsum moisture blocks. The blocks were read in September 1981 (before rock placement) and in July 1982. Rainfall for the period of September 1981, to June 1982 was 15.03 cm, or 76% of normal.

Results and Discussion

Rock cover increases soil moisture levels (Table 13). The 5-, 30-, and 60-cm-deep soil under the rock cover experienced an increase in matric potential, or soil moisture. Sensors located at the 5- and 30-cm depths in the vegetation treatment sites indicated decreased moisture contents over time. This decrease in available moisture indicates that moisture was removed by evapotranspiration. The 60-cm sensor average for both treatments indicates a slight increase in soil moisture over time.

Volumetric moisture data collected from the 30-cm depth indicate higher levels of moisture in February than in July (Table 14). The highest 30-cm soil moisture levels occurred under the rock cover, as expected. The 60-cm soil moisture was highest in July, with the rock cover treatment again having the highest value (Table 14). The vegetation cover did not appear to extract the moisture from the 60-cm soil depth. The August plant cover estimate was 18% with a variability of 13%. The primary species of vegetation at the site were Agropyron spp. (wheatgrass), Amaranthus rexoflexis (red root pigweed), Salsola kali (Russian thistle), and Kochia scaparia (summer cypress).

FIGURE 8. Cross Section of Multilayer Plot

FIGURE 9. Multilayer Plot with Treatments and Instrument Locations

TABLE 13. Matric Potential in Soils Under Vegetation and Rock Cover Treatments^(a)

	Depth, cm	Matric Potential, -bars		
		September 1981	July 1982	Change
Vegetation	5	26.3 (44.0) ^(b)	203.3 (107.2)	-177.0
	30	3.0 (2.4)	5.8 (7.5)	-2.8
	60	3.0 (2.1)	2.1 (1.4)	0.9
Rock cover	5	20.7 (25.7)	2.7 (1.4)	18.0
	30	2.4 (2.3)	1.3 (3.3)	1.1
	60	3.9 (2.1)	0.6 (0.4)	3.3

(a) Rock was applied in November 1981.

(b) $\pm$ one standard deviation.

Moisture redistribution downward under the rock was probably responsible for the elevated 60-cm soil moisture content in July. The small increase in the moisture content at 60 cm under the vegetation may represent downward movement, but the changes were near the resolution of the neutron probe. In addition, soil samples collected at the soil/rock cover interface had higher

TABLE 14. Volumetric Moisture Content at Two Depths of the Test Plot for Two Dates in 1982

	Depth, cm	Volumetric Moisture Content, $\text{cm}^3/\text{cm}^3 \times 100$	
		February 19	July 20
Rock	30	22.3(4.6) (a)	12.2(1.7)
	60	12.2(1.6)	14.8(2.4)
Vegetation	30	12.8(1.7)	10.9(1.7)
	60	11.9(2.8)	12.6(2.3)

(a) Percent moisture ($\pm$ standard deviation).

moisture contents than the soil material at the surface of the vegetation treatment. The moisture content under the rock cover was 0.0581 g/g with a standard deviation of ± 0.0022 ; at the vegetation soil surface the moisture content was 0.0199 g/g with a standard deviation of ± 0.0027 .

Conclusions

This study demonstrates on a field scale that unvegetated rock covers will allow moisture to accumulate in tailings covers. This conclusion supports the simulation and lysimeter studies. Accumulation occurs in the absence of vegetation even at arid sites such as Grand Junction. To minimize moisture accumulation, stabilization design using rock should include vegetation, which should be established as soon as possible after closure.

VEGETATION AND VEGETATION/ROCK COVERS

To minimize moisture accumulation in tailings covers, vegetation should be established. Applying rock to the surface can greatly reduce soil loss at sites where vegetative cover is insufficient. Vegetation/rock covers provide some degree of redundancy to insure long-term stabilization.

Thin rock covers that allow plant growth are likely to alter the characteristics of the soil, especially near the surface, and can in turn affect the structure and response of vegetation. Under natural conditions, rocky soils have different types of plants from soils without substantial amounts of rock. Plant attributes that are sensitive to soil characteristics include: seed

germination, size of plants, vigor, woodiness, depth of roots, reproduction, and susceptibility to stress. In the West, rocky, gravelly soils generally favor woody and forb species over perennial grasses while even-textured loams or silty soils favor such grasses. Clay soils typically have higher salt content and favor salt-tolerant forbs and shrubs.

It was hypothesized that rock covers used to stabilize cover material would, over the long-term, result in the establishment of vegetation composed primarily of shrubs and forbs. This type of vegetation is typically deep-rooted (Grime 1979) and could result in root growth into tailings. Presented here are the results of a field-scale experiment designed to: 1) determine whether soil covered with rock similar to that likely to be used on tailings affects the kind and extent of vegetation, 2) evaluate the success of seed mixtures, transplants, and irrigation when surface rock is used; and 3) examine the effects of vegetation and vegetation/rock covers on soil moisture.

Methods

The study was conducted on Utah International's San Juan Mine, Waterflow, New Mexico. The soils consisted of shale overburden covered with 25 to 35 cm of sandy loam. This soil configuration is similar to tailings cover systems using fine-textured soil (shale or clay) as a radon barrier with topsoil (typically loamy soil) on the surface.

The site, established in August 1981, occupied an area 53 m by 49 m plus a border on the mine's juniper reclamation area. Three major surface treatments were considered: 1) topsoil only, 2) topsoil plus 15 cm of sorted cobble 7 to 10 cm in diameter, and 3) topsoil plus 15 cm of unsorted (pit-run) river rock (Figure 10).

Six plant material combinations were tested:

- A) seeded with a grass-dominated seed mixture; 90% grass seeds (six species) and 10% forbs and shrubs (11 species) by weight (Table 15)
- B) seeded with a shrub/forb-dominated seed mixture; 90% shrub and forb seeds (same 11 species as in A) and 10% grass seeds (same 6 species as in A)

FIGURE 10. Diagram of the San Juan Experiment Design

- AP) seeded with the grass-dominated mixture (A) plus shrub transplants (Atriplex canescens, Chrysothamnus nauseosus, Rhus trilobata and Juniperus osteosperma)
- BP) seeded with the shrub/forb-dominated mixture (B) plus transplants (same four species as in AP)
- P) planted with transplants only (same species as above)
- C) control; no planting or seeding.

Seeds were broadcast at a rate of approximately 325 pure live seeds per square meter.

The effect of various amounts of irrigation on vegetation establishment was studied by using a sprinkler system that applied variable rates of irrigation to each plot (Hanks 1980; Figure 11). During the 1981-1982 water year (October-September), the system applied approximately 120 cm of water near the sprinklers and decreased to zero near the edge. A down-well neutron moisture meter (Gardner 1965) was used to measure soil moisture at 216 locations on the plot to a depth of 90 cm. The test plot was irrigated on the same schedule as the reclaimed areas at the mine. Irrigation water was applied immediately after seeding and repeated after 2, 4, and 6 weeks in the fall. Irrigation was terminated on October 5, 1981, resumed in April 1982, and continued through the summer as needed.

Vegetation cover was estimated for each species in 1-m² quadrates using the Daubenmire cover scale (Mueller-Dombois and Ellenberg 1974). Three quadrates were sampled in each subplot (Figure 14).

TABLE 15. Plant Species Seeded at the San Juan Test Plot

Forbs	Grasses	Shrubs
<u>Sphaeralcea grossulariaefolia</u>	<u>Oryzopsis hymenoides</u>	<u>Chrysothamnus nauseosus</u>
<u>Aster tanacetifolia</u>	<u>Sporobolus airoides</u>	<u>Atriplex canescens</u>
<u>Ratibida columnaris</u>	<u>Sporobolus cryptandrus</u>	<u>Atriplex confertifolia</u>
<u>Hedysarum boreale</u>	<u>Sitanion hystrix</u>	<u>Cercocarpus ledifolius</u>
<u>Oenothera pallida</u>	<u>Hilaria jamesii</u>	<u>Kochia prostrata</u>
<u>Penstemon palmeri</u>	<u>Bouteloua gracilis</u>

FIGURE 11. Line-Source Irrigation System with Moisture Gradients Formed by up to Three Overlapping Patterns from Closely Spaced Sprinkler Heads. Numbers indicate the number of pattern overlaps (zones). Overlapping patterns do not form discrete areas of overlap because random variations within a given sprinkler pattern, effects of winds on aerial spray, and water movement in the soil result in decreasing moisture away from the line source.

Results and Discussion

Data were collected during August of 1982 and 1983. Analysis of variance for a split-split plot arrangement of treatments supplemented by orthogonal and multiple comparisons (Cochran and Cox 1957) was used to analyze 1983 data. Only the latter were treated statistically because they represent established vegetation that was not dependent on irrigation. The random variables included vegetation cover for five functional groups expressed as the percentage of ground covered and soil moisture expressed as percentage by weight. Plant species were grouped into total cover, weeds, forbs, shrubs, and grasses to facilitate comparisons based on functional aspects. Total cover consisted of the sum of the cover values for all species. Weeds were short-lived species that tended to overgrow the plot during the first year; primarily Russian thistle (Salsola kali L.) and summer cypress (Kochia scoparia L.). Forbs consisted of herbaceous plants other than grass. Shrubs were four-wing salt-bush (Atriplex canescens [Pursh] Nutt.) and greasewood (Sarcobatus vermiculatus [Hook.] Torr.). Grasses consisted of ricegrass (Oryzopsis hymenoides [R. & S.] Ricker), squirrel tail (Sitanion hystrix (Nutt.) J. G. Smith), blue grama (Bouteloua gracilis [H.B.K.] Lag.), hiliaria (Hilaria jamesii [Torr.] Benth.), and dropseed (Sporobolus cryptandrus [Torr.] A. Gray), which are perennial species; and cheatgrass (Bromus tectorum L.) and annual fescue (Festuca octoflora Walt.), which are annual species.

The first growing season (1982) was a period of germination and initial growth. The vegetation on the site was dominated by weeds. Comparisons of treatments during 1982 are therefore questionable. Comparing the growing seasons 1982 and 1983 suggests that structural changes in the vegetation occurred (Figure 12). The total cover in 1983 remained similar to 1982, but the components of the vegetation changed. Weeds decreased, probably due to the lack of irrigation, while forbs, shrubs, and grass increased. Shrubs showed the greatest increase.

The type of surface treatment (soil, cobble, or rock) influenced the vegetation components in 1983. Total cover was significantly higher ($\alpha < 0.1$) on the rock than on the soil and cobble (Figure 13). A major contribution to

FIGURE 12. Comparison of the Vegetation Structure at the San Juan Test Site

the higher total cover on rock was its significantly greater ($\alpha < 0.05$) weed cover compared to cobble or soil. Weed cover on cobble tended to be greater than on soil, but the difference was not significant. Shrubs had significantly higher ($\alpha < 0.1$) cover on rock than on soil or cobble with the lowest cover on cobble; no statistical difference was found between soil and cobble. Forbs showed a pattern similar to that of weeds, with a significantly greater ($\alpha < 0.1$) cover on rock than on cobble or soil. So far, all plant groups but one have shown highest cover values for rock; grass, however, had significantly higher ($\alpha < 0.05$) cover on soil than on cobble or rock. The cover treatments (soil, cobble, and rock) could not be randomly assigned to the study plots. Because of the inability to randomize the treatments, it is not possible to prove statistically that the response of the vegetation on the cover types was not a result of factors inherent in the soil due to position. However, the

FIGURE 13. Mean Percent Cover of Five Types of Vegetation at the San Juan Test Site as Affected by Surface Rock Material

soil at the site was very homogeneous and the slopes were similar and generally less than 4%. Because of this uniformity, any position effects were probably negligible.

The effectiveness of vegetation in preventing erosion is due not only to the total amount of cover it provides, but also to its structure. For example, grasses provide more protection than forbs because they eliminate raindrop impact and reduce run-off velocity. The results suggest that the presence or absence of surface rock affects the success of particular plant types. The choice of seed mixtures, then, could affect the revegetation success and the effectiveness of vegetation in preventing erosion. The forb/shrub-dominant seed mix showed higher total cover than the grass mix on all cover types, with the highest cover occurring on the rock (Figure 14). The differences among cover types were not statistically significant but a trend of higher cover on rock was observed. Whether or not the difference becomes significant as the plants mature remains to be determined. However, the implication is that the surface cover (rock or soil) should be considered when selecting plant species.

FIGURE 14. Mean Percent Total Cover of Vegetation at the San Juan Test Site in 1983, Comparing Shrub/Forb-Dominated Seed Mix with Grass-Dominated Seed Mix

The choice of seed mixtures depends on the presence or absence of rock and on site conditions such as climate and soil. The San Juan site is arid and has relatively saline soils. The differential success (as reflected in total cover for all cover types combined) of the plant material combinations (Figure 15) is probably related to site conditions. The shrub/forb mixes resulted in significantly higher ($\alpha < 0.01$) cover than the grass mixes. Transplanting shrubs did increase the total cover of the grass-dominated seedings. Seeded plots had significantly higher ($\alpha < 0.01$) cover than those that were not seeded.

Irrigation zones (see Figure 11) apparently affected the cover of the vegetation (Figure 16). Grass cover was significantly less ($\alpha < 0.05$) in zone 0 while no differences were found among zones 1, 2, and 3. Shrubs showed a graded response with the least cover in zone 0, and the greatest in zone 3; statistically, zones 3 and 2 were different from zone 0, which was significantly different ($\alpha < 0.05$) from zones 3, 2, and 1. Weeds showed no significant differences during 1983. Total cover tended to be directly related to

FIGURE 15. Mean Percent Total Cover at the San Juan Test Site as a Function of Planting Treatments

FIGURE 16. Vegetation Cover at the 1983 San Juan Test Site; by Irrigation Zones

irrigation zones but no statistical significance was found. For those species considered to be important for erosion control (i.e. perennial grasses and shrubs), irrigation appears to benefit establishment; however, something less than the amount of water received in zone 3 appears sufficient. Because irrigation zones could not be randomized, applying these data to the interpretation of irrigation effects must be done with caution.

The effect of vegetation with and without rock or cobble covers on soil moisture is important to moisture dynamics in the tailings cover system. A cover that allows soil moisture to increase could result in drainage from the tailings at some time in the future (Mayer, Beedlow, and Cadwell 1981). No significant differences were found in soil moisture (percentage by weight) among soil, cobble, or rock treatments (Table 16). This suggests that rock covers with vegetation will not increase the moisture in the containment system. Conclusive evidence would require monitoring soil moisture throughout the year. Continuous monitoring would show whether or not pulses of moisture penetrated below the root zone during the seasons when no transpiration occurred.

TABLE 16. Summary Statistics for Percent Moisture by Weight from San Juan Test Plot, 1983^(a)

Depth, cm	Statistic ^(b)	Cover Type		
		Soil	Cobble	Rock
30	$\bar{X}\%$	13.8	7.5	10.7
	S	6.4	7.1	5.8
	N	71	72	72
60	$\bar{X}\%$	27.2	20.6	21.9
	S	6.9	6.8	4.6
	N	65	71	68
90	$\bar{X}\%$	30.7	25.7	26.1
	S	7.5	7.0	4.9
	N	61	60	65

(a) Sample size differs because of inability to measure soil moisture at all depths at each location. Differences are not statistically significant.

(b) $\bar{X}$ = mean (in percent); S = standard deviation; N = sample size.

Conclusions

Total cover on the test site changed negligibly from the first growing season to the next. However, after the second growing season, weed cover was markedly reduced while the cover of perennial shrubs and grass increased. The decrease in plant cover often seen on revegetation sites after irrigation has been stopped did not occur at San Juan. Possible reasons for the sustained cover include: 1) the plant species used were adapted to the climate and soils of the site; 2) irrigation supplemented the fall rains (a period of seed germination for many species), but only as needed to keep the young plants alive during the first summer; and 3) the vegetation cover was not supported at abnormally high levels by excess irrigation. Irrigation can promote the establishment of perennial grasses and shrubs. Perennial grasses and, to some extent, shrubs are most desirable for soil stabilization because they are long-lived and their more extensive root systems provide greater soil stability than forbs and annual weeds. Proper use of irrigation could permit the establishment of a protective cover of vegetation within a year of seeding.

In comparison to soil and cobble, pit-run rock was associated with increased cover of weeds, shrubs, and forbs and decreased grass cover. Total cover was also highest on rock. Rock material placed on tailings piles to increase surface stability is likely to favor vegetation composed primarily of shrubs and forbs, which usually have deeper root systems than do grasses. Cover designs must consider the increased risk of root penetration when surface rock is used. Cobble generally had an intermediate affect on vegetation, and could be useful for some surface cover designs. Additionally, observations at the San Juan site suggest that pit-run rock may be more susceptible to erosion than cobble. Run-off channels were found on the rock cover after the longer irrigation treatments; none were found on comparable slopes in the cobble or the soil.

The most successful planting treatment at the San Juan site was seeding predominantly with shrubs and forbs whether or not surface rock was applied. The climate and soils in the vicinity of the test site support vegetation communities that are shrub dominated. Thus, the climatic and edaphic conditions as well as rock cover tend to favor shrub and forb growth.

Efforts should be made to establish vegetation on tailings piles in semi-arid and arid areas rather than relying on natural colonization. At the San Juan site, treatments that did not receive seed had significantly less cover than seeded plots. The natural establishment of perennial species in arid areas is typically episodic, depending on favorable temperature and soil moisture conditions which result from the timing, amount, and duration of precipitation (MacMahon and Schimpf 1981). Rainfall becomes less predictable the drier the climate (Bailey 1981). Consequently, favorable conditions for plant establishment are less likely to occur on a regular basis in drier climates. However, by seeding and irrigating properly during the first growing season, favorable conditions for plant establishment can be created.

An alternative treatment to seeding is to place rock material on the tailings surface and allow natural plant colonization. This alternative could leave the surface with a less-than-achievable plant cover for considerable lengths of time. Annual weedy species are likely to be abundant when moisture conditions permit, but perennial species will become established slowly. Unseeded tailings covers in arid areas may experience widely fluctuating vegetation cover due to the population fluctuations of annual weeds. The best procedure is to establish vegetation on the surface whether or not rock is applied.

Unvegetated rock covers reduce soil water loss, which could lead to accumulation and drainage from tailings piles (Mayer, Beedlow, and Cadwell 1981). The present work shows that rock covers that support vegetation appear not to significantly increase soil moisture relative to vegetation alone. Tailings covered with vegetation/rock are not likely to accumulate more moisture than soil in the surrounding area.

PREDICTING EROSION OF TAILINGS COVERS

A means to quantify the erosion stresses likely to be acting on an impoundment is critical in designing long-term protective covers. The development of design specifications requires estimates of erosion rates, as does the selection and justification of particular cover schemes. In anticipation of UMTRAP's need to estimate erosion rates, PNL conducted a survey of available erosion models. In general, soil loss models have been developed for agricultural purposes. The adaptation of erosion models to long-term stabilization of waste sites has been initiated only recently (e.g., Nyhan and Lane 1982).

FLOOD EROSION

Tailings piles are often located on flood plains or along surface-water pathways, making stream erosion a serious long-term problem. The most common method of protecting against flood damage is by the use of rock riprap. Walters (1982) discusses rock riprap design methods and their applicability to long-term protection of tailings against flood damage. Tailings piles present design problems, not previously encountered, that are associated with irregular shapes and long-term protection requirements: 1) selection of design flood criteria, 2) rock durability over long time periods, and 3) extent of local scour from high-velocity flows.

WIND EROSION

Bander (1982) reviews the mechanics of wind erosion and predictive models. The best model is the equation developed by Chepil (Skidmore 1974), which contains more wind erosion factors pertinent to tailings piles than any other model reviewed. Charts and graphs for obtaining the various factors in the equation, and the development of a computerized program, make the equation fairly easy to use.

The amount of soil lost from a tailings pile as a result of wind erosion over many years is provided by the Chepil equation. However, 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 predicted annual values would be to incorporate probability functions for some of the dynamic variables (Skidmore 1974).

OVERLAND EROSION

A variety of mathematical models are available to determine erosion of natural and disturbed land surfaces due to overland flow. There are two basic kinds of models: 1) regression models, such as USLE and MUSLE,^(a) which are derived from empirical data and interpret input-output relations using simplified forms that may or may not have physical significance; and 2) physical process simulation models, such as ARM, CREAMS, and MULTSED,^(b) which formulate the governing processes controlling erosion.

Regression models are simple to use and can accommodate regional types of data. Process models require computers for computation and use much more detailed input data. Limitations of the regression models result from their empirical nature. Regression models are most accurate for the specific locations where soils and climate data used to construct the models were collected. Large errors may occur when regression models are applied to sites for which no empirical data exist. The major limitations of process models are their extensive data and computational requirements. Furthermore, some process models use empirically derived relationships in some portions of their sediment yield calculations. Again, where empirically derived factors are used, the relevance to a particular site is highly dependent on the experience and skill of the model user. Data requirements and limitations of these models are discussed by Walters (1983).

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- (a) USLE--Universal Soil Loss Equation
MUSLE--Modified Universal Soil Loss Equation.
 - (b) ARM--Agricultural Run-off Management
CREAMS--Chemical, Run-off, and Erosion from Agricultural Management
Systems
MULTSED--Multiple Watershed Water and Sediment Routing.

Both types of models should be used in cover design. Regression models could 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 erosion protection materials; the relative erosion rates of different soil materials and slopes can be quickly evaluated.

Complex hydrological landscapes are common at tailings sites in the West. Design of protective covers in these areas must account for run-off not only from the tailings themselves but also from the surrounding watershed. Many tailings piles are located beside streams that present potential flood danger. Under flooding conditions, hydraulic and process models may be needed for designing protective covers (Walters 1982).

CONCLUSIONS

Regardless of the computational method used to predict erosion stresses at a given site, model implementation and interpretation of results must be based on a thorough knowledge of geomorphological processes at that site. During site reconnaissance, a qualitative analysis of prevailing and potential types of erosion should be made by inspecting the pile and surrounding land forms. For example, the presence and extent of rills and gullies at a site would indicate the significance of overland and gully erosion.

Following the reconnaissance, appropriate computational methods can be selected and the necessary site data can be collected. Required site data will vary according to the model selected. As discussed above, several models will probably be necessary.

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 100 years is quite different from designing a cover to withstand a 100-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 for which

climatic data have been recorded (10 to 100 years), we can estimate event sequences on a statistical basis with some confidence; but climatic predictions for longer periods must take long-term climatic changes into account or rely on "worst-case" scenarios. "Probable maximum" events have been prescribed by the NRC for determining worst-case erosion stresses at new and existing mills (NRC 1982). This method is very conservative and may lead to higher costs for protective covers, but it has precedence. Other, statistically based events such as the 100-year storm may also be appropriate. However, design climatic conditions must be defined before erosion models can be used for anything other than relative comparisons.

AN APPROACH TO DESIGNING SURFACE COVERS

The wide range of site conditions and availability of cover materials complicates the design of appropriate surface covers. At each site, environmental conditions must be considered in conjunction with the characteristics of the tailings pile and the availability of materials. As a basis for design planning, a decision tree is presented in Figure 17. The tree outlines the process of gathering site information necessary for designing a protective cover and for evaluating its effects on the containment system.

The decision tree shows the design process in three phases: the first, or assessment, phase involves collecting the appropriate site information to construct a preliminary plan for the protective cover. The preliminary plan (Phase II) describes the general characteristics and presents alternatives. The plan is used in conjunction with preliminary designs of the other components of the containment system to produce a conceptual site design. After a conceptual design has been formulated, Phase III begins. During this phase, optimization results in a detailed, site-specific surface cover design, which is evaluated with respect to the entire containment system to produce a finalized design. A brief discussion of the steps involved will illustrate the procedure.

Phase I involves collecting the necessary data and evaluating site conditions so that a preliminary plan for the protective cover can be formulated. Initially, the required data must be gathered from existing reports and from site visits. The general types of data should include:

- topographic maps showing the pile location and the upstream and downstream drainage area
- drawings and photographs of important features of the tailings pile; for example, sectional drawings of material zoning and foundation stratification, and top and bottom elevation profiles
- foundation data and geological features from boring logs, geological maps, profiles, and cross sections
- physical and chemical properties of the tailings

FIGURE 17. Decision Tree for Designing Protective Covers for Inactive Mill Tailings

- drainage area and basin characteristics, including soils, vegetation, and geomorphological features
- data on flood histories and on discharges from all watercourses
- climatic data for calculating erosive forces
- availability, quality, and costs of soil, rock, and plant materials
- information on animal burrowing and human activity in the vicinity
- site geomorphologic assessment.

The potential cover vegetation can be estimated by evaluating the existing vegetation on soils that are available for use as cover material. Careful examination should be made of the chemical and physical properties of candidate soils throughout their profiles. Because of mixing, soils that are excavated may possess different characteristics when placed on a tailings pile. Eventually, where soils and topography are similar, vegetation on the covered tailings can be expected to resemble that in the surrounding area.

The potential for plant and animal intrusion can be determined from survey data in conjunction with published information. Important characteristics include rooting and burrowing depth, animal and burrow size, ability to incorporate hazardous materials into tissues, and propensity for plant growth or burrowing in disturbed soils. An assessment of human intrusion potential can be made by characterizing human activities in the area. Site data on vegetation, climate, soils, and geomorphology can then be used to determine the erosive forces acting on the pile. Areas exposed to stream flooding may need riprap or other forms of engineered armor. Those not exposed to flooding can be adequately stabilized with vegetation and/or unengineered rock covers. Based on the calculated erosion rates and criteria for stability, the adequacy of vegetation for surface protection should be determined, because even if no surface treatment is applied vegetation will become established in time. If vegetation is considered adequate, a preliminary revegetation plan is produced. If vegetation is judged to be inadequate for long-term erosion control on all or parts of the pile, other means must be used to prevent erosion damage. The need for and cost of suitable rock to cover the entire pile or portions of pile exposed to high erosion rates must be determined. Some types of rock can be

very effective in reducing erosion, but they may not be locally available. If rock must be hauled to the site, at some distance it may no longer be affordable.

If rock cover is feasible, a preliminary plan can be produced using rock or rock/vegetation covers. If suitable rock is not available, the use of additional overburden, greater amounts or better quality topsoil, or the recontouring of the pile may reduce erosion rates; once these options are identified, erosion potential is recalculated. This process may require several iterations before a preliminary plan is produced.

The preliminary plan for the protective cover is intended to provide information and alternatives for planning other elements of the containment system, and to adapt the protective cover to the overall plan. Once the overall containment system concept has been approved, Phase III begins.

In the third phase of the design process, the available options for protection at the site are determined in some detail. The cost and effectiveness of the alternatives are optimized in conjunction with other containment system components. Before the final design can be chosen, effects of the protective cover on the functioning of the entire system must be evaluated. Erosion rates are determined using site environmental data and engineering specifications. Effects of surface covers on soil moisture should take radon and biological barrier designs (and liners, when appropriate) into account. The risk and possible effects of biointrusion caused by the proposed surface cover must be evaluated at this time. If the consequences of the protective cover design do not jeopardize the functioning of the system based on the above evaluations, the design can be finalized. If the surface cover does jeopardize the functioning of the system, then alternative designs are considered. Several iterations of this process may be necessary.

The major benefit of the decision tree approach is the flexibility it allows. It does not specify types and amounts of cover material but requires only that designs provide adequate surface erosion control and containment of toxic compounds. Adequate erosion control is, logically, that required to keep

the protective layer intact for the design life of the containment system. A surface cover, therefore, can be any combination of soil, rock, and vegetation that is effective and economical.

The protective layer of the soil is the most important factor in determining the rate of soil erosion. The protective layer is the layer of soil that is directly in contact with the atmosphere. It is the layer of soil that is most exposed to the elements and is therefore the most vulnerable to erosion. The protective layer is the layer of soil that is most exposed to the elements and is therefore the most vulnerable to erosion.

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