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EVOLUTION OF DISPOSAL CELL COVER DESIGN USED FOR URANIUM MILL TAILINGS LONG-TERM CONTAINMENT

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ABSTRACT

Technology used to design protective covers overlying hazardous and low-level radioactive waste cells evolved significantly during the course of the Uranium Mill Tailings Remedial Action (UMTRA) Project. Our country's operational experience in long-term containment of hazardous and radioactive wastes has been gained primarily through efforts expended by the UMTRA Project administered by the U.S. Department of Energy. Covers overlying waste facilities have two primary purposes: to minimize or prevent infiltration of precipitation and to prevent escape of toxic gases. Observed degradation to barrier layers intended to control fluid movement has led to modifications in the design of protective layers. For long-term containment, the adage "what goes in must come out" is applicable to infiltration of precipitation. Accordingly, UMTRA design efforts focused on cover technology as opposed to liner technology. Compacted clay barriers were selected by the UMTRA Project for barrier layer construction to isolate wastes from the environment because this material can be constructed with a low hydraulic conductivity. Also, clay has a proven geologic service life and durability well beyond regulatory design limits of hundreds to thousands of years. These barrier layers must be protected from degradation by climatic forces throughout the life of the facility without active maintenance. As observation of existing UMTRA disposal facilities continues and performance data are compiled, the knowledge gained is used to update design methods. One result of current studies suggests that information gleaned from analog studies can benefit long-term cover performance.

INTRODUCTION

Design philosophy of cover systems used for long-term containment of hazardous and low-level radioactive wastes has undergone significant changes since initial designs were conceptualized following passage of the Uranium Mill Tailings Radiation Control Act (UMTRCA) in 1978 (1). Regulatory change and applications of lessons learned resulted in a modification in design philosophy in 1987. Designs changed from static barrier-type designs to more dynamic ecosystem-type designs following publication of the draft ground water standards by the U.S. Environmental Protection Agency (EPA).

Covers, or caps, are the primary component controlling the release of contaminants from hazardous and radiological waste-disposal facilities to the environment. Release of contaminants from low-level radiologic waste must be controlled for the long-term, for 1,000 years to the extent possible, and in no case less than 200 years (1,2). Disposal facilities that are designed for long-term containment minimize maintenance by using a passive design philosophy relying on barrier layers formed from earthen materials (3).

Results of published research from the fields of geotechnical engineering and soil science from the 1960s through the 1980s indicate that soil barrier layers used in containment of wastes that are compacted to have a low hydraulic conductivity are predisposed to crack formation. The desired low hydraulic conductivity is compromised significantly by preferential flow through cracks. Cracks form by a variety of processes, of which many are induced by climatic forces. The next generation of cover designs places more attention on assurance that the low-permeability of the barrier layer predicted by laboratory test results will be achieved and maintained. Protection of the barrier layer from degradation by climatic forces became paramount in designs.

Protection of the barrier layer can be achieved by managing the soil water balance within the cover system. In arid and semiarid environments, lack of abundant soil water can cause plants to send roots deep in the cover system, penetrating the barrier layer in search of water. Decomposition of roots create macropores within the barrier layer. Alternative covers that control soil water movement are being designed, constructed, and monitored. An example of an alternative top-slope water-balance cover designed to manage soil water beneficially is under construction in Monticello, Utah. Preliminary research has also been conducted on a vegetated, rocky side slope that serves as an analog of a naturally stable side-slope cover. Results indicate that a combination of vegetation and rocks can be used together on disposal cell side slopes to achieve both water-balance control and erosion resistance.

BACKGROUND

Regulatory Framework

In 1978, the U.S. Congress passed UMTRCA that authorized the U.S. Department of Energy (DOE) to stabilize, dispose of, and control uranium mill tailings and other contaminated material at uranium processing millsites. This act also directs the U.S. Environmental Protection Agency (EPA) to promulgate standards and to mandate remedial actions in accordance with the standards; charges the U.S. Nuclear Regulatory Commission (NRC) to license the disposal facilities; and directs DOE to provide long-term care. Design life for long-term disposal of low-level radioactive waste is defined in this act as 1,000 years to the extent possible, and in no case less than 200 years.

In January 1983, EPA issued final standards for the cleanup of inactive uranium mill tailings sites (2). This act lead to establishment of the Uranium Mill Tailings Remedial Action (UMTRA) Project. To date, design of 19 and construction of 18 disposal facilities by the UMTRA Project have been completed, forming the base of our country's experience in designing and constructing covers to be operable for hundreds to thousands of years.

In 1985, the Tenth Circuit Court of Appeals set aside the groundwater provisions of Title 40 *Code of Federal Regulations* (CFR) Part 192.20(a)(2) and (3) and remanded them to EPA. The court directed EPA to bring these standards in line with groundwater standards applied to operating uranium millsites and to match more closely the standards set forth by the Resource Conservation and Recovery Act (RCRA) (4). In 1987, EPA published draft groundwater standards in response to the 1985 ruling. In April 1989, DOE's UMTRA Project Office began implementation of the draft standards under the assumption that the standards would soon become final. EPA promulgated the final groundwater standards of closure in 1995.

FUNCTION OF COVERS

When contaminants harmful to human health and the environment cannot be stabilized by treatment, containment of the waste is the accepted solution. A cover or a cap overlying the waste is the first component of containment.

Contaminants may possibly escape from disposal facilities by water and gas transport. Primary goal of the cover is to prevent moisture from entering the waste and to restrict gases, radon-222, from being released from the waste. The primary goal of early UMTRA cover design was to contain radon-222 produced from radioactive decay of radium-226 contained in uranium mill tailings.

Elimination of water infiltration into a waste facility is necessary because when the amount of water entering a disposal facility exceeds the field capacity of the waste, water will eventually exfiltrate. Therefore, if no water enters a waste facility, there will be no water to transport contamination to the environment.

Cover Components

Current goals of a cover are to limit infiltration of moisture and to inhibit release of gases. A barrier layer consisting of compacted clay soil is the primary component used to accomplish these goals. Clay soils are normally selected because low hydraulic conductivities can be achieved. The integrity of this barrier layer must be maintained throughout the design life of the facility. Protection of the barrier layer is provided by constructing additional soil layers over the barrier layer and using a combination of the design features listed below.

The amount of moisture percolating through the cover is limited by

Sloping the cover surface to remove excess precipitation by promoting surface and subsurface runoff

Incorporating soil layers to store moisture for plants to transpire any moisture that infiltrates.

Constructing a protective soil layer over the barrier layer to prevent degradation from climatic forces.

Escape of gases is limited by

- Isolating the radiologic or toxic gas source as far as possible from the cover.
- Providing a tight barrier resistant to vapor flux.
- Constructing a sacrificial protective soil layer over the barrier layer to prevent degradation from climatic forces.

Top Slope─Top-slope cover systems are constructed with gradients from 2 to 5 percent to improve runoff by lateral drainage. Other layered components used in a top-slope cover system, described from the top layer downward may include

- An erosion-protection layer.
- A protective soil layer used as a water-retention, frost protection, and plant rooting layer.
- A subsurface drainage layer.
- A compacted soil barrier layer.

Limiting infiltration is the primary design goal of the top-slope cover system. Cover materials composed of soil materials have a proven longevity throughout geologic time thus satisfying long-term design requirements. The fine fraction of earth materials, clays and silts, are compacted to form a physical barrier to radon emanation and to infiltration of water. Fine-grain earth materials achieve their lowest saturated hydraulic conductivity and highest unit weight when compacted at or above their optimum moisture content, w_{opt} (5,6). Unit weight parameters are determined from standard moisture-density relationships.

Erosional processes and climatic forces will deteriorate the barrier layer if it is left unprotected. Water and wind cause soil loss by overland flow, rill erosion, and wind deflation. Although the prominent erosive force varies from site to site, guidance for long-term stabilization dictates that covers designed to resist water erosion are adequate to resist wind erosion (7). Soil loss occurs by physical removal of particles from the barrier layer, compromising the characteristic low permeability. Current regulations allow for either a rock cover or a vegetated cover to provide erosional stability. Erosional resistance is often furnished with an armor stone layer of riprap rock overlying the barrier layer. The dimension of stone needed for protection is determined by sizing the stone so that tractive lift forces generated when water flows across the top of a stone are less than the weight of the stone.

Alternatively, the barrier can be protected from deterioration with a vegetated water-balance cover. A vegetated cover consisting of native plants and soil specifically selected for the site will be resilient to climatic change, while maximizing moisture transpiration and resistance to erosion. A sufficient thickness of soil to store infiltrating water enhances plant growth. This soil layer must also be thick enough to protect the barrier layer from freezing. Permeability of a compacted soil layer has been shown to increase 10,000 times when subjected to freeze-thaw cycles (8,9). Site specific design procedures using site climatic and soil properties are available to determine an adequate thickness (13). Because a vegetated cover provides a home for burrowing animals, a biointrusion layer above the barrier layer is required to prevent intrusion of the barrier layer.

Side Slope--Side slopes are required when abovegrade or partially belowgrade disposal facilities are designed. Waste volume in a disposal facility is substantially increased when waste can be placed beneath a side slope. Paramount in side slope design is erosional stability while limiting infiltration. Providing both these goals often proves problematic. Side slope covers must resist gully development and headward migration of headcuts and nickpoints.

Current design guidance allow only the use of rock riprap only for side slope erosional stability. While rock provides excellent erosional resistance, deep infiltration of water is increased beneath a rock cover (10,11). An example of this infiltration property is illustrated in the water harvesting technique used to increase domestic water supplies in arid regions. Because the supply of surface water is limited in arid regions, efforts are made to increase surface runoff. A common water-harvesting design technique is to increase surface runoff by removing rocks from the surface to reduce infiltration (12).

COVER DESIGN STANDARDS

UMTRA Design Guidance, Pre-groundwater Standards

"The release of radon gases from uranium mill tailings piles is a major concern in reclamation of existing tailings piles" (13). This statement indicates that the initial cover design philosophy was focused on controlling release of radon-222. Covering low-level radioactive material with a soil barrier layer was the selected method. This layer is also the primary feature to reduce infiltration.

Average flux of radon emanating from a covered disposal cell cannot exceed 20 picocuries per square meter per second ($pCi \cdot m^{-2} \cdot s^{-1}$) at the upper boundary of the barrier layer (1,2,3). Design thickness of the radon barrier is determined by the computer code (RAECOM) (3), a one-dimensional, steady-state radon diffusion model through porous media. Thickness of the soil barrier layer is computed by a trial-and-error procedure until radon emanation at the surface is less than 20 $pCi \cdot m^{-2} \cdot s^{-1}$. An initial radon-barrier layer thickness is selected and input into RAECOM, along with characteristics of the rest of the materials. RAECOM then computes radon flux at the surface of the barrier layer. The radon barrier thickness is modified until the radon flux falls below the standard. The complete disposal cell can be modeled with multiple material layers. Materials with low-radiologic contamination levels can be placed in upper portions of the disposal cell, thus determining the thinnest possible barrier layer necessary to protect human health and the environment (3).

In the initial guidance, it was realized that long-term protection of the barrier layer was crucial. Rock was chosen as the earthen material to withstand erosive effects from wind and water. Longevity standards set forth in UMTRCA are strictly applied to design of the rock cover. Prospective rock sources are evaluated against conservative durability standards specified by NRC (13) to ensure long-term survivability of stone armor.

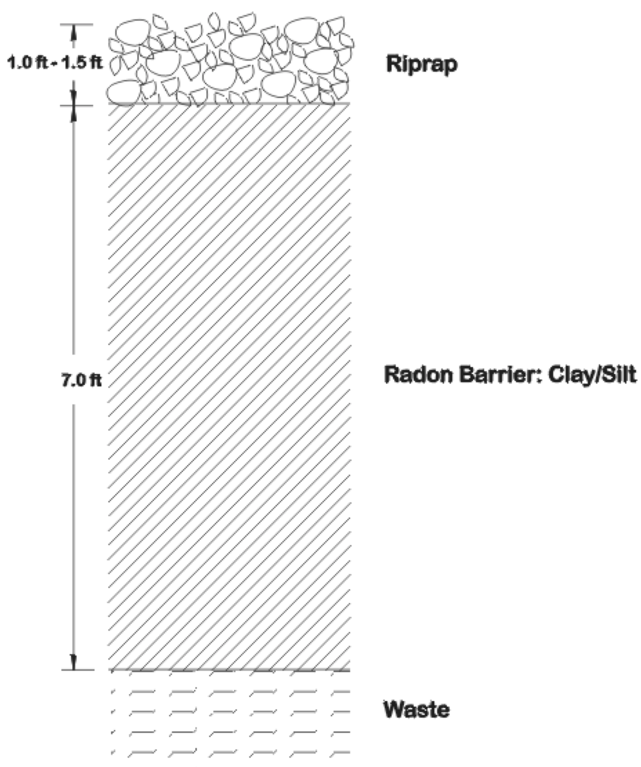
Initial water-resources protection strategy guidance from the UMTRA Project included qualitative considerations of the following factors:

Infiltration through the cover system
The quality of the existing aquifer beneath the disposal site.
The potential discharge rate and volume.
The contaminated tailings pore-fluid chemistry.

Numerical infiltration rates were not specified, but water passing through the barrier layer exacerbates all the factors used in water-resource protection. Minimizing infiltration is achieved by using the guideline that "materials and compaction efforts used to construct the radon barrier are generally sufficient to produce low enough permeabilities to limit infiltration" (14).

Example Pre-groundwater Standards Cover Design

The cover system used to encapsulate uranium mill tailings at the Shiprock, New Mexico, disposal cell provides an example of an early cover design. Fig. 1 presents a profile of this cover design. The Shiprock cover consists of an approximate 7-foot-thick barrier layer of compacted silty sand and clay. This large thickness is used because of a high radium-226 content in the tailings. A 1-foot-thick rock layer on the top slope and a 1.5-foot-thick layer on the side slope form erosion protection. A bedding/filter layer was not considered necessary because of the sandy, self-filtering nature of the barrier layer.



UMTRA Design Guidance, Post-groundwater Standards

Major changes to Title 40 CFR Part 192 after the draft regulation was implemented in 1989 required groundwater cleanup standards be considered and/or be developed at processing sites. Groundwater monitoring programs and concentration limits for listed contaminants were specified. As a result, RCRA infiltration standards for covers were informally adopted. Infiltration standards are numerically specified in RCRA documents. When encapsulated waste is nonhazardous, the cover cannot have a saturated conductivity, or permeability, greater than 10^{-5} centimeter per second (cm/s) (15). Caps over hazardous waste must have permeabilities less than or equal to 10^{-7} cm/s and must be less permeable than the liner underlying the waste. The latter requirement prevents moisture from ponding, or bathtubbing, within the waste (15). Although RCRA guidance specifies infiltration standards, there are no longevity requirements.

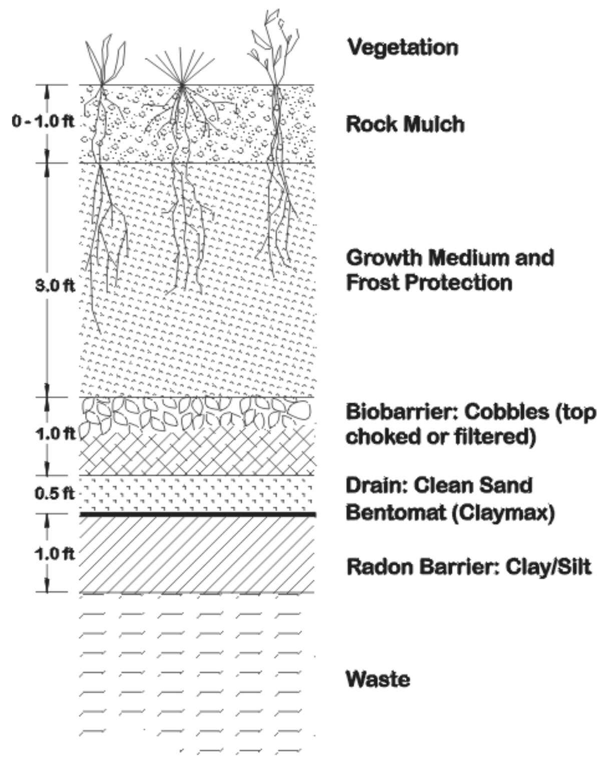
UMTRA cover design standards developed in 1987 before publication of EPA's draft groundwater standards do not incorporate methods to reduce processes that lead to increases in hydraulic conductivities. Evidence was emerging at that time in geotechnical research that standard construction and quality assurance practices used for construction of compacted clay soil barriers were not achieving design permeabilities that were based on laboratory test results. Daniel (16) reported several possible reasons why compacted clay barriers did not achieve design permeabilities:

- Clay soils were compacted dry of optimum water content.
- Clay clod formation.
- Insufficient bonding between lifts.
- Desiccation cracking.
- Shrink-swell cracking.
- Freeze-thaw cracking.
- Biointrusion.

Research performed by Daniel and other researchers indicated that the operating permeabilities of compacted soil layers were much greater than those predicted in laboratory experiments. Design permeabilities based on laboratory tests results measure only the matrix permeability. A secondary porosity formed by cracks in compacted clay soils was found to control the permeability in the field. Secondary porosity controls flow by allowing preferential flow through cracks. Cracks are a natural product of soil development, but formation is accelerated along bedding planes, around clods, and by the desiccation, shrink-swell, and freeze-thaw cracking phenomena reported by Daniel.

UMTRA Project design guidance was modified in 1989 to attempt to eliminate potential problems associated with these findings. A "checklist" cover was proposed (3), as shown on Fig. 2, with individual components selected on a site-specific basis. Objectives of the checklist cover from the *Technical Approach Document Revision II* (3) are

Control erosion.
Limit infiltration.
Provide freeze-thaw protection.
Inhibit radon emanation.
Drain or shed precipitation.
Control biointrusion.
Be self-renewing and adaptable to climatic change if vegetation is used.

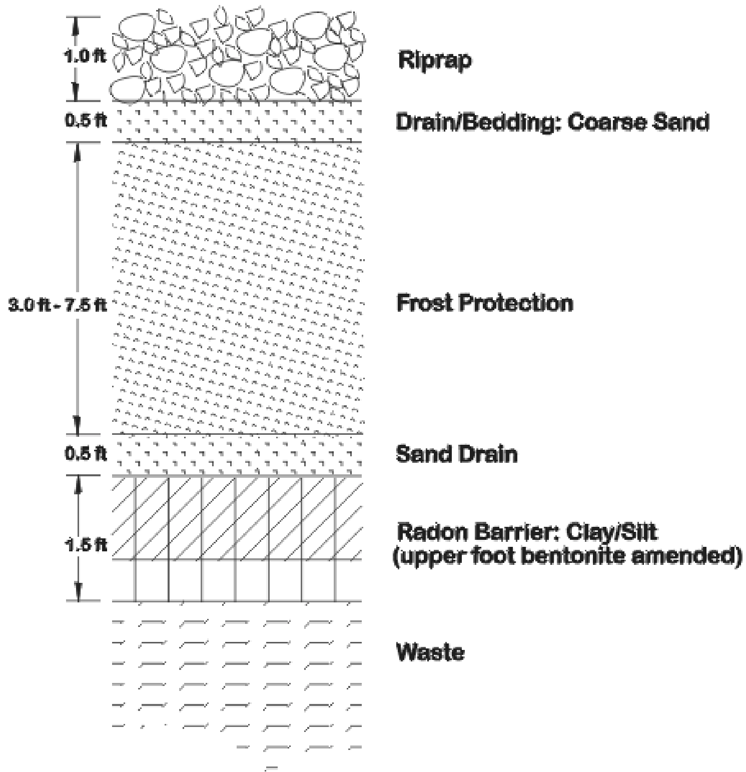


A review of this list and of the profile shown on Fig. 2 indicates that controlling infiltration became paramount in cover design after EPA published the draft groundwater standards. Considerable effort is now placed on protecting the barrier layer with a low-maintenance soil cover.

The design used to cap the Estes Gulch, Colorado, disposal cell, which was constructed to dispose of uranium mill tailings from both the Old Rifle and the New Rifle, Colorado, processing sites, illustrates the next generation of top slope covers. Fig. 3 presents a profile of that cover.

The protective layer components consist of a surface rock cover to provide erosion protection for the radon barrier. A drainage/bedding layer underlies this rock cover. A thick soil layer (3 to 7.5 feet thick) that underlies the drainage/bedding layer provides frost protection and stores infiltrating water. The underlying clean sand drainage layer provides a minor capillary break, causing moisture to be stored in the thick soil layer. Although plants are not part of the design, plants are expected to establish by using the moisture available in the thick soil layer.

An 18-inch radon barrier layer of compacted silty clay soil with the upper 12 inches amended with bentonite was designed with the RAECOM program. The bentonite amendment reduces the permeability and increases the radon attenuation capacity, allowing a thinner layer.



CURRENT STATUS AND RESEARCH

Alternative Water-Balance Cover Designs

Some waste facilities with compacted clay soil barrier layers that were constructed in semiarid regions for long-term encapsulation have experienced unwanted plant biointrusion (17). All these sites have a rock cover to resist erosive forces. Evidence suggests that this biointrusion has been enhanced by two phenomena:

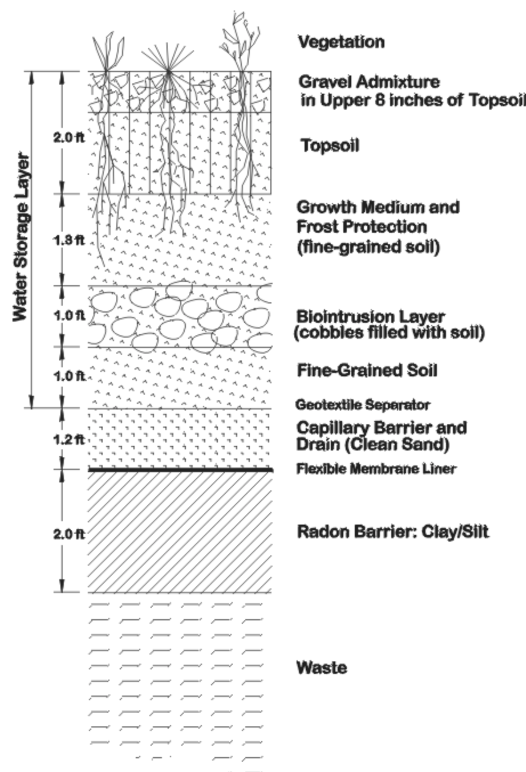
1. Voids in rock covers fill with a thin layer of soil, allowing plant establishment. Moisture passes through the thin soil veneer, temporarily ponding on the barrier layer before infiltrating. Deep-rooted plants seek out ponded moisture and send roots into the barrier layer, thus compromising the low permeability of the barrier layer.

2. Infiltration increases through rock covers provides a continual source of water to plants (10,11). Water accumulation in the bedding/drainage layer is suggested as the means that promotes seed germination. Plants root in the bedding/drainage layer and continue into the barrier layer, forming preferential flow paths that degrade the function of the barrier layer.

Alternative water-balance cover designs have been proposed to control infiltration of precipitation. These covers, similar to the full checklist cover previously discussed, include a capillary barrier to provide a restriction to the downward unsaturated flow of moisture according to the Richards' phenomena (18). The capillary barrier impedes unsaturated flow from the overlying fine-texture material into larger pores of underlying coarse-texture soils because of high capillary tensions in smaller pores of the overlying soil. Moisture stored in the rooting zone will be transpired to the atmosphere by plants.

Monticello Top Slope Cover

The design top slope cover of the Monticello, Utah, repository is an example of an alternative water-balance cover constructed with a fine-grained moisture storage layer and clean sand capillary barrier. Fig. 4 presents a section of the Monticello cover.



This cover is similar to the UMTRA checklist cover. A distinct textural break is provided by a geotextile separator between the overlying fine-grain rooting soil (clay loam to silt loam) and the coarse-grain drainage layer sand. Interbedded in the lower portion of the water-storage layer is a lens of cobbles and gravels that is designed to deter burrowing animals. Erosion protection is provided by a surface soil layer consisting of topsoil mixed with gravel. This soil top dressing is designed with an adequate amount of fine-grain soil to hold precipitation and to promote establishment of vegetation, while providing a large enough coarse fraction to resist water erosion until erosion is resisted by plant establishment. Monitoring performance of the cover is planned after construction is completed in 1999.

Side Slope Water Balance Analog

While advancements have been made in the design of water-balance components of top slope covers, side slopes have received little attention. Vegetated rocky side slopes are ubiquitous in semiarid and arid environments. A preliminary study of a vegetated rocky side slope was conducted in a semiarid area south of Grand Junction, Colorado (19). This slope flanks the Beaver Gulch drainage located at the Delta County-Mesa County boundary. Results of the investigation reveal that the slope has an average gradient identical to disposal cell design guidance of 20 percent. Geomorphic and pedological evidence indicate that this slope has been erosionally stable for more than 1,000 years. Moisture infiltration is limited by transpiration to approximately 2 feet, as shown by the development of a thick caliche layer at that depth. Surface erosional stability is provided by vegetation consisting of approximately 54-percent plants and litter cover; 37-percent rock cover consisting of coarse sand, gravel and cobbles; and the remainder bare soil. Successful imitation of this analog slope in future side slope cover designs will allow wastes to be placed beneath side slopes with the assurance of erosional infiltration control.

Geosynthetics

Geosynthetics are required in covers regulated by 40 CFR 264. However, the use of geosynthetics to prevent infiltration through covers for use in long-term disposal sites remains unproven and needs to be evaluated before acceptance. Geosynthetics are susceptible to microbacterial degradation, to cracking because of loss of elasticity from antioxidant reduction and to an unknown response to root activity. Koernor and Daniel state the operational life of geosynthetics ". . . to be at least a few centuries, and possibly 1,000 years" (20). Extrapolating the future life of a material intended for use in an earth environment should be used cautiously unless an adequate historical record is available (21).

CONCLUSIONS AND RECOMMENDATIONS

Observation of existing UMTRA Project disposal cells indicates that nature is attempting to alter some cells in the short time they have been in existence. Vegetation is encroaching on top slope covers when moisture is present, and moisture will be present on all sites at some time. Vegetation may or may not cause a problem, depending on the design. When plants are included in the design, beneficial transpiration and erosion resistance aspects can be incorporated. However, if plants are not considered in the design, unwanted problems are probable.

Some control of internal moisture must be provided in all cover designs. Data showing the effectiveness or noneffectiveness of capillary barriers need to be gathered. Monitoring performance of full-scale facilities, such as the Monticello, Utah, repository will demonstrate the usefulness of capillary barriers to enhance internal moisture control. Vegetated rocky side slope designs need to be improved. Research to determine the optimum percentage of coarse material (e.g., boulders, cobbles, gravels, and coarse sands) to the soil fraction for erosion resistance for a given slope gradient and length needs to be quantified. Optimum thickness for the coarse fraction in the cover (i.e., to what depth should the coarse fraction extend into the surface layer without compromising plant establishment and transpiration effectiveness) needs to be addressed.

Understanding the effects of pedogenesis also requires further study. Soil formation at the Beaver Gulch, Colorado, site suggests that pedogenesis plays an important role in the long-term effectiveness of earth covers. When earthen materials are placed in an environment that is not harmonious with the surrounding system, rapid changes in characteristics of the placed soil start immediately as nature begins to bring the entire system into equilibrium. Alteration of soil structure has been documented in 30- to 50-year old soil (22,23). A more complete understanding of beneficial and detrimental effects of pedogenesis is needed.

Future cover designs intended for long-term closures need to abandon the barrier control philosophy and move toward an ecosystem-type approach. Incorporating plants in combination with rock materials on top slope and side slope cover designs will create self-sustaining covers that can approach total elimination of moisture infiltration while providing erosion resistance. Vegetated rocky covers are an example of an ecosystem-type approach that will change with changing environments.

ACKNOWLEDGMENTS

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