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Basis for Technical Guidance To Evaluate Evapotranspiration Covers

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ABSTRACT

This report provides technical information to evaluate evapotranspiration (ET cover design criteria with emphasis on applications to long-term disposal sites such as Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA sites. Water balance covers, also known as ET covers, reduce percolation by storing precipitation then allowing vegetation to cycle it back to the atmosphere. For long-term (over 200 years waste isolation, ET covers may provide significant benefits over conventional, resistive covers that rely on engineered components, such as compacted clay barriers and geomembranes, to divert precipitation. UMTRCA covers were designed to impede and attenuate radioactive radon-222 gas flux from the underlying tailings, while minimizing percolation of any contaminants to groundwater. Such covers have implicit regulatory compliance post-construction. Alternative cover systems, such as ET covers, must explicitly meet some anticipated performance, and demonstrate beneficial use. While all engineered structures will change over time, an ET cover evolves with nature rather than resisting it, which may perpetuate a more reliable waste isolation system. For example, UMTRCA sites must provide safe and environmentally sound disposal, long-term stabilization, and control of uranium mill tailings and remain effective for up to 1,000 years, to the extent reasonably achievable, and, in any case, for at least 200 years. UMTRCA covers rely on the engineered properties to meet regulatory requirements during and immediately after construction. Subsequent compliance is implicit in the design. The design of an ET cover is far more dependent on mesoscale meteorology, native vegetation, and edaphic soil properties, which are site-specific. Therefore, the design and anticipated performance of an ET cover should be demonstrated through a combination of modeling, natural analogue and pilot studies, and then verified with monitoring data. There is no single ET cover design that can likely meet performance standards across different climates, available soils, and vegetation. The technical information presented in this report reviews guidelines and performance criteria commonly used for ET covers at municipal solid waste facilities and the consideration factors of such covers to meet the regulatory requirements at long-term disposal sites.

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EXECUTIVE SUMMARY

Engineered covers for waste containment and isolation rely on multilayer resistive components to limit the infiltration of precipitation or percolation into the underlying waste. Such covers are designed to meet requirements for post-closure regulations at permitted landfills and hazardous waste facilities. The primary objective of these covers is to minimize the escape of any hazardous constituents to the environment and ongoing maintenance. Such covers conventionally use compacted soils and geomembranes with prescribed properties designed to last the 30-year post-closure period. Evapotranspiration (ET) covers are alternative covers designed to achieve equivalent reduction in percolation and equivalent protection from water and wind erosion to a conventional cover. ET covers use a water storage layer to retain precipitation and vegetation to recycle it back to the atmosphere thereby minimizing percolation. By allowing a natural ecosystem to become established, and co-evolve with the cover, ET covers have the potential to provide long-term benefits and added resilience over conventional covers at long-term disposal sites. However, the design and evaluation of ET covers differs considerably because each site has a unique climate, soil, and vegetation that must be accounted for in its design. The design phase of an ET cover is conceptualized, then refined and evaluated using numerical models, natural analogues, and pilot studies to ensure performance requirements are adequately met.

Conventional cover designs assume that engineering properties are static in time; however, surficial waste covers are open-systems freely exchanging and consuming energy (solar radiation, nutrients, and carbon) and mass (precipitation, organic matter, and dust) with the environment. Research studies have documented changes in engineered covers over relatively short, decadal periods including increases in saturated hydraulic conductivities of compacted soil layers, freeze-thaw fractures, deeply rooted vegetation, and geomembrane wear among others. ET covers incorporate ecologic processes and natural systems evolution into the design rather than resisting them. However, such covers are not commonly used for long-term waste isolation needed for long-term waste streams such as nuclear waste or uranium mill tailings, nor is there sufficient technical guidance on the use of ET covers at such facilities.

Uranium processing has produced large volumes of waste, particularly across the southwestern United States. Congress enacted the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA) to provide for the safe and environmentally sound disposal, long-term stabilization, and control of uranium mill tailings. These types of disposal sites rely on vegetated or rock-armored covers to effectively minimize disturbance and dispersion by natural forces and provide permanent isolation of tailings and associated contaminants for a minimum of 200 years, and to the extent achievable, for 1,000 years. These UMTRCA covers were designed to meet regulatory requirements to reduce surface emissions of radon gas to below 20 picocuries per square meter per second (pCi m^{-2} s^{-1}), or 0.74 becquerels per square meter per second (Bq m^{-2} s^{-1}).

Historically, the most effective means to meet this requirement was to use a radon barrier of compacted, moist clay with tortuous flow paths of adequate length to allow for the sufficient decay of radon-222 gas emanating continuously from the uranium mill tailings. The diffusion of radon to the surface is controlled by the overall thickness of the radon barrier and the soil moisture content. The required thickness of these covers was determined by steady-state empirical models of diffusive radon transport through soils and the radon flux coming from the tailings. Fine-grained materials were compacted in excess of 85% Proctor density and at a saturation of over 80%. Adequate soil moisture content in the radon barrier inhibits gas transport and minimizes desiccation cracks within the barrier.

For long-term disposal sites with radon barriers, an ET cover system should (1) reduce percolation using a functioning, water-limited ecosystem to remove excess moisture from only the water storage layer, while effectively maintaining soil moisture in the radon barrier, and (2) provide a more resilient, and long-term solution for surface erosion control. The former requires a more complicated balancing act to isolate and maintain moisture in the radon barrier, while the latter is simply an added layer of protection for the cover surface. To use an ET cover at long-term disposal sites, the performance criteria should first be determined, followed by the development of a conceptual design based on local site characterization, vegetation, and climate. The initial performance should be demonstrated through modeling scenarios and pilot studies. The final cover design is an iterative process to optimize performance metrics within the economic constraints of the project.

Although guidance on ET covers systems for municipal solid waste (MSW) landfills is available and well-established in the literature, documentation for ET covers at long-term waste disposal sites is limited. ET covers at MSW landfills generally use a minimum thickness of 100 cm of loamy soil for water storage and rooting over a coarse-textured capillary barrier. A fine-over-coarse capillary barrier increases the water storage capacity of the rooting zone allowing ET to remove it over the growing season. In arid and semiarid climates, the percolation threshold below the capillary barrier is generally less than 3 mm/y.

Over the long-term, pedological and ecological processes can have both beneficial and deleterious impacts on ET cover performance. Soil structure, desiccation fractures, and radon flux may deviate significantly as the cover ages; therefore, adequate cover performance cannot rely solely on maintaining an intact cover. A long-term ET cover system requires performance-based modeling and monitoring to ensure regulatory requirements are met. An ET cover system working with natural processes may be more resilient to the short- and long-term effects of soil development, climate change, biointusion, erosion/deposition, and even ecological change.

This report discusses the applicability of ET covers to long-term waste disposal sites and provides consideration factors from conceptual design to refinement and long-term monitoring. Many existing long-term disposal sites, such as UMTRCA sites, are now over 30 years old. Long-term surveillance and maintenance remain a critical component of UMTRCA stewardship; however, ET covers may provide improved waste containment assurance and a more beneficial solution over the long-term. The objective of this report is to provide technical information for future NRC technical guidance on the design, construction, monitoring, and long-term performance of ET covers at long-term disposal sites. The report mainly focuses on UMTRCA sites as the Department of Energy, Office of Legacy Management (DOE/LM) is contemplating modifying several UMTRCA covers from bare, earthen covers to include ET cover components. However, the information presented in this report is also applicable to ET covers at other sites such as low-level waste (LLW) disposal sites and Waste Incidental to Reprocessing (WIR) facilities.

ABBREVIATIONS

ACAP	Alternative Cover Assessment Program
API	Application Programming Interface
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
DInSAR	Differential radar interferometry
DOE	U.S. Department of Energy
DOE/LM	U.S. Department of Energy, Office of Legacy Management
ERT	Electrical resistivity tomography
EMI	Electrical magnetic induction
EPA	U.S. Environmental Protection Agency
ET	Evapotranspiration
GPR	Ground penetrating radar
FDEM	Frequency-domain electromagnetics
FLM	Flexible membrane liner
LTSM	Long-term surveillance and maintenance
LTSP	Long-term surveillance plan
MSW	Municipal solid waste
NetCDF	Network Common Data Form
NDVI	Normalized difference vegetation index
NMR	Nuclear magnetic resonance
NP	Neutron probe
NRC	U.S. Nuclear Regulatory Commission
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RCRA	Resource Conservation and Recovery Act
SAR	synthetic aperture radar
SAVI	Soil adjusted vegetation index
SMAP	Soil Moisture Active Passive
SWS	Soil water storage

TDEM	Time domain electromagnetics
TDR	Time domain reflectometry
TLO	Transmission line oscillators
UMTRCA	Uranium Mill Tailings Radiation Control Act of 1978
UAS	Unmanned aerial systems
USGS	U.S. Geological Survey

SYMBOLS

α	Air-entry potential of a porous material
C_m	Porous media complexity factor
d	Day
D_0	Gas diffusion coefficient in free air
D_c	Gas diffusion coefficient in cover
ε	Air-filled porosity of a porous material
ε^*	Air-filled fracture porosity
ε_{100}	Air-filled porosity at -100 cm of tension
J_c	Radon diffusion flux at surface of the cover
J_t	Radon diffusion flux at surface of the tailings
K_s	Saturated hydraulic conductivity
h	hour
l	Pore connectivity factor
λ	Radon decay constant of $2.1\times10^{-6}\ \mathrm{s}^{-1}$
φ	Total porosity of a porous material
P	Precipitation
ψ	Matric potential, pore-water pressure head
θ	Volumetric soil water content
θ_r	Residual soil water content
θ_s	Saturated soil water content
m,n	Empirical pore-size distribution parameters
S_w	Degree of saturation ratio
x_C	Radon barrier thickness
X_m	Matrix tortuosity factor
y	Year

1 INTRODUCTION

Waste isolation is a key strategy for mitigating human and ecological risks from municipal solid waste (MSW) landfills, industrial biproducts, and other hazardous waste streams. Large volumes of waste residing on the land surface may pose a significant threat to human health and the environment when improperly stored or managed. The risk to local communities and the underlying groundwater system can be reduced by engineered surface covers designed to limit percolation through waste and contaminant transport to receiving water bodies. Conventional earthen cover systems use covers with low hydraulic conductivity (i.e., permeability) and geosynthetic liners or geomembranes to isolate waste from the environment. These conventional cover systems are designed to meet regulatory requirements at the time of construction. However, the engineered properties of the restrictive layers, or as-built specifications, created by compacting fine-textured soils, change over time due to the natural acclimation of the cover to environmental forces, developing soil structure, macropores, and increased (K_s) over relatively short (<10 years) periods (Albright and others, 2006b; Benson and others, 2007; Benson and others, 2011a).

Vegetation has long been successful at limiting recharge by returning precipitation stored in the soil to the atmosphere via evapotranspiration (ET), particularly in arid and semi-arid environments (Gee and others, 1992). Beginning in the 1990's, waste management has pivoted from conventional covers to alternative cover systems, which are defined as any cover used in place of a conventional cover. Alternative covers include monolithic ET covers, capillary barrier ET covers, bioengineering management covers, and modified asphalt covers and are used in conducive environmental conditions to control moisture and percolation, manage surface water runoff, minimize erosion, and prevent direct exposure to waste (EPA, 2011). ET covers incorporate a non-compacted, water storage layer to retain precipitation and allow vegetation to transpire it back to the atmosphere, thereby naturally minimizing percolation (Scanlon and others, 2005). Unlike conventional covers with implicit regulatory compliance, ET covers are site-specific and designed to meet or exceed performance criteria; both factors complicate the implementation of alternative cover designs (Khire and others, 1997; Ho and others, 2002; Albright and others, 2010; Khire, 2016).

The U.S. Environmental Protection Agency (EPA) evaluated the performance of conventional and ET covers with the Alternative Cover Assessment Program (ACAP). The goal of this program was to develop guidance on alternative covers at Resource Conservation and Recovery Act (RCRA) Subtitle C (hazardous waste) or Subtitle D (MSW) landfills across the United States over a period of 4-8 years (Albright and others, 2002). Regardless of climate, conventional covers with composite barriers (i.e., geomembrane(s) over fine soil) were most effective at limiting percolation to 0.4 to 1.4% of annual precipitation, while percolation rates for conventional covers with resistive barriers were least effective with percolation ranging from 6 to 17% of precipitation (Albright and others, 2004). They also found ET covers to be highly effective in subhumid, semiarid, and arid sites where percolation was <0.4% of precipitation, or <2.2 mm/y, but far less effective in humid environments. Albright and others (2004) conclude that detailed, site-specific designs are critical to the success of any ET cover design (Albright and others, 2004). Alternatively, ET cover systems are less dependent on engineered properties, such as low hydraulic conductivity barriers and geosynthetics, and more reliant on the natural storage capacity of soils and water needs of vegetation. The integrity of these components is expected to remain unchanged over the expected 30-year post-closure performance of conventional covers (EPA, 1989). However, cover systems at some waste sites, such as Uranium Mill Tailings Radiation Control Act (UMTRCA) disposal sites, are expected to perform for up to 1,000 years, or at least 200 years; the performance of ET covers for this time period is uncertain.

Beginning in the 1940's, uranium mills generated enormous quantities of waste or tailings – the biproduct of the uranium enrichment for the development of nuclear weapons and nuclear energy. Uranium mill and disposal sites remain an indefinite risk due to the quantity and concentration of radioactive materials in the tailings, including uranium-238, which has a half-life of 4.5 billion years. The most serious radiological health concern posed by uranium decay is radiation from radon-222 gas emitted from the tailings. In response to growing public health concerns about exposure to radiological waste material, Congress enacted the Uranium Mill Tailings Radiation Control Act of 1978 to limit long-term gas emission and groundwater contamination by requiring earthen covers (or approved alternative covers) over tailings and waste.

The primary goal of an UMTRCA cover is to minimize residual radioactive releases of radon-222 gas and to immobilize and isolate contaminants from groundwater, while minimizing erosion, disturbance, and dispersion by natural forces over the long-term (up to 1,000 years). This was achieved using either a radon barrier of highly compacted native fine-grained soil or a bentonite-amended soil of sufficient thickness and moisture to attenuate radon-222 decay below the control standard value of 0.74 Bq m^{-2}), which applies to post-construction measurements. The low hydraulic conductivity of the compacted clay in the radon barrier also limits percolation into the waste while the surface is protected by rock or vegetation.

UMTRCA covers have started to show signs of post-closure change; however, there are no indications that the radon flux standard has been exceeded to date. The "Radon Barriers Project" evaluated four UMTRCA disposal sites 20-years post-closure and found that natural processes, including ecological succession and soil formation, were changing engineered covers in ways that could negatively impact percolation and radon flux requirements (Fuhrmann and others, 2019a; Williams and others, 2021). Recognizing potential long-term performance issues with compacted earthen radon barriers and potential benefits of ET covers, the Department of Energy, Office of Legacy Management (DOE/LM) is contemplating modifying UMTRCA covers from bare, earthen covers to include ET cover components. In some instances, UMTRCA covers are naturally converting to vegetated ET covers. There is a potential reduction in risk and cost savings in long-term surveillance and monitoring (LTSM) using ET covers. Furthermore, future NRC licensee's disposal sites may also propose ET covers designs. ET covers typically use local vegetation and may provide better protection to the radon barrier than rock armor or riprap (Bowerman and Redente, 1998). However, a coupled cover design that incorporates an ET cover over a radon barrier (ET-radon cover system) should minimize percolation while simultaneously maintaining sufficient moisture in the clay barrier to attenuate radon-222 decay.

The design criteria for ET covers is extensively covered in textbooks (e.g., Caldwell and Reith, 1993; Albright and others, 2010), federal guidelines (EPA, 2011), state regulatory documents (e.g., Valceschini and Norris, 1997; ITRC, 2003; MDEQ, 2011; CADMUS, 2013; NJDEP, 2014; TCEQ, 2017), and literature cited herein. The above references generally conclude that the design of an ET cover is site-specific and that numerical models are required to refine the design and demonstrate the beneficial performance over a conventional cover. The existing regulatory guidance on ET covers is limited to a 30-year post-closure period and does not consider the longevity of uranium mill tailings disposal sites. An ET-radon cover system would also need site-specific designs that consider the local climate, vegetation, and soil edaphic properties that affect the ability of soil to sustain biological production and diversity. The conceptual design is refined in the final cover design and documentation of the anticipated performance and benefit. This document provides the technical information and considerations for future NRC technical guidance on implementing ET covers at long-term disposal sites and factors affecting the short- and long-term performance of these covers. This report has a particular emphasis on ET-radon cover systems at UMTRCA disposal sites but remains applicable to other types of disposal sites (e.g., low-level waste (LLW) and Waste Incidental to Reprocessing (WIR) sites) with long-term performance objectives.

1.1 Uranium and the Uranium Mill Tailings Radiation Control Act of 1978

Uranium is a naturally occurring radionuclide that has historically been mined and used for its chemical properties. Uranium-238 is the most common uranium isotope with a relative abundance of over 99%. Uranium-235, which must be refined, is the only naturally occurring fissile isotope, but has a much lower relative abundance of only 0.7%. Uranium mining in the United States began in the 1940s, primarily to produce uranium for nuclear weapons related to the Manhattan Project. Since the 1970s, uranium ore continues to be mined and further processed in the nuclear fuel cycle to fuel nuclear reactors for electricity generation. Uranium mining was widely conducted across the Colorado Plateau, Wyoming, and the Gulf Coast of Texas by either open pit mining or underground workings, which bring the ore to the surface for milling and processing (Riccitiello, 1979). Milling crushes the ore to a fine-grained consistency which is then chemically leached to obtain uranium oxide (i.e., yellow cake), while the remaining ore becomes mill tailings. Uranium mining produces considerable quantities of bulk waste materials including the overburden, weakly uranium-enriched waste rock, and subgrade ores, which are commonly left onsite in waste piles.

Each radionuclide common in uranium ore, including uranium-238, uranium-235, and thorium-232, has a complex decay chain of both long and short half-lives that ultimately end at stable isotopes of lead (Mitchell and others, 2013). The uranium-238 (4.5×10^9 years half-life) decay chain produces radon-226 (1,590 years half-life) which is left behind in the processed tailings. This radionuclide decays to radon-222 (3.8 day half-life), which in turn decays to several short-lived progeny, some of which are also alpha emitters (Nazaroff, 1992). Alpha radiation can damage cell linings in the respiratory tract and lead to lung cancer. Thus, the mill tailings and waste material resulting from uranium mining and milling pose a hazard to public health and safety (Beedlow and Hartley, 1984). In western mining areas, waste material was often used as building materials for roads, schools, and homes. Wind erosion may carry fugitive dust from the tailings piles out of the impoundment area (Li and others, 1983). Surface and groundwaters can also be contaminated (e.g., arsenic, molybdenum and selenium) by these waste biproducts, which may then become bioavailable (Dreesen and others, 1982). Indian Nations residing near areas of mining or milling have had and continue to have their health compromised (Moore-Nall, 2015).

By 1957, both federal and commercial demands for uranium had decreased, thus slowing production, and closing many operations. Conventional uranium mill operations across the southwestern U.S. had produced 2.75×10^5 million tons of uranium oxide (U_3O_8) or yellow cake and an estimated 1.5×10^8 million tons of tailings by 1979, most of it located on inactive and abandoned sites (NMSS, 1980). During this time, Congress enacted the UMTRCA of 1978 to provide for the safe and environmentally sound disposal, long-term stabilization, and control of uranium mill tailings in a manner that minimizes or eliminates exposure to the public (Public Law 95-604). Two types of UMTRCA sites are defined: Title I sites are sites that were inactive or no longer in use when UMTRCA was passed, and Title II sites are sites that were in use or issued a license after the act was passed. Currently, there are 21 Title I sites and 6 Title II sites (Figure

1-1), although more will likely be added over time. UMTRCA sites are either processing sites, where uranium was extracted from ore, or disposal sites, which store the spent mill tailings (Table 1-1).

Requirements for Title I sites are provided in Title 40 CFR 192.02, “Standards,” Subpart A, “Standards for the Control of Residual Radioactive Materials from Inactive Uranium Processing Sites.” Specifically, 40 CFR 192.02 provides requirements for the control of residual radioactive materials and their listed constituents. Control must be effective for up to 1,000 years, to the extent reasonably achievable, and, in any case, for at least 200 years. Controls must provide reasonable assurance that releases of radon-222 from residual radioactive material to the atmosphere will not: (1) Exceed an average release rate of 20 picocuries per square meter per second (pCi m^{-2} s^{-1}), or (2) Increase the annual average concentration of radon-222 in air at or above any location outside the disposal site by more than one-half picocurie per liter (pCi L^{-1}). Furthermore, Title I sites must provide reasonable assurance of conformance with any groundwater protection provisions.

Requirements for Title II sites are provided in 10 CFR 40.28, “General License for Custody and Long-Term Care of Uranium or Thorium Byproduct Materials Disposal Sites,” with technical criteria in Appendix A, “Criteria Relating to the Operation of Uranium Mills and the Disposition of Tailings or Wastes Produced by the Extraction or Concentration of Source Material from Ores Processed Primarily for Their Source Material Content,” to 10 CFR Part 40, “Domestic Licensing of Source Material”. Criterion 1 states that the “general design goal or broad objective in siting and design decisions is permanent isolation of tailings and associated contaminants by minimizing disturbance and dispersion by natural forces, and to do so without ongoing maintenance.” Criterion 4d requires a full, self-sustaining vegetative cover or rock cover to reduce wind and water erosion to negligible levels. Criterion 5 incorporates groundwater protection standards imposed by the U.S. Environmental Protection Agency (EPA) under 40 CFR Part 192, Subparts D and E, and Criterion 7 requires groundwater monitoring. Criterion 6 requires an earthen cover (or approved alternative) over wastes and that the site shall be closed “in accordance with a design which provides reasonable assurance of control of radioactive hazards to (1) be effective for 1,000 years, to the extent reasonably achievable, and in any case for at least 200 years, and (2) limit release of radon-222 from uranium byproduct materials to the atmosphere so as not to exceed an average release rate of 20 pCi m^{-2} s^{-1} [0.74 Bq m^{-2} s^{-1}] to the extent practicable throughout the effective design life determined pursuant to (1)(i) of this Criterion.” The average release rate applies to the entire surface of each disposal area over a period of at least one year.

Established in 2003, DOE/LM manages the agency’s responsibilities associated with the closure of federally operated Cold War-era sites used to research, produce, and test nuclear weapons. Currently, DOE/LM provides LTSM (Young and others, 1986) at over 100 sites. Regulatory drivers are congressionally-recognized statutes or programs that direct the cleanup and management of these sites. Such regulatory drivers include UMTRCA (Titles I and II), as well as the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), the RCRA, Nuclear Waste Policy Act Section 151, State Water Quality Standards, the Formerly Utilized Sites Remedial Action Program, the DOE Decontamination and Decommissioning Program, the Nevada Offsites, Manhattan Engineer District/Atomic Energy Commission Legacy Sites, and Plowshare/Vela Uniform Program Sites.

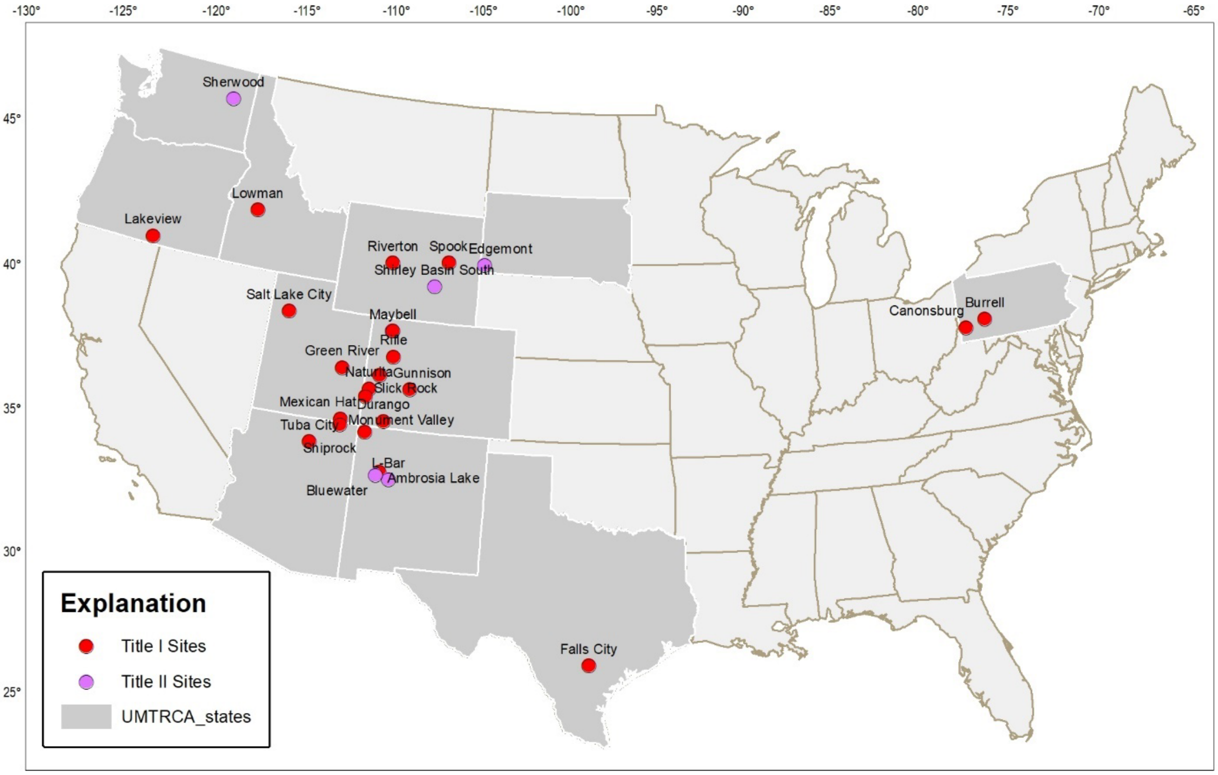

Figure 1-1 Department of Energy, Office of Legacy Management Currently Manages 21 Title I and Six Title II Processing and Disposals Sites Under the Uranium Mill Tailings Radiation Control Act (UMTRCA)

1.2 Definition of Fluxes and States

For clarification and consistency, the terminology of physical processes used throughout this document related to the movement or amount of water, gas, and other contaminants are defined here. A flux describes the rate of material transfer, which depends on both velocity and direction while a state variable defines how much of something is there (i.e., soil moisture, temperature, or mass).

Fluxes

Total fluxes can include both diffusive and advective flow – both of which generally assume non-turbulent flow. Diffusive flux is the random motion of molecules within a fluid driven by concentration gradients. Advective flux is the transport of a substance within the mean fluid flow in the subsurface. Laminar flow tends to be the norm in subsurface flow (Smith and Sayer, 1964) while most atmospheric fluxes are turbulent (Lee and others, 2004).

Table 1-1 Current UMTRCA Title I and Title II Ore Processing and Tailing Disposals Sites Managed by the Department of Energy, Office of Legacy Management

	Site Name	State	Site type	Milling start	Milling end	Cell Closure	Ore processed [tons]	Mill Tailings [tons or *yard*^{3}]
	Title I Sites							
1	Ambrosia Lake	New Mexico	Disposal Site	1958	1963	1998	3,000,000	6,931,000
2	Burrell	Pennsylvania	Disposal Site	1940	1960	1987		86,000
3	Canonsburg	Pennsylvania	Disposal Site	1911	1975	1985		226,000
4	Durango	Colorado	Disposal/Processing Sites	1942	1963	1996	1,200,000	*2,500,000*
5	Falls City	Texas	Disposal Site	1961	1982	1994		7,100,000
6	Grand Junction	Colorado	Disposal/Processing Sites	1950	1966	1994	2,200,000	4,400,000
7	Green River	Utah	Disposal Site	1957	1988	1989	183,000	*382,000*
8	Gunnison	Colorado	Disposal/Processing Sites	1958	1962	1995	540,000	1,140,000
9	Lakeview	Oregon	Disposal/Processing Sites	1958	1961	1988	130,000	*926,000*
10	Lowman	Idaho	Disposal Site	1955	1960	1992	200,000	222,230
11	Maybell	Colorado	Disposal Site	1957	1964	1998	2,600,000	3,500,000
12	Mexican Hat	Utah	Disposal Site	1957	1970	1995	2,200,000	4,400,000
13	Monument Valley	Arizona	Processing Site	1955	1968	1994		1,300,000
14	Naturita	Colorado	Disposal/Processing Sites	1939	1959	1998	704,000	
15	Rifle	Colorado	Disposal/Processing Sites	1924	1981	1996		3,500,000
16	Riverton	Wyoming	Processing Site	1958	1963	1989		*1,800,000*
17	Salt Lake City	Utah	Disposal/Processing Sites	1951	1968	1989		*2,800,000*
18	Shiprock	New Mexico	Disposal Site	1954	1968	1986	1,500,000	2,520,000
19	Slick Rock	Colorado	Disposal/Processing Sites	1931	1961	1996		1,112,260
20	Spook	Wyoming	Disposal Site	1962	1965	1989		*315,000*
21	Tuba City	Arizona	Disposal Site	1956	1966	1990	800,000	2,250,000
	Site Name	**State**	**Site type**	**Milling start**	**Milling end**	**Cell Closure**	**Ore processed [tons]**	**Mill Tailings [tons or *yard*^{3}]**
				Title II Sites				
1	Bluewater	New Mexico	Disposal Site	1953	1982	1995		23,000,000
2	Edgemont	South Dakota	Disposal Site	1956	1972	1989		4,000,000
3	L-Bar	New Mexico	Disposal Site	1977	1981	2004	2,100,000	2,100,000
4	Maybell West	Colorado	Disposal Site	1975	1982	2005		1,975,000
5	Sherwood	Washington	Disposal Site	1978	1984	1996		2,900,000
6	Shirley Basin South	Wyoming	Disposal Site	1962	1985	2001		6,300,000

Radon-222 is the gaseous biproduct of the decay of radium-226. While radon-222 has a short half-life of 3.8 days, it is the daughter or progeny of radium-226 which in turn is a daughter of thorium-230, which have half-lives of 1,600 and 80,000 years, respectively. Thus, the uranium-decay series produces a continuous stream of radon-222. Regulatory agencies, including the U.S. Nuclear Regulatory Commission (NRC), specify fluxes over an area. For example, UMTRCA sites shall not exceed an average annual upward flux of 0.74 Bq m^{-2} s^{-1} for radon-222.

Precipitation (*P*) is the condensation of water vapor in the atmosphere to form water droplets that fall to the surface as rain, sleet, hail, or snow. The precipitation rate or intensity is given in units of length over some duration (e.g., millimeters per hour, mm/*h*).

Evapotranspiration (ET) refers to the combined processes of evaporation and plant transpiration – both of which use solar radiation (energy) to convert liquid water into vapor. This water, whether from precipitation or irrigation, is cycled back to the atmosphere. Water loss by plants is directly proportional to available water in the root zone, atmospheric demand for moisture, plant growth and productivity, and plant physiology, which regulates the stomata on leaf surfaces. The stomata open to obtain carbon dioxide and release water obtained from the root zone as vapor. ET is reported in units of length per time (e.g., millimeters per day, mm/d). Potential ET, also in units of length per time, refers to the water vapor flux, or ET, given adequate water supply and ideal conditions. Reference ET is the theoretical ET over an extensive surface of well-watered and actively growing reference vegetation, usually alfalfa or grass.

Percolation is the downward movement or flux of water and is generally considered to be the amount of drainage below the cover in units of length per time (e.g., millimeters per day, mm/*d*). Precipitation enters the soil through infiltration where it is stored and either returned to the atmosphere through ET or percolates deeper. For ET covers, percolation is generally the performance criterion.

States

States are extensive variables that change with size and situation. Soil moisture is a key state variable in hydrology and climate systems, coupling the water and energy cycles. Soil moisture is quantitatively measured as volumetric soil water content (θ) in units of volume of water per volume of soil (e.g., cubic meter per cubic meter, m^3/m^3). The amount of water within a specified depth of soil is the soil water storage (SWS) which is in units of length.

Dissolved constituents in water are measured in concentration or mass of constituent per volume (e.g., milligrams per liter, mg/*l)*. The mass can be either an actual constituent mass, its molality, or its molecular charge equivalents.

1.3 Purpose and Scope

This report provides a review of available technical information on ET covers and the necessary conceptual design requirements needed to implement an ET cover at a disposal site with long-term regulatory requirements, such as UMTRCA disposals sites. The scope of this document includes waste cover objectives and common cover components (Chapter 2), necessary site characterization requirements (Chapter 3) to develop an initial, site-specific cover design based on steady state models and assumptions (Chapter 4). The cover design is refined through an iterative process using transient numerical simulations, alternative designs and scenarios along with uncertainty analysis (Chapter 5) to optimize cover performance in the final cover design (Chapter 6), see Figure 1-2. Factors affecting the design life of the ET cover over the short- and long-term are discussed in Chapter 7. Monitoring methods for performance monitoring and LTSM are presented in Chapter 8 along with relevant case studies in Chapter 9.

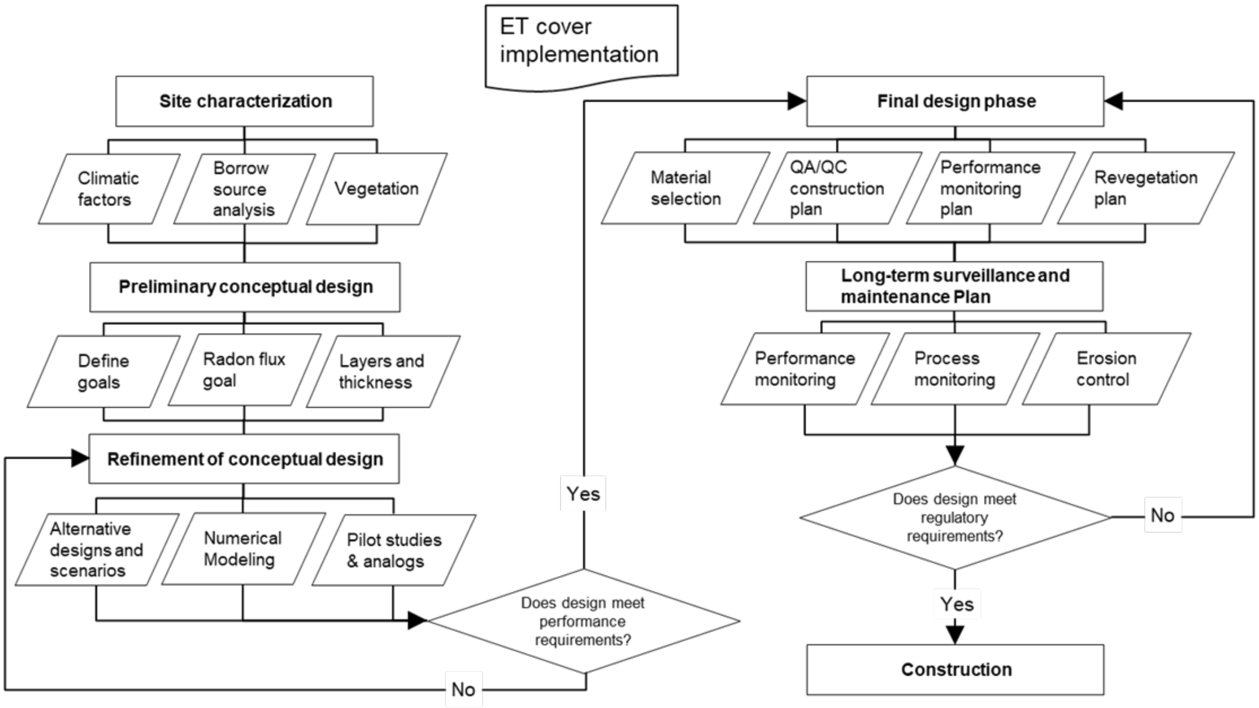

Figure 1-2 **Flow Diagram Outlining the General Implementation of an ET Cover System at a Disposal Site from Conceptualization to the Initial Construction Phase**

2 WASTE COVER OBJECTIVES AND DESIGNS

Waste cover systems are designed to isolate hazardous materials from the environment for some specified period of performance. For example, the design objective check list for long-term waste cover system at UMTRCA (DOE/UMTRCA, 1989) suggests that all reasonable cover components should:

- Provide erosion control (wind, surface water erosion, flooding, settlement),
- Limit infiltration into waste,
- Provide freeze-thaw protection,
- Inhibit emissions of hazardous gas to the environment,
- Drain and shed precipitation,
- Control biointrusion from roots and fauna, and
- Be self-renewing and minimize the need for long-term maintenance.

Conventional disposal of solid or hazardous waste in the United States requires a hydraulic barrier (e.g., geomembrane, compacted clay) to limit percolation water into the waste and inhibit mobilizing contaminants. A typical RCRA multi-layer soil cover system generally consists of at least 60 cm of either vegetated or armored soil, underlain by a granular or synthetic drainage layer with a transmissivity of no less than $3x10^{-5}$ square centimeters per second ($cm^2\ s^{-1}$), over a hydraulic barrier of compacted granular material or geosynthetic with a K_s no greater than 10^{-7} centimeters per second (cm/s; (EPA, 1989)). Under this guidance, site closure is reasonably assured over the 30-year lifespan of most sites (EPA 40 CFR 264, 2021). As such, a conventional cover is designed to meet a predefined regulatory limit of percolation using a material with low hydraulic permeability according to RCRA Subtitle C (hazardous waste) or Subtitle D (MSW) landfills, or radon-222 emissions for an UMTRCA site using a radon barrier. Compliance is implicit to the conventional cover design and its prescribed components.

By the mid-1990’s, the new paradigm for waste disposal facilities shifted from an emphasis on regulatory compliance to alternative closure designs and technologies (Caldwell and Reith, 1993). New landfill cover designs, particularly in semi-arid environments, were developed using ET covers consisting of multi-component soil layers and native vegetation that demonstrated beneficial performance over conventional covers at landfills across a variety of climates (Albright and others, 2013). However, there is no single ET cover design that can universally meet performance requirements for any specific site given the dependence of the cover design on local soils, vegetation, and economic constraints. Furthermore, the locality, risk of exposure, and climate for each site are necessary considerations in defining the pertinent components of a waste cover system. The use of a multi-component ET cover, if properly designed, constructed, and maintained, can provide long-term protection from gaseous radon emissions and release of contaminants to groundwater.

In many ways, UMTRCA covers are similar to ET covers at RCRA landfills, except that the UMTRCA hydraulic barrier is also used to control gaseous radon emissions. Given these similarities and the successful performance of ET covers at landfills, as well as at radioactive waste facilities (e.g.,Nyhan and others, 1997; Ward and Gee, 1997; Fayer and Gee, 2006; Zhang, 2016), DOE/LM is pursuing ET covers as an option to retrofit or adapt existing or planned UMTRCA sites.

2.1 Waste Cover Designs

Waste covers are designed to meet acceptable percolation rates and gas fluxes under achievable economic costs for construction, closure requirements, and long-term operations and maintenance. The current catalog of waste cover designs is based on the unique regulatory requirements for each waste stream.

2.1.1 Conventional Covers

Most landfills and other near-surface waste containment systems use single component or monolithic covers. Additionally, a geomembrane or composite liner may be placed between the waste and soil cover. Conventional covers may consist of a fine-grained, compacted soil having a prescribed maximum K_s or a composite barrier consisting of a thin synthetic geomembrane underlain by fine-grained soil (Albright and others, 2004). The fine-grained soil inhibits the downward percolation of precipitation into the underlying waste. Conventional covers are the simplest and lowest cost solution. When constructed properly, percolation can be limited to 2.8 millimeters per year (mm/*y*, 0.4% of the mean annual precipitation) across a range of climates; however, percolation rates can be significantly higher if the geomembrane is damaged during construction (Albright and others, 2013). Furthermore, the service life of linear low density polyethylene geomembranes is on the order of 50-125 years (Benson and others, 2011a).

2.1.1.1 RCRA Covers

Conventional covers specific to MSW landfills and disposal cells containing hazardous waste are regulated by EPA and are required to use RCRA covers to minimize infiltration into the waste. A cell is a discrete volume of a hazardous waste landfill which uses a liner to provide isolation of wastes from adjacent cells or waste. EPA (1989) recommends a multi-component design with a top layer of vegetated soil or rock for erosion and freeze-thaw control, a drainage layer, and two-component low-permeability layer consisting of a flexible geomembrane liner and compacted soil (Figure 2-1a). The implied design life of a RCRA cover is the 30-year post-closure period (EPA, 1989).

2.1.1.2 UMTRCA covers

The UMTRCA program has two basic cover designs at disposal sites that are either rock armored (Figure 2-2a) or vegetated (Figure 2-2b). The vegetated covers were not specifically designed as ET covers; the purpose of the vegetation is to reduce erosion. Both cover designs are underlain with a bedding layer of sand that protects the radon barrier and sheds excess water away from the waste. The soil moisture in the compacted clay impedes radon-222 diffusion by increasing the flow path length, or tortuosity, for long enough to allow radon-222 to decay to acceptable levels (DOE/UMTRCA, 1989). Radon diffusion from the uranium mill tailings is controlled by both the saturation of the compacted clay and the thickness of the barrier (DOE, 1989). See Waugh and others (2001) for an overview of UMTRCA covers.

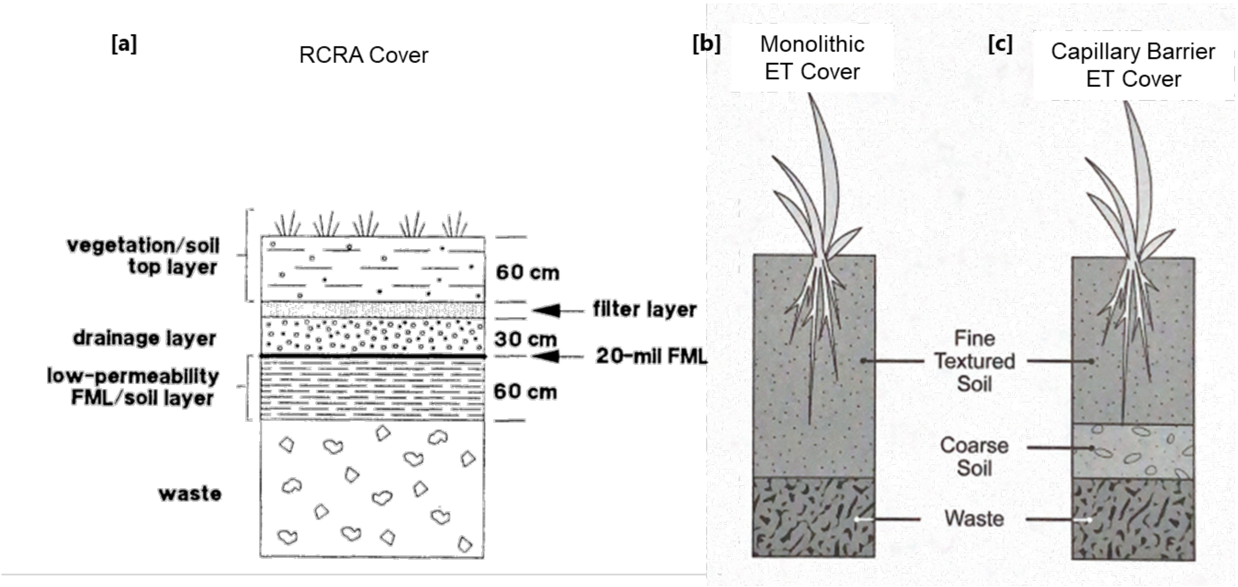

Figure 2-1 **[a] EPA Recommended Resource Conservation and Recovery Act (RCRA) Multi-Component Waste Cover Using a 20-mil Thick Flexible Membrane Liner and a 60 cm Layer of Low-Permeability ($<10^{-9}$ m/s) Compacted Soil (EPA, 1989). Alternative ET Covers are Either [b] Monolithic or [c] Use a Capillary Barrier. Adapted from Albright and Others (2010)**

2.1.2 ET Covers

In waste management, ET covers are referred to by several names including water storage covers and water balance covers. The design of an ET cover system is site-specific and dependent on its intended function. ET covers can be a single layer of soil called a monolithic ET cover (Figure 2-1b), two layers incorporating a capillary barrier (Figure 2-1c), or complex multi-layer systems that include synthetic materials (Albright and others, 2010; EPA, 2011). All ET covers function similarly by storing water in wet periods then releasing it to the atmosphere during drier periods through ET with the objective to minimize percolation (Albright and others, 2004). Unlike conventional covers that use low permeability layers, ET covers use a water storage layer (Chapter for 4.1 more information) that encourages infiltration and storage. The water storage layer must provide sufficient storage to retain enough accumulated moisture as to minimize percolation. During the growing season, vegetation rooted in the water storage layer photosynthesizes carbon dioxide from the atmosphere into sugars and oxygen, while transferring water from the root zone to the atmosphere through stomates on leaves. Roots generally remove all available soil moisture in a single season. Beneath the water storage layer, ET covers commonly use a coarse-textured (e.g., well-graded gravel) capillary barrier to retain moisture in the finer-textured root zone and limit percolation (Chapter 4.2 for more information).

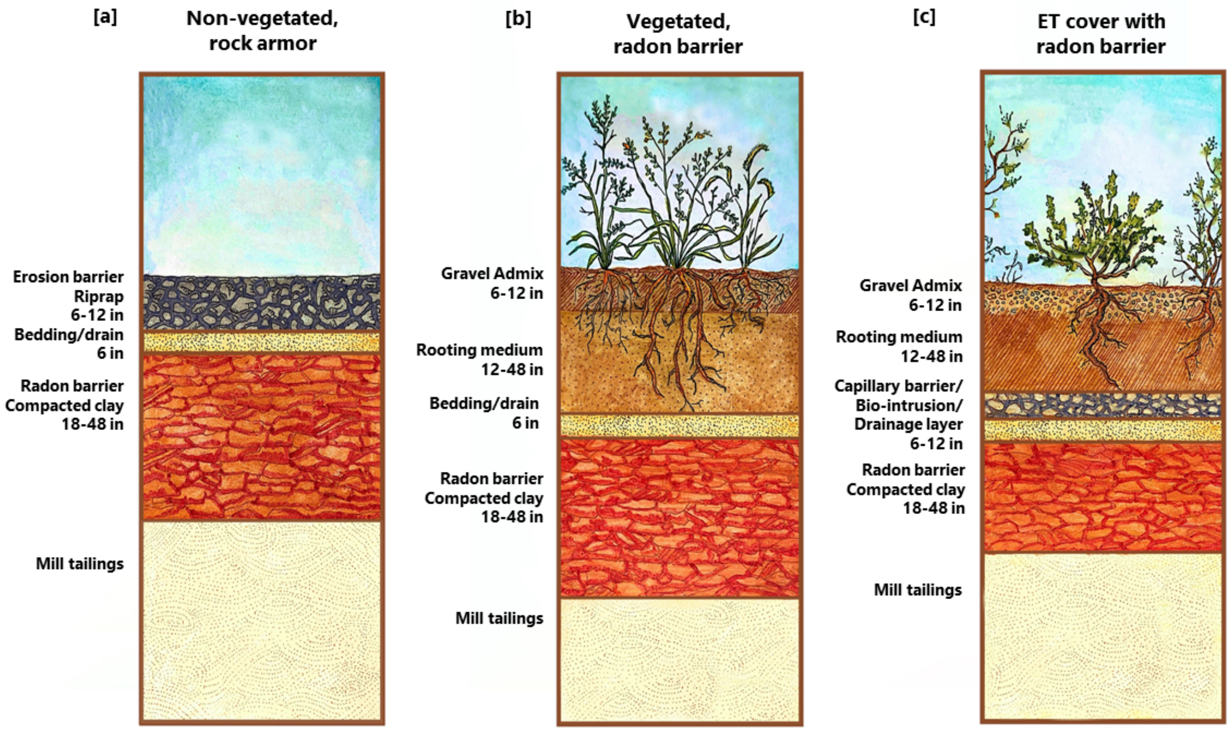

Figure 2-2 Existing UMTRCA Covers are [a] Rock Armored or [b] Vegetated Covers. In Either Case, a Thin Bedding Layer of Sand Protects the Radon Barrier and Serves as Drainage Layer. Either Could Potentially be Adapted to [c] a Multi-Component ET-Radon Cover System

2.2 ET Cover Components

Both monolithic and capillary barrier ET covers use a water storage layer. The primary function of a capillary barrier is to increase SWS in the water storage layer while also providing drainage and some biointrusion protection.

2.2.1 Water Storage Layer

The water storage layer is the most critical component of an ET cover. Deep percolation can be controlled to an acceptable limit by selecting a soil that provides sufficient infiltration capacity to minimize surface runoff (and erosion), sufficient water storage capacity to retain the infiltrated water, and a rooting media to sustain active vegetation with sufficient transpiration capacity to remove any stored water (Apiwantragoon and others, 2015). The thickness of this layer is determined by the target soil hydraulic properties of the source or borrow soil, the estimated storage based on rainfall and climate, and the characteristics of the vegetation (Ward and Gee, 1997). It is common to add a gravel-admix layer to the top of the water storage layer to minimize erosion from wind and water, particularly while vegetation is becoming established (Waugh and others, 1994b). Guidance on the water storage layer is presented in Chapter 4.1.

2.2.2 Capillary Barrier

A capillary barrier or capillary break, below the water storage layer, creates a "fine-over-coarse" soil layer. While counterintuitive, the coarser-grained material under finer-grained soil reduces downward percolation; the equilibrium capillary pressure at the interface creates an order of magnitude lower unsaturated hydraulic conductivity in the coarser material (Nyhan and others, 1990). In essence, the finer-grained layer must approach saturation before water will enter the larger pores of the coarser-grained soil once the air-entry potential is exceeded. As such, the finer-grained soil retains more moisture. In an ET cover, the capillary barrier increases SWS in the rooting layer where it can be removed though ET. A capillary barrier provides several protections over a monolithic ET cover [from Nyhan and others (1990)]:

1. Soil water is retained in the upper fine-grained layer and more likely to be transpired.
2. Restricts plant roots from growing through the gravel barrier and potentially accessing waste.
3. Any percolation entering the coarse-grained layer can be removed by drains placed at the base of this layer.

Further guidance on capillary barriers is presented in Chapter 4.2.

2.3 UMTRCA Cover Components

Like other conventional covers, UMTRCA covers have a common formula that consists of a few key components: a surface erosion barrier of either rock armor or vegetation, a bedding layer, and a radon barrier. Table 2-1 presents the cover components found at each UMTRCA disposal site. The barrier component thicknesses are presented from the radon barrier atop the mill waste up to the surface rock or topsoil.

2.3.1 Erosion Barrier

Erosion is a common concern for any waste cover system (Walters and Skaggs, 1986). Bare flat soil surfaces are prone to erosion and gullying from sheet flow whereas side slopes of the apron are more subject to gully erosion by focused drainage channels. Tunneling erosion around drainage systems and diversion channels can be difficult to control and stabilize (DOE/LM, 2020a). Rock armor is a layer of durable rock to help shed the energy of falling rain, promote long-term stability, design for low maintenance, and meet radon release limits (Johnson, 2002). A rock amor layer of 30 cm (12 inches) is present on the surface of most UMTRCA covers (Table 2-1). In some situations, a rooting media of topsoil, often around 30 cm (12 inches) thick, is used to encourage vegetation growth to stabilize the surface, but not designed to function as a water storage layer.

2.3.2 Frost Barrier

Frost protection may be needed in colder regions where freezing temperatures can penetrate deep into the soil and cause frost heaving. A frost barrier is simply additional soil or fill that buffers the radon barrier from frost penetration. Northern or high elevation UMTRCA covers have frost barriers that are typically several feet thick. Rooting media in the erosion barrier provides some frost protection. The design frost depth is the maximum distance measured downward from the surface into a moist soil with a temperature at or below freezing which is based on climatic factors presented in DOE/UMTRCA (1989).

Table 2-1 Existing UMTRCA Disposal Site Details Including Cell Design, Existing Barrier Components and Slope of the Surface and Apron

					Barrier Component thickness [in]						Slope	
Site Name	**Radium-226 [Curies]**	**Site [Acre]**	**Cell [Acre]**	**Height [ft]**	**Radon**	**Bio[1]**	**Frost**	**Bed[2]**	**Rock**	**Top-soil**	**Surface**	**Apron[3]**
Title I Disposal Sites												
Ambrosia Lake	1,850	290	91	50	30			6	6		2.5%	20%
Burrell	4	72	4		36			12	12		3.0%	33%
Canonsburg	100	37	6		36			18		12	3.0%	20%
Durango	1,400	120	42		24	18	30	6	6			
Falls City	1,277	231	127	62	24			6	6	30	1.0%	20%
Grand Junction	571	360	94	40	24		24	6	12		2.3%	20%
Green River	30	22	6	0	36			6	12			20%
Gunnison	175	115	29	50	18		72	6	6		2.5%	
Lakeview	42	40	16		18			6	18		3.0%	20%
Lowman	12	18	8		18			6	12		10.0%	20%
Maybell	455	250	66		18		48	6	8		3.0%	20%
Mexican Hat	1,800	119	68	50	24			6	8		2.0%	20%
Naturita	79	27	9		36		66	6	12		4.0%	
Rifle	2,738	205	71		18		144	6	12		8.7%	20%
Salt Lake City	1,550	99	54	35	84			6	24		2.0%	20%
Shiprock	746	105	77	48	76			6	12		3.0%	20%
Slick Rock	149	62	12	50	18		24	6	8		3.0%	20%
Spook	125	14	5		18			120			3.0%	
Tuba City	940	145	50	44	48			6	18		3.5%	20%
Title II Disposal Sites												
Bluewater	11,200	3,300	354		20				12			20%
Edgemont	527	360	100		36			60		12		
L-Bar		738	100		49					48		20%
Maybell West	95	180	72	75	48			6	12		20.0%	
Sherwood	470	380	100		192				6	6		
Shirley Basin South	974	1,512	142	35	24		24			10		
				Median:	24	18	39	6	12	12		
				Minimum:	18	18	24	6	6	6		
				Maximum:	192	18	144	120	24	48		
				Number:	25	1	8	21	20	6		

[1]Bio, biointrusion layer; [2]Bed, bedding layer; [3]Apron, side-slopes of the cover.

2.3.3 Bedding and Drainage Layers

The integrity of the radon barrier is crucial to minimize emission of radioactive biproducts. The bedding layer is a thin layer of homogeneous sand that protects the radon barrier from the overlying erosion control layer (gravel or riprap). The bedding layer can be gently sloped to provide secondary function as a drainage layer to shed infiltrated water away from the radon/infiltration barrier. UMTRCA covers commonly use a 15-cm (6-inch) bedding layer over the radon barrier. In multi-component conventional covers, a drainage layer consisting of uniform sand or gravel is placed on top of an infiltration layer to help shed excess water away from the waste. More specifically, EPA 40 CFR 264 (2021) specifies that the layer must be constructed of granular drainage materials with a K_s greater than 1 mm/s, a thickness in excess of 30 cm (12 inches), and with a bottom slope of one percent or more for a drainage or leachate collection layer at hazardous disposal sites.

2.3.4 Biointrusion Barrier

The degree of potential biointrusion is more pertinent in humid and subhumid climates, and environmentally related to the presence of local deep-rooted plants and burrowing mammals and invertebrates. Biointrusion barriers are layers of poorly-graded cobbles or rock to impede root growth and digging. As shown in Table 2-1, biointrusion layers are not present at existing UMTRCA sites except for the Durango site.

2.3.5 Radon Barrier

Radon-222 gas moves primarily by molecular diffusion from high to low concentrations through air-filled soil pores (Nazaroff, 1992). A radon barrier is a homogeneous, compacted clay or fine-grained material of sufficient thickness and moisture content to allow substantial decay of radon-222 during its diffusion upwards in the barrier (Nelson and others, 1980). Soil water acts as an obstruction to gas flux increasing the tortuosity and travel time of the gas. Thus, a radon barrier must remain moist and be intact to meet the emission criteria. To protect the radon barrier's integrity and help retain soil moisture, an overlying layer of rock material can be used as a capillary barrier; this layer also prevent the upward migration of water and salt from the tailings to the soil surface (Simmons and Gee, 1981). Most UMTRCA covers use a 30 to 61 cm (12 to 24 inch) thick layer (Table 2-1) of clay compacted to greater than 85% Proctor density (a standardized measure for compacting soil material before construction) (Rogers and others, 1984); thus, essentially functioning as both a radon and infiltration barrier. Placing moist, compacted soil at a depth below three feet helps prevent long-term desiccation and de-densification of the compacted clay, which by design has a high residual moisture content (Gee and others, 1984).

For conventional waste covers, infiltration or hydraulic barriers reduce the flux of precipitation into the waste by diverting it away. These layers are made by compacting fine-grained soil, bentonite-amended sands, or using a geomembrane to create a layer of low permeability. Note, bentonite can induce shrink/swell behavior and geosynthetics are not ideal for the anticipated life-span of an UMTRCA cover. Similarly, EPA 40 CFR 264 (2021) specifies that the lower component of a hazardous waste cover must be constructed of at least one meter of compacted soil material with a hydraulic conductivity of less than 10^{-9} m/s.

2.4 Commonalities Between Cover Components

For existing UMTRCA disposal sites, there are some common components in place that could be integrated into an ET-radon cover system (Figure 2-2c). Rock armored covers function as biointrusion barriers. This layer, and the bedding layer beneath, would effectively serve as a capillary barrier, which would increase SWS in the water storage layer that could potentially be placed above. The water storage layer would provide additional frost protection and provide some additional radon-222 attenuation.

3 SITE CHARACTERIZATION

The first phase of any waste cover design process is site characterization to determine key design factors related to weather, available materials for construction, and local vegetation. Previous site assessments, past performance evaluations, and collaboration with LTSM experts are helpful for identifying sites with potential for ET cover adaptation. A new Title II site would ideally follow similar site characterization protocols already developed. Under UMTRCA, the requirements for proposed remedial action at disposal sites include evaluations of geologic suitability (e.g., stratigraphic, structural, and geomorphic setting, along with seismicity), and geotechnical stability of tailings embankment and the cover design (including slope stability, settlement, liquefaction susceptibility, and proposed cover design). Three additional factors are required to incorporate an ET cover onto a conventional radon barrier: a more detailed assessment of climate variability and extremes, borrow soils capable of sustaining vegetation, and knowledge of existing or desired vegetation on the cover. Cover systems constructed at existing long-term disposal sites are well-documented, and information is available through DOE/LM including quality control during construction, waste concentration and quantity, and borrow sources.

3.1 Climate and Weather

The design and efficacy of an ET-radon cover system are dependent on local climate, soil properties, and vegetation. Initial water storage layer thickness (Chapter 4.1 for more detail) requires long-term climate data whereas performance assessments, using numerical simulations, require long-term meteorological data (Chapter 7.7 for more detail). Climate is the long-term average weather of a specific region, while meteorology or weather refers to short-term, actual atmospheric conditions at a specific time.

Climate or climatology normals are defined as the 30-year average, maximum, minimum, and standard deviation of meteorological conditions, which includes precipitation (rain and snow) and air temperature computed hourly, monthly, or annually using direct, quality-controlled measurements or models (Arguez and others, 2012). For example, 30-year normals in the Parameter-elevation Regressions on Independent Slopes Model (PRISM) geospatial datasets (precipitation, temperature, vapor pressure deficit) are continuous fields produced at either 4 km or 800 m over the U.S. (Daly and others, 2008).

Station quality requires routine maintenance and upkeep while data quality relies on quality control measures that are traceable and well-documented. Erroneous data are often not reported in meteorological records which can contain missing data or gaps. Any weather data source should meet World Meteorological Organization standards for data collection (WMO, 2008). Several established networks exist including the National Oceanic Atmospheric Administration’s U.S. Climate Reference Network (Bell and others, 2013), the U.S. Department of Agriculture’s SNOTEL (Snowpack Telemetry) and SCAN (Soil Climate Analysis Network) networks (Schaefer and Paetzold, 2001), Historical Climatology Network (Menne and others, 2009), and state mesonets (Mahmood and others, 2017). It is critical to note the environmental setting of any climate station prior to its use. Several western U.S. networks, for example the California Irrigation Management Information System and the AgriMet Cooperative Agricultural Weather Network, are not appropriate as they are located near irrigation or over well-watered reference grass either of which can depress the vapor pressure deficit and potential ET.

Improved sources of continuous, both spatially and temporally, weather data are produced by blending station data with remotely sensed data and numerical models to create continuous, gridded data fields. These products are used in various land surface models, come in different spatial and temporal resolutions, and are generally long-term (starting in 1980). Three commonly used data sources are described below. Each of these contain data sufficient to integrate into most soil-water balance models (Chapter 5 for more detail) that require precipitation and potential ET.

3.1.1 North American Land Data Assimilation System (NLDAS)

The NLDAS data archive contains 11 variables at an hourly (and monthly) timestep from 1979 to present over the conterminous U.S. (Mitchell and others, 2004). The dataset includes precipitation, air temperature, long- and shortwave radiation, wind speed at 10 m, and absolute humidity at 2 m (Xia et al., 2012). The data are gridded at 1/8° (~16 km) spatial resolution and available at https://ldas.gsfc.nasa.gov/nldas/v2/forcing. The files are disseminated in General Regularly-distributed Information in Binary form (i.e., GRiB) hourly files, which can be cumbersome to manage for a single site. Note, potential ET in NLDAS Forcing A Data is the modified Penman scheme of Mahrt and Ek (1984) which could be used directly in vadose zone models that need potential ET. NLDAS is operational with a latency of 50 hours.

3.1.2 GridMET

GridMET is a regional-scale (4 km) reanalysis of NLDAS using daily gauge-based precipitation that is used to derive a spatially and temporally complete daily gridded dataset of surface meteorological variables for the contiguous U.S. from 1979 to present (Abatzoglou, 2013). GridMET downscales NLDAS data from 16 to 4 km using elevation correlations derived from PRISM dataset. GridMET provides daily maximum and minimum temperature, precipitation, shortwave radiation, mean wind-speed, maximum and minimum humidity, specific humidity, and grass-reference ET as a derivative product. Data are available at http://www.climatologylab.org/gridmet.html for direct download in Network Common Data Form (NetCDF) format. GridMET is operational and updated soon after NLDAS is posted.

3.1.3 Daymet

Daymet is a collection of 1 km gridded estimates of weather data from 1950 to 2020 over the conterminous U.S. Daymet relies on elevation data and discrete observations of maximum and minimum temperature and precipitation from ground-based meteorological stations. Output parameters include daily surfaces of maximum and minimum temperature, precipitation, humidity, and radiation. The Daymet model is based on (Thornton and others, 1997) and maintained by Oak Ridge National Laboratory (http://daymet.ornl.gov). Daymet is updated annually, usually by the following spring, and files are in annual NetCDF format.

All the above datasets are large volumes of data and can be challenging to manipulate and manage. Fortunately, simpler tools or Application Programming Interfaces (API) are available to access these data (e.g., Google Earth or CUAHSI). NASA Earth Data is currently offering Data Rods that allow the extraction of a time series variable at a single coordinate point (Teng and others, 2016). Another option for GridMET is Climate Engine (Huntington and others, 2017), which also allows for an easy extraction of time series or climatology data by a point location (https://app.climateengine.com/). Tools are constantly evolving (https://climatetoolbox.org/) and processing scripts are available in various GitHub repositories. Lastly, the Weather Tools for Retrospective Assessment of Restoration Outcomes was developed to provide climatology assessment for rangeland restoration efforts after wildfire (Moffet and others, 2019). The Application Programming Interface (API), available at http://www.grazing.okstate.edu:3838/RangeTools/ClimateReport/, produces (1) a detailed annual/monthly climatology report based on historical Gridmet data, (2) weather files extracted directly from Gridmet, and (3) numerical simulation of soil temperature and matric potential (ψ) at 2 cm using the Simultaneous Heat and Water model.

The resources described above are useful for the long-term geoclimatic design of ET covers, documenting extreme historical events, and as weather inputs for numerical models. Some caution with API services is needed. Some of these tools may reproject coordinates or perform aggregation of the original datasets. Any data should be fully traceable and reproducible, regardless of how it was obtained.

3.2 Borrow Sources

The source of materials (i.e., borrow source) for constructing an ET cover, or the adaptation or construction of an ET-radon cover system, must maximize functionality while remaining economically viable. The design of an ET cover is a process involving the following three-steps: 1) assess borrow source quantity and material characterization, 2) develop engineering specifications for the transport, storage and placement of the borrow on the cover, and 3) develop a construction quality control plan (ITRC, 2003). Transport and quality control considerations are presented in Chapter 6.1. The borrow source is particularly important when designing an ET cover since it must support biologic activity while remaining economically feasible. The ideal borrow source for the water storage layer has similar physical and chemical properties to a natural analogue site in the region of the facility. The other components of an ET cover are generally more common in the vicinity of disposal facilities and defined more by particle size than anything else.

A water storage layer should be constructed from soils with desirable water-retention characteristics and meet agronomic requirements to support a resilient plant community. Ideal soil should have a loamy texture to facilitate optimal infiltration capacity, storage, and plant-available water (DOE, 1989). Soil should retain 30 percent or more of its weight in water at field capacity, but will release all but 10 percent to plants at the wilting point (DOE, 1989). Soils deficient in nutrients or high in sodium should be avoided. The selected rooting medium should be as close as possible to the naturally occurring soils that the desired plant community inhabits (Valceschini and Norris, 1997). Material testing may include grain size distribution, saturated hydraulic conductivity, soil water retention function, water holding capacity, tilth, pH, cation exchange capacity, available nutrients, organic matter, and sodium content. Similar analyses should be conducted on soils from the natural analogue (Chapter 3.3) location to ensure the soil ephaptic conditions will be consistent. Incorporating pea-sized gravel (admix) into the top 6 to 12 inches of the water storage layer is commonly done to add erosion control until vegetation is established. Any rock materials should be resistant to chemical and physical weathering. Ideally, the surface cover should be thick enough to accommodate animal burrowing and tunneling, and deep-rooted vegetation – estimated from natural analogues.

A capillary barrier should be constructed from material that is coarser than the water storage layer. For an existing radon barrier, the riprap and bedding layer materials, where applicable, could be repurposed as a capillary barrier. Material tests should include particle size distribution, soil water retention function, hydraulic conductivity, and carbonate content. Carbonate materials, which are slightly soluble in water, may reduce hydraulic conductivity, if present in excessive amounts. The capillary barrier material should be clean (i.e., minimal silt or clay) sands and gravels to create a distinct change in pore-size.

A bedding or drainage layer should be constructed of material that has a high hydraulic conductivity and is resistant to plugging or clogging (i.e., lacks carbonates and fines). Appropriate borrow material may include clean and well graded sand, pea gravel, or other well-graded coarse materials. Any bedding or drainage layers must also be clean because the addition of just a few percent fine material can reduce the drainage layer’s hydraulic conductivity by 100 fold or more (Cedergren, 1989). Material tests should include particle size distribution, hydraulic conductivity, and carbonate content. The materials for the drainage layer are more often obtained from a commercial supplier. If borrow materials are available, processing by sieving and washing to remove oversized particles and fines may be necessary.

Any biointrusion layer should be constructed from cobble-size rock with a low coefficient of uniformity. Aggregate sources may be found in alluvium deposits, including river valleys and terraces. The rock material should be resistant to chemical and physical weathering. Additional material testing should be performed to confirm the chemical composition and structural integrity of the borrow material.

A radon barrier is generally constructed from soils that contain significant quantities of inorganic clay (C); soils classified as low plasticity clay (CL), high plasticity clay (CH), or clayey sands (SC) in the Unified Soil Classification System and ASTM D-2487. These soils are characterized by low hydraulic conductivities and high water-retention properties. Sources of such materials may include lacustrine deposits, glacial tills, aeolian materials, and residual soils. If available borrow soils are not sufficient in clay content, soils can be modified by blending with bentonite to obtain the desired hydraulic conductivity. However, bentonite can have an extremely high swelling potential particularly when exposed to low electrolyte solutions such as those found in native soil pore-water. To ensure that construction specifications will be met, material tests on borrow soils should include water content, Atterberg limits (liquid, plastic, and shrinkage water content limits), particle size distribution, compaction curve, and saturated hydraulic conductivity (Zornberg and others, 2003). These tests provide information on the optimum water content that is necessary to obtain the desired soil plasticity.

3.3 Representative Vegetation and Natural Analogues

The performance of an ET cover is directly linked to the species, vigor, plant cover, and root distribution of the vegetation (Jarchow and others, 2020). The goal of a vegetated cover is to mimic nature, which is essentially how to design for perpetuity (Caldwell and Reith, 1993). To effectively immobilize and isolate waste for millennium, the cover should mimic a proximal stable geomorphic landform, as well as the vegetation and soils intrinsic to it. Choosing such a location requires some knowledge of the area and its geologic history. Pragmatically, it could be a location that represents the intended trajectory of the cover over the short-term (less than 50 years) or the long-term.

Over the short-term, an ecological reference site, or natural analogue, aids in the evaluation of potential vegetation types and their potential performance on the borrow soil. The ideal natural analogue site should be chosen to share similar parent material, biota, relief, and climate as the disposal site. The natural analogue can be used first to aid cover design in regard to vegetation, target bulk densities, and necessary soil amendments needed for the borrow soil (Waugh and others, 1994a). Revegetation plans are one of the most critical components of an ET cover and the best metric of the potential performance is using natural analogues.

An analogue site can also be used for long-term vegetation monitoring to ensure that plant vigor on the cover is similar to the analogue (Chapter 7.7.3). Over time, changes in vegetation biomass and diversity will occur (Hamerlynck and others, 2002; Breshears and others, 2005; Shafer and others, 2007). Furthermore, a natural analogue can be used to inform long-term trends as soils develop on the cover (Williams, 2019).

An analogue also provides evidence of changes in past environments that can be applied to evaluate the future performance of engineered barriers (Waugh and others, 1994a). Natural analogue studies can provide information about processes affecting covers that cannot be fully explored through laboratory experimentation and modeling because of the extended period of required performance (Chatters and others, 1990). In soil pedology, a chronosequence is a spatial sequence of soils in which the only factor of soil formation that is significantly variable is time (Phillips, 2015). For example, sequences of alluvial fan deposits were used to study the effect of soil develop on hydraulic properties over geologic time (Young and others, 2004; Caldwell and others, 2012). A space for time substitution is used to isolate the impact that temporal change has on soil morphological properties responsible for regulating engineering performance, specifically hydraulic conductivity, gas diffusivity, and erosivity (Shafer and others, 2007; Williams, 2019). Covers should be designed to mimic the natural soil-water balance of natural analogues, with a goal of sustaining performance with little or no maintenance. In addition, vegetation performance over time can be better assessed if a natural analogue is available for direct comparison and to guide revegetation goals. Finally, any proximal geomorphic surface that has been stable over geologic time provides lessons on proper design for interminable performance (Caldwell and Reith, 1993).

4 PRELIMINARY ET COVER CONCEPTUALIZATION

Reliance is commonly placed on the natural system to isolate contaminants at waste sites in the arid west (Andraski and Prudic, 1997). Arid and semiarid conditions favor ET covers that can effectively store and release precipitation back to the atmosphere rather than the conventional approach of using restrictive layers of low permeability to slow or shed water away. Conventional covers have a distinct advantage in that they are designed upfront to meet regulatory requirements based on strict engineering principles. On the other hand, the design of an ET cover is more organic and requires different philosophical approach (Caldwell and Reith, 1993). The initial conceptualized design is based on simple hydrological principles. The initial design is then refined and evaluated using models and data-driven methods to determine the cover performance that meets or exceeds the performance of a conventional cover. This chapter documents the conceptualization of an ET cover design using steady-state models and analytic solutions. Specific considerations are given to UMTRCA sites. Chapter 5 refines this design through transient numerical modeling, uncertainty analysis, and pilot studies.

4.1 Water Storage Layer

The primary design considerations for an ET cover include the cover thickness and slope, soil edaphic properties, soil hydraulic properties, vegetation properties, and expected meteorological conditions (McCartney and Zornberg, 2006). Generally, EPA (2011) recommends that ET covers be constructed with water storage layers ranging from 0.6 to 3 meters (2 to 10 feet) in thickness; but this may be reduced to 0.15 to 0.6 meters (0.5 to 2.0 feet) when there is also a capillary barrier. The performance objective of an ET cover is to minimize percolation by allowing ET to naturally remove stored water. An ET cover generally consists of a thick, fine-textured water storage layer over a thin coarse-textured capillary barrier. The capillary barrier increases water storage capacity above by reducing the drainage potential, as discussed later. The required SWS is based on the difference between the historical precipitation and potential ET data. In cold climates, where transpiration is negligible in winter, required SWS must account for periods when precipitation exceeds ET (ITRC, 2003). However, these quantities are better defined through transient models in the refinement stage. For early conceptualization, a starting point is simply to have enough SWS to accommodate local mean annual precipitation at a minimum.

The storage capacity of any soil is determined by available pore space between field capacity and wilting point, generally obtained from the van Genuchten (1980) soil water retention function (Figure 4-1a) as:

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{(1 + |\alpha\psi|^n)^m} \qquad \text{Eq. 1}$$

where θ_r and θ_s are the residual and saturated water contents (m^3/m^3), respectively; α (m^{-1}) is an empirical parameter related to the inverse of air-entry pressure of the soil; ψ (m) is the absolute value of soil water pressure head; and n (-) describes pore size distribution where $m = 1 - 1/n$.

The unsaturated hydraulic conductivity function [$K(\psi)$], as shown Figure 4-1b, is then:

$$K(\psi) = K_s \frac{[1 - (|\alpha\psi|)^{mn}[1 + (|\alpha\psi|)^n]^{-m}]^2}{[1 + (|\alpha\psi|)^n]^{ml}}$$ Eq. 2

where K_s is the saturated hydraulic conductivity (m/s), and l is an empirical pore connectivity parameter that is assumed to be 0.5.

Plants will remove water until capillary forces in the soil are greater than those in the plant and transpiration ceases. The SWS of a water storage layer can be estimated by integrating over the total depth (x) of the soil layer as:

$$SWS = \int_0^x \theta dz = x\big(\theta(\psi_{fc}) - \theta(\psi_{wp})\big)$$ Eq. 3

Soil water typically drains from the largest pores until the capillary forces create enough hydraulic head to overcome gravity. Field capacity is specified as the maximum θ retained after gravity drainage which is estimated by a ψ of -33 kPa (~3.5 m of water or ψ_{fc}). Wilting point is the minimum θ at which vegetation can sustain root-water uptake which is estimated at a ψ of -1,500 kPa (~150 m of water or ψ_{wp}). It should be noted that while field capacity is considered a static property, soils at or below field capacity continue to drain (Assouline and Or, 2014). Drought tolerant vegetation in warm deserts can survive xylem water potentials of nearly -5,000 kPa (Hamerlynck and others, 2002) and evaporation can reduce soil moisture to well below $\theta(\psi_{wp})$. Figure 4-1a shows the available storage (0.27 – 0.07 = 0.20 m^3/m^3) of a hypothetical silt loam loosely compacted to 1.4 g/cm^3. Assuming the layer is 0.9 m (~3 ft) thick, the SWS would be 180 mm. Annual potential ET commonly exceeds 1,000 mm in most arid and semi-arid regions and can effectively empty SWS capacity over a single growing season; however, 2 m of soil depth is recommended to provide adequate protection for extreme years (Anderson and others, 1993).

If necessary, the water storage layer should include barriers to burrowing animals or invertebrates as well as vegetation roots. Negative impacts include erosion of soil displaced to the surface as well as compromising waste containment. The potential impact of burrowing animals and invertebrates, and plant roots, could be evaluated as part of what is referred to as a baseline ecological survey. Albright and others (2010) note that an ideal ET cover would be thicker than the burrowing depths and vegetation root depths that could be expected at the site. They also note that clean rock layers placed below the water storage layer, or at the surface, may also be effective in deterring some burrowing animals. The surface of the water storage layer must be protected from erosion while vegetation is growing and becoming established. Waugh and others (2006) performed a lysimeter study at an ET cover at the Monticello, Utah, Superfund site and observed that it was not until vegetation had become well established that drainage was minimized. Another important consideration is compaction of the cover. Specifically, the cover soil should not be over-compacted during construction, as high bulk densities are detrimental to total SWS and root development. McGuire and others (2009) specified an ET cover construction goal was to achieve compaction on the cover surface that was not greater than about 80% of the Proctor dry density. Section 5.3.1 of ITRC (2003) provides recommendations to achieve the optimal soil density for an ET cover including cover placement equipment and methods. Section 5.3 of ITRC provides guidance on vegetation establishment methods including the use of fertilizer and irrigation. ET covers in arid and semiarid regions effectively remove SWS annually; however, establishing the vegetation from seed or seedling using natural precipitation alone may not be enough. The quantity and timing of water is critical to the revegetation of the surface and would likely require some form of irrigation. Section 5.3.4 of ITRC (2003) provides detailed guidance on the different irrigation systems that could be used to irrigate these revegetated areas during the vegetation establishment phase.

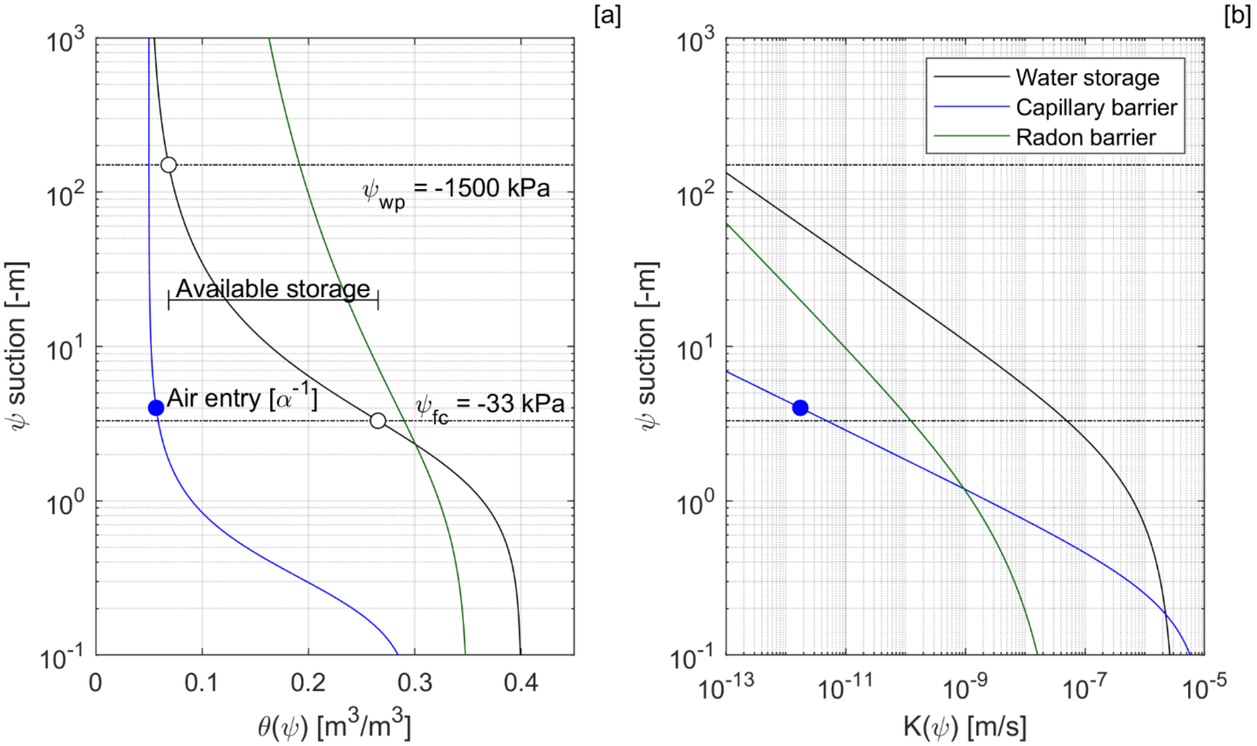

Figure 4-1 [a] Soil Water Retention, θ(ψ) and [b] Hydraulic Conductivity, K(ψ), for a Silt Loam Water Storage Layer, Coarse Capillary Barrier, and a Clay Radon Barrier

4.2 Capillary Barrier

A capillary barrier or capillary break in an ET cover is a coarse-textured layer beneath a finer-textured water storage layer. The contrast in pore-sizes limits downward migration of percolating water by exploiting the continuity interface pore-water pressures and the disparity in K(ψ) between layers. EPA (2011) recommends a capillary break to be a coarser-grained layer ranging in thickness from 0.5 to 2 feet. The coarse-textured capillary barrier has large pores which easily drain when ψ approaches air entry potential (α^{-1}) or -4 m as indicated by the blue dot in Figure 4-1a. At this point on the hydraulic conductivity curve (Figure 4-1b), the unsaturated conductivity has dropped to 10^{-12} m/s because water flux is limited to a very small pore-sizes. Pore-water pressures at the interface between the water storage layer (fine) and capillary break (coarse) are equivalent (Khire and others, 2000); however, the values of θ is quite different. At the equivalent interface matric potential (ψ^*) of -4 m, which is just below field capacity, the water storage layer maintains a much higher θ (~0.25 m^3/m^3). The barrier conductivity is 4 orders of magnitude lower than the water storage layer's, which is 10^{-8} m/s. The flux into the barrier can only occur once ψ exceeds air-entry potential at which point it remains extremely low and moisture remains in the water storage layer longer, allowing more time for ET to remove it.

Combining equations 1 and 3, Stormont and Morris (1997) created a more precise analytic expression of SWS to account for the additional storage capacity derived from the presence of a capillary barrier beneath a soil layer:

$$SWS = \theta_r x + (\theta_s - \theta_r)\int_0^x (1 + [\alpha(z + \psi^*)]^n)^{-m} dz \qquad \text{Eq. 4}$$

Assuming ψ* is -4 m and the soil water storage layer is 0.9 m thick, SWS increases from 180 mm (Eq. 1) to 214 mm. While steady-state solutions can be good first approximations, numerical simulations can further refine site-specific needs.

Note that the discussions in Chapter 4.1 and 4.2 are applicable to the initial conceptual design of an ET cover, as well as to the adaption of an ET cover at an existing disposal site. The soil layer and capillary barrier (if present) may be placed directly over the waste, which may already have existing cover components such as rock armor or geomembranes.

4.3 Bedding and Drainage Layers

The bedding and drainage layers protect the radon barrier during the emplacement of the erosion barrier and shed excess water laterally away from the radon barrier. Drainage layers typically have a fines content (particles pass a No. 200 sieve or <0.07 mm in diameter) of less than 5% while also passing through a 3-inch (7.6 cm) sieve (Johnson, 2002). Most UMTRCA covers have a six-inch bedding layer (Table 2-1) of well-graded sand and gravel.

4.4 Radon Barrier

As discussed in Chapter 2.3.5, radon barriers are designed to attenuate the radon-222 flux from the mill tailings as it diffuses through the radon barrier toward the surface. A radon barrier has three key design properties (Gee and others, 1984) including:

1. sufficient compaction to greater than 85% Proctor density,
2. adequate soil moisture to impede radon transport, and
3. sufficient thickness to allow decay.

The movement of gas within a porous media such as soil is a combination of molecular diffusion and convective mass flow (Troeh and others, 1982). Convective transport is controlled by pressure gradients related to meteorology like atmospheric pressure and rain which can increase or decrease radon flux (Schery and others, 1984). Net convection is negligible over time (Holford and others, 1993). Much of the diffusion theory for radon transport is based on empirical models derived from repacked laboratory cores and gas flux measurement under ideal conditions. The influence of soil structure and soil cracking on diffusion coefficients as radon barriers mature is presented in Chapter 7.6.

The relatively slow rate of diffusion through moist soil is due in part to the reduced volume available for gas movement and increased path lengths, or tortuosity, the gas molecules must follow. Compaction is necessary to minimize available porosity (φ) which decreases the radon diffusion coefficient (D_c) of the radon barrier while also reducing K_s and increasing capillary forces that retain soil moisture in the barrier. A successful radon barrier requires uniform pore size distribution to ensure slower, diffusion-only transport within the barrier.

Adequate soil moisture ensures that most pores are mostly water-filled, thereby hindering gas transport. The degree of saturation ratio (S_w) is an index of the water-filled porosity, ranging from 0 (dry) to 1 (saturated):

$$S_W = \frac{\theta}{\varphi} \qquad \text{Eq. 5}$$

where θ is in m^3/m^3 and φ is the total available porosity of the material (m^3/m^3). Gas transport in soil is generally considered a diffusion process controlled by Fick's first law, the gas diffusion coefficient in free air (D_0), and the diffusion coefficient in soil or cover (D_c); both in units of $m^2\ s^{-1}$. Penman (1940) introduced the following steady-state empirical model, which was validated in the laboratory using a brass diffusion apparatus filled with granular solids:

$$D_c = 0.66 * D_0 \varepsilon \qquad \text{Eq. 6}$$

where ε is the air-filled porosity (m^3/m^3) and is related to S_w by:

$$\varepsilon = (1 - S_w) * \varphi \qquad \text{Eq. 7}$$

Millington and Quirk (1961) combined the characteristic length factors from Penman (1940) and added a spherical pore factor resulting in the following relationship:

$$D_c = D_0 \frac{\varepsilon^{10/3}}{\varphi^2} \qquad \text{Eq. 8}$$

According to Eq. 8, diffusive flow is proportional to the 10/3 power of the air-filled porosity and has become the most well-established formulation of gas diffusion (Moldrup and others, 2000a).

Rogers and others (1984) developed an empirical relationship for radon transport using sieved and repacked (i.e., unstructured) soil cores over a range of S_w and compaction densities such that:

$$D_c = 0.07 exp\left[-4S_w\left(1 - \varphi + {S_w}^4\right)\right] \qquad \text{Eq. 9}$$

This empirical, curve-fitted model was later updated by Rogers and Nielson (1991) to:

$$D_c = \varphi D_0 exp\left(-6S_w\varphi - 6{S_w}^{14\varphi}\right) \qquad \text{Eq. 10}$$

where D_0 for radon gas is $1.1 \times 10^{-5}\ m^2\ s^{-1}$. Lastly, Moldrup and others (2000a) introduced a water-induced linear reduction model for repacked soil that suggests an increased tortuosity in wetter soils:

$$D_c = D_0 \frac{\varepsilon^{5/2}}{\varphi} \qquad \text{Eq. 11}$$

For comparison, these conventional, steady-state diffusion models for radon gas are shown in Figure 4-2a as a function of S_w. Radon barriers typically have S_w values above 0.80 after construction (DOE, 1989). At this saturation level, D_c ranges from ~$4 \times 10^{-7}\ m^2\ s^{-1}$ using Penman (1940) to $1 \times 10^{-8}\ m^2\ s^{-1}$ using Millington and Quirk (1961); the largest differences are observed above a S_w of 0.6. Thus, the choice of diffusion model and estimated S_w will alter the required cover thickness. The original guidance for UMTRCA covers used Rogers and others (1984) which falls between these two extremes; the remainder of this section assumes this derivation for D_c (Eq. 11).

The steady-state analytic solution of the radon diffusion flux at the cover surface (J_c) for a two-region model using Eq. 10 was given by Rogers and others (1984) as:

$$J_c = \frac{2J_t \exp\left(\sqrt{\lambda/D_c}\,x_c\right)}{\left(1+\sqrt{A_t/A_c}\tanh\left(\sqrt{\lambda/D_t}\,x_t\right)\right)+\left(1-\sqrt{A_t/A_c}\tanh\left(\sqrt{\lambda/D_t}\,x_t\right)\right)\exp\left(2\sqrt{\lambda/D_c}\,x_c\right)}$$

Eq. 12

where J_t is the radon flux (pCi or Bq m^{-2} s^{-1}) from the tailing surface, λ is the radon decay constant of 2.1x10^{-6} s^{-1}, x_C is the radon barrier cover thickness in cm, and the attenuation factors (A_t and A_c) are given as:

$$A_i = \varphi_i^2 D_i\left(1-0.74S_{w(i)}\right)^2$$

Eq. 13

where $S_{w(i)}$, D_i, and φ_i are derived from the properties (i) of either the tailings (t) or cover (c) material.

For implementation, J_c can be set to a desired regulator limit (e.g., 0.74 Bq m^{-2} s^{-1}) and Eq. 12 can be solved for the corresponding cover thickness, x_c as:

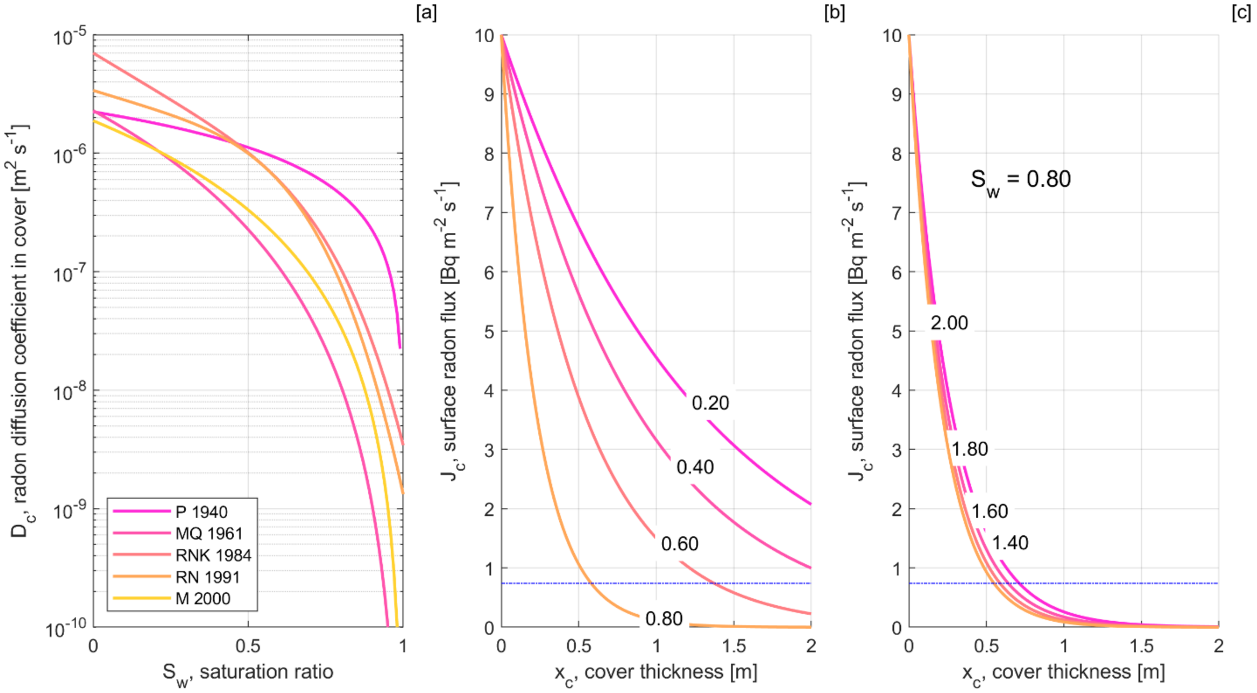

Figure 4-2 [a] Five Common, Steady-State Analytical Expressions Of The Effective Radon Diffusion Coefficient (D_c). Surface Radon Attenuation (J_c) and Barrier Thickness (x_c) Across a Range of [b] Saturation Levels (S_w) at a Constant Bulk Density of 1.6 g/cm^3, and [c] Compaction Densities in g/cm^3 and a Constant S_w of 0.80. Both Scenarios Assuming 10 Bq m^{-2} s^{-1} of Radon Flux from Bare Tailings (J_t). Dashed Blue Line Denotes the Acceptable J_c of 0.74 Bq m^{-2} s^{-1}

$$x_c = \sqrt{\frac{D_c}{\lambda}}\, ln\left[\frac{2\,{}^{J_t}\!/_{J_c}}{\left(1+\sqrt{{}^{A_t}\!/_{A_c}}\tanh\left(\sqrt{{}^{\lambda}\!/_{D_t}}\,x_t\right)\right)+\left(1-\sqrt{{}^{A_t}\!/_{A_c}}\tanh\left(\sqrt{{}^{\lambda}\!/_{D_t}}\,x_t\right)\left({}^{J_t}\!/_{J_c}\right)^2\right)}\right]$$

Eq. 14

For simple two-region cover situations where A_t is equivalent to A_c, and x_t is sufficiently large, the hyperbolic tangent (tanh) component goes to unity, and Eq. 8 reduces to:

$$J_c = J_t \exp\left(-\sqrt{{}^{\lambda}\!/_{D_c}}\,x_c\right)$$

Eq. 15

And Eq. 14 can be reasonably approximated by:

$$x_c = \sqrt{\frac{D_c}{\lambda}}\, ln\left[\frac{2\,{}^{J_t}\!/_{J_c}}{1+\sqrt{{}^{A_t}\!/_{A_c}}+\left(1-\sqrt{{}^{A_t}\!/_{A_c}}\right)\left({}^{J_t}\!/_{J_c}\right)^2}\right]$$

Eq. 16

Figure 4-2b illustrates the sensitivity of J_c to barrier thickness over a range of S_w assuming a common radon-222 flux from the tailings (J_t) of 10 Bq m^{-2} s^{-1}. Most UMTRCA radon barriers were designed and built with an S_w of 0.8, which requires100 cm of barrier to meet 0.74 Bq m^{-2} s^{-1} regulatory limit. Reducing S_w to 0.6 requires 200 cm of barrier while S_w of 0.4 requires 300 cm. The cover design criterion is highly sensitive to S_w at construction and any potential long-term desiccation. Compaction density, on the other hand, has less impact on surface flux. Figure 4-2c shows J_c at a constant S_w of 0.8 and bulk densities ranging from 1.4 to 2.0 g/cm^3. Using Eq. 8, the required x_c to meet a J_c of 0.74 Bq m^{-2} s^{-1} ranges from 54 cm of cover thickness compacted to 2.0 g/cm^3 to 70 cm thick compacted to 1.4 g/cm^3. While proper compaction does ensure uniform barrier properties, reaching high target densities can be reduced by adding another layer of lift of soil to increase overall thickness. Similarly, the addition of a one-meter-thick ET cover, packed to 1.4 g/cm^3 at 0.4 S_w, over an UMTRCA cover would further reduce J_c by approximately 70%. Currently, nearly all UMTRCA surface disposal sites (Table 2-1) have radon barriers with thicknesses ranging from 46 cm to 366 cm (18 to 144 inches) and a median thickness of 61 cm (24 inches). Adaption of an ET-radon cover system would enhance radon-222 attenuation by providing addition transport distance for radioactive decay although S_w would be lower.

4.5 Erosion Barrier

Erosion protection is a critical design criterion for uranium mill tailings sites to prevent releases following extreme events, provide long-term stability, reduce maintenance, and meet regulatory radon release limits. Erosion protection provides long-term stabilization of the waste cover system, protecting the radon barrier from wind and water erosion. Under 10 CFR Part 40, the design of erosion barriers is dependent on site-specific conditions allowing for unique combinations of cover systems (Table 2-1). Protective covers for both Title I and II UMTRCA Sites were designed with four objectives (Johnson, 2002):

1. Prevent radioactive releases due to wind or water erosion,
2. Provide long-term stability,

3. Require minimal maintenance to assure performance, and
4. Meet radon release limits.

The designs were based on the premises to protect against concentrated sheet flow, potential phenomena such as differential settlement, and wind erosion that can provide pockets for erosion and preferential flow paths to occur. In addition, freezing/thawing of the soil cover can cause deterioration and damage (e.g., frost heave) to slopes increasing the potential for concentrated flow (Johnson, 2002).

Rock armor or riprap (Table 2-1) is the most commonly used surface erosion barrier at UMTRCA sites. Johnson (2002), Appendix F, noted that it is difficult to properly construct a riprap layer, particularly as rock size increases. The layer thickness should be at least 1.5 to 2 times the average rock size. The guidance presented therein notes necessary rock durability based on design slopes and maximum anticipated shear stresses from flowing water and wind. It is also noted that vegetation naturally reduces such stresses; however, the establishment and survival of vegetation in more arid settings must be considered. Self-sustaining vegetation may provide additional long-term stabilization in some semiarid to humid climates, provided that the slopes are sufficiently flat. Steeper slopes of the apron are typically rock-armored.

4.6 Design Considerations for UMTRCA Sites

An existing UMTRCA cover could be modified or completely rebuilt depending on location and on the final performance criteria. A new cover, for example at a Title II site, may benefit from pilot studies to better understand storage needs and plant requirements. Regardless, the components of an ET cover and UMTRCA cover share several commonalities that could be incorporated into the conversion of UMTRCA covers to ET-radon barriers (Figure 2-2c). An UMTRCA cover typically has three components from bottom to top: a radon barrier, a sand/gravel bedding layer, and a riprap surface for erosion protection. An ET cover, from bottom to top, employs a capillary barrier, a water storage layer for rooting, and gravel admix for erosion protection. The riprap and bedding layers of a radon barrier could effectively serve as a capillary barrier and biointrusion layer in an ET-radon cover system, while the added soil thickness from the water storage layer would provide additional radon attenuation, freeze-thaw protection, and erosion control.

The water storage layer has an added benefit of radon-222 attenuation, even at lower levels of soil moisture. Here, we calculate the radon-222 travel time (t) as a function of a wet (radon barrier, S_w = 0.8) and dry (water storage, S_w = 0.2) cover component thicknesses (x_c) assuming $t = x_c^2/D_c$ and radon-222 half-lives in Figure 4-3. For example, a one-meter water storage layer adds 5 days travel time or just over one additional half-life to the cover. For higher saturation levels, the choice of diffusion model becomes far more important. At S_w of 0.8, a one meter layer provides 100 days travel time using (Rogers and Nielson, 1991) while only 20 days using (Penman, 1940). This is equivalent to 26 versus 5 half-lives, respectively. As discussed in Chapter 4.4 and 7.6**,** there are many empirically-based models for D_c based on repacked, intact, and cracked soils.

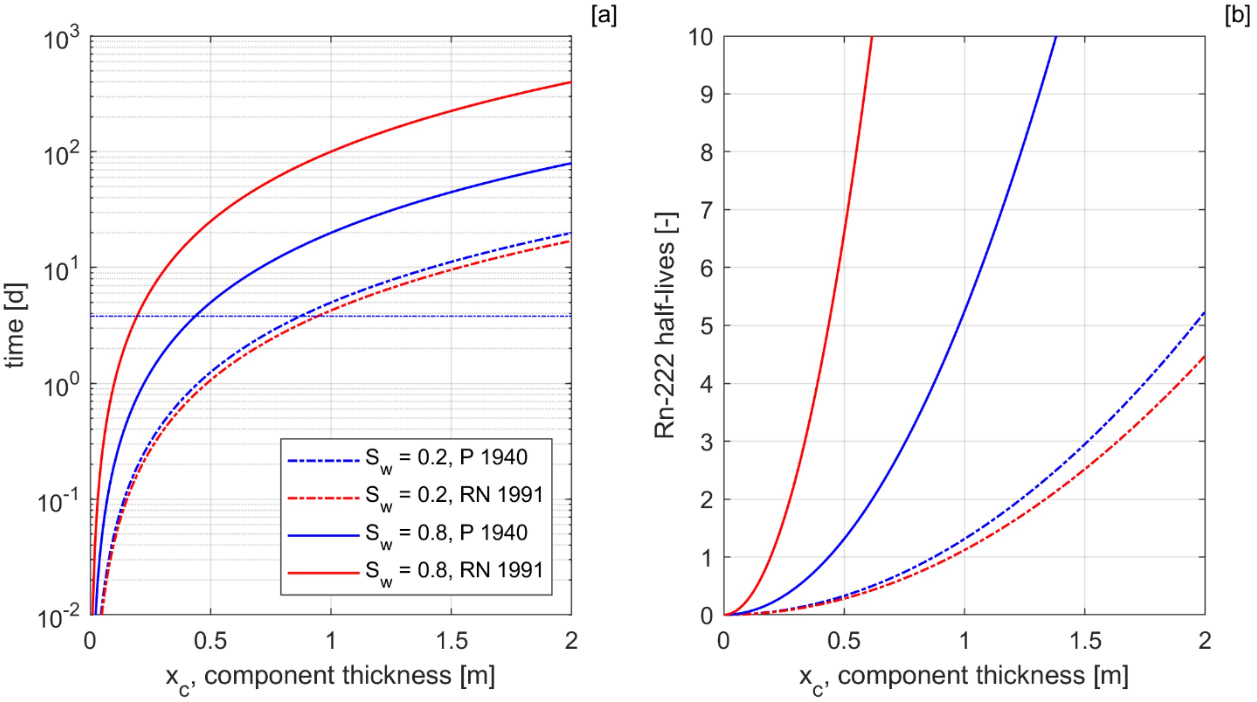

Figure 4-3 [a] Travel Times and [b] Half-Lives for Radon-222 Using D_c from Penman (1940), and Rogers and Neilson (1991) at S_w of 0.2 and 0.8 or Dry and Wet, Respectively. Horizontal Line in [a] Represents a Radon-222 Half-Life

The existing riprap erosion barrier on an UMTRCA cover could be incorporated into the ET cover design as a capillary barrier and also provide some biointrusion protection. Bowerman and Redente (1998) found evidence of biointrusion into radon barriers by various species of plants, burrowing mammals, and invertebrates at UMTRCA sites and recommend a more complete incorporation of ecological processes into the cover design. For instances where water percolates through the water storage layer and capillary break, the gradual (2-4%) surface slope of the existing UMTRCA covers including the riprap and drainage layer would promote the lateral drainage of excess water (Aubertin and others, 2009). In fact, the drainage capacity of a sloping sand layer over a gravel is maximized when it has sufficient moisture to be relatively conductive, yet remains unsaturated so as to prevent failure of the capillary break (Stormont and Morris, 1997).

4.7 Defining the Performance Criteria for an ET-Radon Cover System

The assumption of performance criteria is to combine currently regulatory requirements for UMTRCA covers with performance requirements from ET covers. The primary regulatory requirement for a radon barrier is to limit radon-222 flux to less than 0.74 Bq m^{-2} s^{-1}. The requirement is met by designing the layer to sufficient thickness and moisture content to reduce the diffusive process of radon-222 gas from the bare tailings below this limit. Regulatory compliance is implicit assuming the radon barrier remains intact.

To prevent the migration of hazardous constituents during the active life and post-closure period, RCRA 40 CFR 264.301 specifies at least 3 feet of compacted soil with a K_s less than 10^{-7} cm s^{-1} which is equivalent to 30 mm/y. For ET covers, the common performance criterion at the base of the capillary barrier is less than 3 mm/*y* (Smesrud and others, 2012). Similarly, test ET covers in the ACAP program were designed to have a percolation rate of less than 3 mm/y. Of the 15 sites, 6 had mean annual percolation rates less than 1 mm/y and 2 sites had mean percolations rates less than 10 mm/*y*; the highest observed percolation rate at a site was 110 mm/*y* (Albright and others, 2010).

Covers at UMTRCA sites are currently designed to shed precipitation, indirectly minimizing percolation into a low permeability radon barrier. An ET cover would intrinsically reduce percolation, but this is not a fundamental requirement at an UMTRCA site. The increased infiltration capacity and vegetation coverage of an ET cover, however, would enhance the overall geomorphic stability of the cover surface. Furthermore, ET covers are inherently self-renewing, which could minimize long-term maintenance. If percolation limit requirements are necessary for an ET-radon barrier cover, it may be more beneficial to justify such limits based on the given aridity, vegetation, and natural groundwater recharge of a site, over a set requirement such as less than 3 mm/y for RCRA covers. The beneficial use of an ET-radon barrier cover would imply percolation is at or below analogous levels to the surrounding environment. For example, Wolock [2003] produced a 1-km data set of mean annual groundwater recharge based on simulations from 1951 to 1980 (Figure 4-4). The recharge values at each UMTRCA disposal site, along with 30-year (1980 to 2010) mean annual precipitation normals from PRISM [2021] are shown in Table 4-1. Only the L-bar site has an annual recharge value at or below the common performance criterion of 3 mm/y cited above. The median natural groundwater recharge value at UMTRCA disposal sites is 13 mm/y or 6% of the mean annual precipitation. Perhaps a more realistic performance goal should consider this ratio of mean annual recharge to mean annual precipitation, rather than a rigid percolation value independent of location and climate.

A combined ET-radon cover would imply the following performance criteria:

1. Limit radon-222 flux to less than 0.74 Bq m^{-2} s^{-1} at the surface,
2. Limit increases to the annual average concentration of radon-222 in air at or above any location outside the disposal site by more than 0.02 Bq/l,
3. Limit percolation below the drainage layer to less than 3 mm/*y,* or to 6% of mean annual precipitation,
4. Remain effective for up to one thousand years, to the extent reasonably achievable, and, in any case, for at least 200 years, and
5. Provide reasonable assurance of conformance with groundwater protection provisions.

The cover design goal is permanent isolation of tailings and associated contaminants by minimizing disturbance and dispersion by natural forces, and to do so with minimal ongoing maintenance. The ongoing annual maintenance in the LTSP is necessary to ensure the regulatory compliance of conventional UMTRCA covers. Natural alternatives, such as ET-radon covers, may be more resilient to long-term disturbances, but will also need documented performance with data from models (Chapter 5 for more detail) and monitoring (Chapter 8 for more detail) to verify regulatory compliance.

Table 4-1 Mean Annual Precipitation, Groundwater Recharge and the Ratio of Recharge to Precipitation at UMTRCA Title I and Title II Disposals Sites

		30-year mean annual normals		
Site Name	**State**	**Precipitation (mm)**	**Recharge (mm)**	**Recharge/ Precipitation (%)**
Title I Disposal Sites				
Ambrosia Lake	NM	262	8	3%
Burrell	PA	1100	242	22%
Canonsburg	PA	988	145	15%
Durango	CO	525	98	19%
Falls City	TX	710	10	1%
Grand Junction	CO	299	34	11%
Green River	UT	181	5	3%
Gunnison	CO	286	47	16%
Lakeview	OR	349	149	43%
Lowman	ID	669	468	70%
Maybell	CO	359	21	6%
Mexican Hat	UT	165	8	5%
Naturita	CO	330	10	3%
Rifle	CO	460	83	18%
Salt Lake City	UT	222	15	7%
Shiprock	NM	187	11	6%
Slick Rock	CO	343	9	3%
Spook	WY	327	10	3%
Tuba City	AZ	157	7	4%
Title II Disposal Sites				
Bluewater	NM	243	7	3%
L-Bar	NM	286	3	1%
Maybell West	CO	359	20	6%
Sherwood	WA	349	36	10%
Shirley Basin South	WY	300	10	3%
	median	**328**	**13**	**6%**
	mean	**394**	**61**	**12%**
	minimum	**157**	**3**	**1%**
	maximum	**1100**	**468**	**70%**

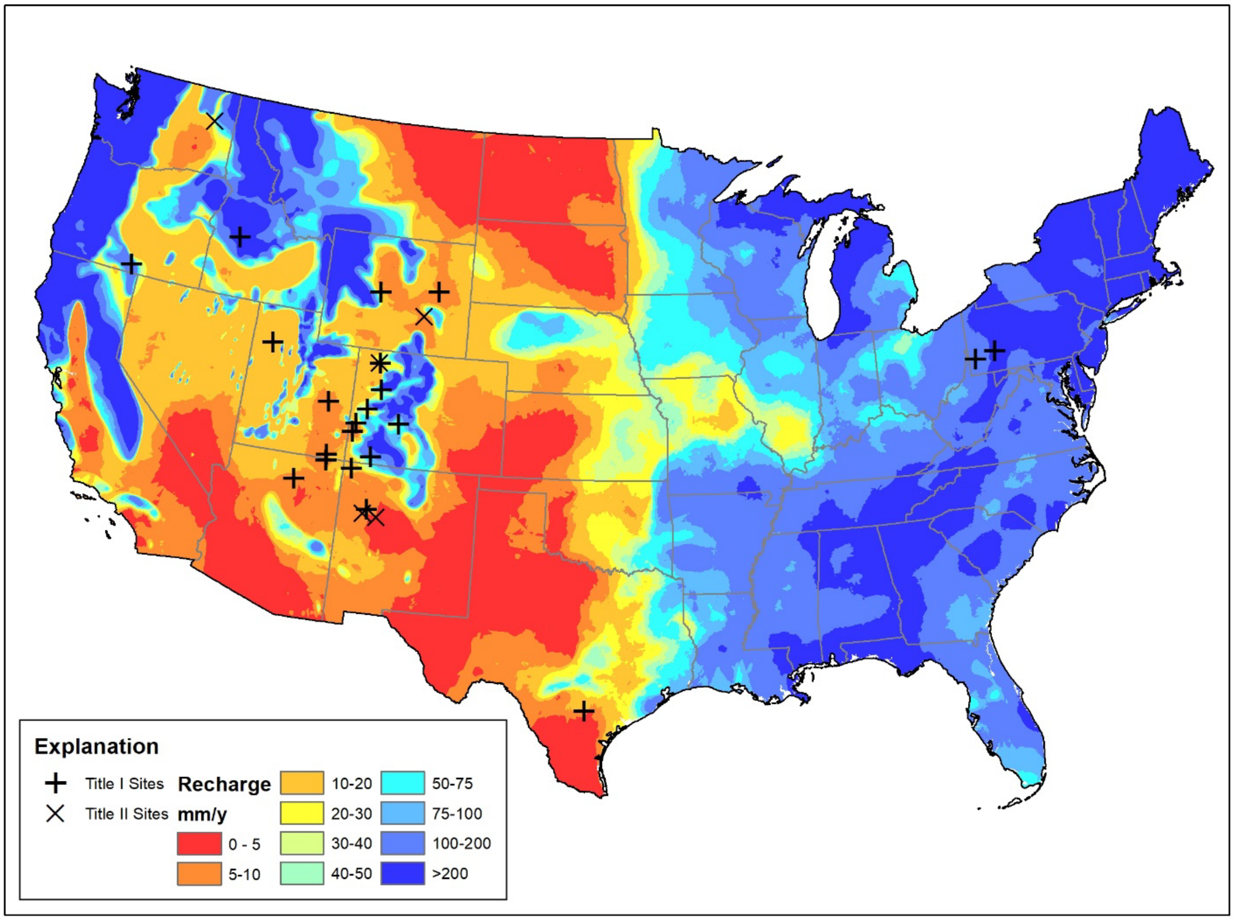

Figure 4-4 Mean Annual Groundwater Recharge Rates and UMTRCA Title I and Title II Sites. Recharge Data Adapted from Wolock (2003)

5 REFINEMENT OF ET COVER DESIGN USING NUMERICAL MODELS

Water balance modeling allows detailed quantification of the key processes related to ETcover systems, which include ET, dynamic SWS, gas flux, and percolation. A modeler needs knowledge of soil and plant physics, meteorology, geotechnical engineering, and computational systems. The modeler also needs some prior expectation of the results to know if the model is realistic, as well as any data for statistical model verification. While the model choice is important, the implementation of any model is perhaps more important.

The preliminary conceptual design and any alternative designs can be rigorously tested and refined through an iterative process of numerical simulations, uncertainty analysis, and pilot-scale studies. The results include documentation of the anticipated performance of the final ET cover design. The conceptual cover needs to be evaluated to ensure sufficient water storage during periods of high precipitation and low ET or the potential of carryover water from one annual cycle to the next. Such predictions are done using numerical modeling. Alternative designs, alternative scenarios, and uncertainty analyses can also help to refine the conceptualization of the final proposed cover system. The numerical modeling for long-term performance is discussed in Chapter 7.7.

5.1 Numerical Modeling

The performance evaluation of an ET cover ensures the optimal design will meet waste containment requirements. While conventional radon barriers were designed to specifications in a quasi-steady state system, ET covers are intrinsically more dynamic in response to climate, vegetation, layer/material properties and slope, which necessitates performing numerical simulations in the design phase (Aubertin and others, 2009). Models can guide the design phase by allowing quantitative comparison of alternatives, making predictions of future performance, and determining key parameters that need to be measured or adjusted. Given the complexity of the actual cover system, models are limited in their ability to provide predictive capabilities (Barbour and Krahn, 2004); however, they provide valuable insight into design options and combinations along with best- and worst-case scenarios.

An alternative cover, such as an ET cover, needs to show equivalent or improved performance over a conventional system and numerical simulations can help to document that assessment. Models provide predictions about future behavior or performance under various potential scenarios (e.g., extreme events, climate change). However, the accuracy of any quantitative prediction is directly related to the physical processes (and assumptions) in the modeling scheme, the specified parameters, and the modeler. These parameters can be measured directly or manipulated to identify critical parameters in the design and used to adjust target values in the field.

The typical inputs to an unsaturated, (vadose zone) model include the local atmospheric boundary conditions, various soil and vegetation properties, and soil layering. All pertinent hydrologic models use a series of nodes to solve various unsaturated flow equations for water, energy, etc. Each node is assigned model parameters such as hydraulic properties, root distribution, and organic content, which the models use to numerically iterate and solve flux equations within the model domain.

5.1.1 Model Processes

Most vadose zone models numerically solve the Richards' equation for variably-saturated water flow and Fickian-based advection-dispersion type equations for heat and solute transport (Vanderborght and others, 2005). The water flow equations incorporate a sink term for ET to account for water uptake by plant roots. The flow equations can use various parameterizations (i.e., hydraulic functions and properties) between hydraulic conductivity and states (ψ or θ). The heat transport equations generally consider transport due to conduction and convection with flowing water, although some models also consider the coupled water, vapor, and energy transport as well. The solute transport equations consider advective-dispersive transport in the liquid phase, as well as diffusion in the gas phase. Notably missing from the standard processes is the energy balance, macropore flow, convective gas flux, and radioactive decay – processes more specific to ET-radon covers. While no single model necessarily considers all these processes, many can be manipulated to closely resemble the more complex nature of radon transport, ET, and water storage. However, there is no one model that can simulate every process and often one component is rigorous (e.g., energy balance modeling) at the expensive of another (e.g., fluid flow).

5.1.2 Model Parameters

All models are a simplification of a real physical system. A parsimonious or economical description of natural phenomena is often better than more complicated, over-parameterized representation (Blöschl, 2017; Beven, 2018). Initially, one-dimensional simulations with only the most essential components and homogeneous parameters are preferred. Complexity can always be added later in stages. Complex geometry and multiple layers can create computational issues (i.e., crashes) that are difficult to resolve. The results should match some reasonable expectation and be grounded to reality.

Geometry

Models solve systems of equations between adjacent nodes within a geometry that can be one-, two- or three-dimensions. Nodes are internally discretized within the geometry. Finite element or difference methods solve differential equations iteratively at each time step until some converge criteria is met and time steps forward. While seemingly trivial, model geometry, the number of nodes and their spacing control the error in water balance calculations and effect the runtime of a simulation.

Boundary and initial conditions

The geometry defines the physical domain of the model with each edge having defined boundary conditions. Boundary conditions feed information in and out of the model geometry. The upper boundary is usually defined as an atmospheric boundary with fluxes in from precipitation and out through evaporation. The surface boundary conditions should rigorously simulate the interactions at the soil-atmosphere interface (i.e., precipitation, infiltration, evaporation, runoff). The lower boundary can be the base of a particular component such as the capillary barrier or radon barrier, or an infinitely deep soil profile. Many models (i.e., HYDRUS-1D, SWIM3, and VS2DH) include unit gradient and seepage face lower boundary conditions. When the hydraulic gradient is unity, water flux equals the unsaturated hydraulic conductivity creating free drainage. Any drainage layer or no-flow boundary (e.g., lysimeter pan or geosynthetic liner) is better represented by a seepage face condition which only allows drainage when the boundary recaches a prescribed pressure head (i.e., saturation). Otherwise, a gravel layer can be used in models with only unit gradient conditions (e.g., UNSAT-H and SHAW) to approximate a seepage face (Scanlon and others, 2002).

Initial conditions (e.g., for θ or ψ) are required for every node within a given geometry to start solving any system of equations in a simulation. Initial conditions can have a significant effect on early simulations times. Therefore, they must be reasonable, or a model can be "spun up" by repeating the atmospheric boundary input until some equilibrium is achieved in the model states.

Temporal discretization

Time discretization is needed to specify fluxes at boundary conditions, as well as for numerical solving and iterations. Most models resolve the numerical time step internally to meet some convergence criteria. If it is not met, the model slows down; otherwise, it proceeds to the next time step. For boundary conditions, models often differ in the representation of time from hourly to daily, or user-specified time steps. The method by which models apply fluxes, like precipitation, also varies. At daily time steps, most models will apply the total daily fluxes (i.e., precipitation and potential ET) amount over 24 *h,* which is likely a much lower rate than reality and also provides little chance for runoff generation. For example, the SHAW model, at daily timesteps, assumes that all precipitation occurs in the first hour and evaporation is simulated for the remaining 23 *h*, while UNSAT-H applies a default rainfall of 1 cm/*h* at the start of each day. Other models, like HYDRUS, use net precipitation as daily input by first subtracting potential evaporation from rainfall. The use of daily precipitation input has a large impact on the partitioning of water between infiltration, evaporation, water storage, and drainage because of the different approaches used by the various models for simulating the upper boundary condition. When applicable, hourly data inputs for atmospheric conditions (precipitation and potential evaporation, in particular) are preferred over daily data to better represent fluxes.

Hydraulic properties

Soil properties can be measured in the lab or estimated from basic information like texture and bulk density. These properties define the relationship between the unsaturated hydraulic conductivity and soil water retention. There are many ways to formulate this relationship but the most common are the Brooks-Corey (Brooks and Corey, 1964), Campbell (Campbell, 1974), and van Genuchten-Mualem equations (Mualem, 1976; van Genuchten, 1980). Depending on the model, other formulations are available that assume different physical structure of the soils such as the log-distribution of soil pores (Rossi and Nimmo, 1994; Kosugi, 1996), dual-porosity (Durner, 1994), and mobile-immobile (Kohne and others, 2009) models, which better incorporate soil structure and nonequilibrium transport. There are advantages to each formulation based on the properties of the materials being simulated and numerical convergence. For example, Brooks-Corey, the simplest formulation, generates greater surface evaporation than van Genuchten-Mualem because unsaturated hydraulic conductivity remains much higher as the water content decreases (Scanlon and others, 2002). In addition, many models need bulk density, texture, and organic carbon inputs when energy fluxes are also computed.

Vegetation Properties

The rate and magnitude of transpiration is controlled by vegetation properties. These properties can include interception, leaf area index, rooting depth, and potential transpiration. Each control either the way precipitation or energy enters the soil or the rate at which it is returned to the atmosphere. Parameters like interception and canopy storage remove or temporally store precipitation. Others, like leaf area index, the ratio of transpiration area to ground surface, partition potential ET between total potential evaporation and potential transpiration. Actual evaporation is limited to available soil moisture flux to the surface while actual transpiration is applied to the entire root zone using the root distribution to apportion it among the computational nodes with designated root lengths. Root water uptake from a particular node is dependent on the pressure head of the soil at a given node. Actual ET is the sum of both actual evaporation and actual transpiration.

5.1.3 Model Output and Evaluation

Numerical simulations produce tabular data of fluxes and state values. Some software allows the visualization of these results; however, most do not. The boundary fluxes are actual ET, often separated into evaporation and transpiration, surface runoff, and drainage. States include SWS and θ, ψ, and temperature at specified nodes or depths. Depending on the modelled processes, derivative values of precipitation (snow verse rain) and energy partitioning between latent and sensible heat, may also be available for evaluation. The modeler needs some rough idea of the anticipated output to make sure input units, geometry, boundaries, etc., are within physical reality, because the model cannot tell otherwise. Models generally do produce a mass balance error which is the difference between flux in, change in storage, and flux out at each time step and summed over the model run. Albright and others (2010) recommend that the mass balance error should be ten times smaller than the quantity being predicted.

Validation, confirmation, or verification of any model is challenged by the non-uniqueness of the results (Oreskes and others, 1994) resulting from multiple parameter combinations (Beven, 2006). While similar model predictions may arise from countless permutations of input parameters, model evaluation, in its simplest form, compares simulated output from one scenario against another or against some measured phenomenon. For a cover system, multiple alternative designs can be evaluated against a baseline design to optimize the configuration. For performance demonstration, models are generally evaluated against either a direct measurement of percolation (Chapter 8.1 for more detail) or an indirect measurement of state (e.g., in situ θ or ψ). This evaluation is a statistical assessment (e.g., root mean square error, correlation, or Nash-Sutcliffe error) of the mean and variance of the model compared to the data. A good model may have the lowest statistical error, but there is no established methodology to reject or accept a model (Beven, 2018).

5.2 Modeling Alternative Designs

An ET cover system consists of five design features that can be optimized through numerical models: (1) cover components, (2) component physical properties, (3) component thicknesses, (4) cover slope, and (5) vegetation properties (i.e., density, effective rooting, and ecophysiological function). Alternative designs can simulate the addition or removal of entire components like a capillary barrier to assess the effect of percolation. Similarly, cover component thicknesses can be manipulated to balance cost with performance. A decision framework should be developed to identify the optimal cover thickness, soil type, soil density, and parameter uncertainty for the water storage layer (McCartney and Zornberg, 2006; Young and others, 2006).

5.3 Alternative Scenarios

Models allow the simulation of “what if” scenarios that may impact cover design life (**Chapter 7**), such as the investigation of cover performance following particularly wet years, and changes to vegetation cover or rooting depths. For example, the State of Utah (Utah Admin. Code 315-303-3) requires numerical models of alternative covers to (1) show the expected performance of the final cover under normal precipitation for a period of time until stability has been reached; and (2) during the five wettest years on record at the site or the nearest weather station.

5.4 Uncertainty Analysis

Model parameters, meteorological forcing data, and model structure all contain sources of uncertainly and underlying assumptions. Common methods of Monte Carlo simulations randomly sample a range of model input parameters including soil properties (Clausnitzer and others, 1998), spatial variance (Holt and others, 2002), or radon diffusion coefficients (Feng and others, 2019) so that their effect on model output can be determined. Ho and others (2004) developed a risk-based, probabilistic performance assessment model that included percolation reaching the uranium mill tailings, radon gas flux at the surface, groundwater concentrations, and dose to a receptor; this study then used a Monte Carlo sensitivity analysis to evaluate alternative cover designs.

5.5 Pilot Studies

Field demonstrations or pilot studies are generally required to document the performance of the ET-radon cover system design under local conditions. An alternative cover design should demonstrate performance equivalent to or better than a conventional cover. For example, Benson and others (2001) showed equivalent performance of an ET cover to a conventional cover based on pilot studies using lysimeters, numerical modeling, and in situ data from the ACAP. They assessed percolation rates obtained from a water balance method, trend analysis, Darcy's Law calculations, tracers, and lysimetry; their results showed lysimeters to be the most precise across a variety of climates for sites in the ACAP. Test sections on smaller areas of the site using drainage lysimeters and other instrumentation can provide direct estimates of percolation (Khire and others, 1997; Smesrud and others, 2012). Pilot studies can be adapted to finalize the vegetation mix and establishment procedures, and to refine parameters necessary in numerical modeling.

5.6 Available Models

A compiled list of numerical water balance models (Table 5-1) was developed from a literature review, experience, and the International Soil Modeling Consortium's Model Portal available at https://soil-modeling.org/resources-links/model-portal, which allows model developers to post links to the most current versions. These models and underlying codes are either water-balance models that use empirical routing processes (RP) based on textural lookup tables or physics-based models that solve differential equations (e.g., Richards' equation) using hydraulic properties (e.g., van Genuchten-Mualem, Brooks-Corey). The performance requirements of an ET-radon cover require estimates of SWS and percolation through vastly different components, which suggests that a physics-based model is more appropriate. Furthermore, all models are evolutionary in nature and adapted from common codes.

The following list of available models is not exhaustive but does contain the most-used modeling platforms related to infiltration, ET, and unsaturated water and gas fluxes. Note, any URLs provided are subject to change.

CREAMS and GLEAMS
A Field Scale Model for Chemicals/ Runoff, and Erosion From Agricultural Management Systems (CREAMS) is a numerical model to evaluate non-point source pollution from field-size areas developed by the USDA-ARS (Knisel, 1980). A field is defined as a management unit having a single land use, relatively homogeneous soils, spatially uniform precipitation, and a single management practice. Inputs include precipitation, solar radiation, and temperature along with soil, vegetation, and terrain properties. The model estimates runoff, percolation, soil

erosion, and dissolved and adsorbed plant nutrients and pesticides (i.e., non-point source pollution). Generally, this model was developed for agriculture as a lumped parameter watershed model and uses empirical formulations like Soil Conservation Service's curve number approach for runoff, and a water-balance approach for ET and soil moisture, and percolation. It has not been extensively used for ET covers. This model has evolved to the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) platform.

GLEAMS is an update to CREAMS and was developed to aid the USDA Natural Resources Conservation Service specialists in assessing nonpoint-source pollution from agricultural areas and to compare impacts of alternative management practices (Leonard and others, 1987; Knisel and Douglas-Mankin, 2012). GLEAMS modified the plant nutrient and pesticide components of CREAMS and improved the model representation of management practices. Devaurs and Springer (1988) noted that the routing routine for soil water flux based on soil texture class performed poorly. Using data from test plots at Los Alamos, Nyhan (1990) found calibrated K_s values were orders of magnitude lower than measured values and percolation was under-estimate by 30%. GLEAMS water balance equations are the same as CREAMS and both are more applicable to on-farm management than ET covers.

CREAMS documentation is available at https://www.tucson.ars.ag.gov/unit/publications/PDFfiles/312.pdf and GLEAMS is available at https://www.ars.usda.gov/southeast-area/tifton-ga/southeast-watershed-research/research/models/gleams-model/.

EPIC and APEX

The Environmental Policy Integrated Climate (EPIC) model and the Agricultural Policy/Environmental Extender (APEX) model are tools for managing whole farms or small watersheds to obtain sustainable production efficiency and maintain environmental quality. Both models were adapted from a prior EPIC model called Erosion Productivity Impact Calculator (Sharpley and Williams, 1990) and also have some components from CREAMS. They operate on a daily time step and are capable of performing long term simulations (1-4000 years) at the whole farm or small watershed level. Hauser and others (2005) found EPIC estimated ET and deep percolation with errors less than 7% and 5%, respectively, using data from lysimeters based on ET landfill cover designs in Ohio and Texas.

The EPIC model is available at http://www.brc.tamus.edu/epic. APEX has restricted access, but documentation is available at https://epicapex.tamu.edu/apex/.

HELP

Hydrologic Evaluation of Landfill Performance (HELP) is a simplified soil-water balance model used primarily to calculate the SWS of landfill covers and bottom liner systems (Berger, 2015). Originally, prior to version 3, the model lacked ET and vegetation, but the current version (V4, released in January 2020), distributed through the U.S. Environmental Protection Agency includes both ET and vegetation, and a snow-melt subroutine (Tolaymat and Krause, 2020). The model uses daily precipitation which tends to under-estimate runoff from high-intensity storms. Other limitations are related to the model interface written as a macro-enabled workbook in Microsoft Excel. Macros can become corrupt with updates or new versions of Excel. It does have synthetic weather generation and other tools related to cover design that make it attractive; however, it does not solve any rigorous equations for energy or mass balance. In particular, HELP has been shown to under-estimate ET due to either a unit-gradient bottom boundary (Scanlon and others, 2002) or an over-prediction of runoff (Khire and others, 1997; Albright and others, 2013). Hauser and others (2005) found the HELP model produced larger errors in runoff estimates by treating frozen soils as impervious, and higher errors of 20% for ET and 15% for percolation. In particular, Albright and others (2013) note that hydraulic properties reflecting the actual, in-service conditions, and not the as-built hydraulic properties of soil layers, should be used in any predictive modeling using HELP. HELP was built for engineers and regulators to evaluate leachate control systems generally using geomembranes or geosynthetic clay liners and its applicability for ET-radon cover systems would require further evaluation.

The HELP model is available at https://www.epa.gov/land-research/hydrologic-evaluation-landfill-performance-help-model.

HYDRUS

HYDRUS is a finite element model for simulating one-, two- or three-dimensional water and solute movement in variably saturated media (Simunek and others, 2012, 2016). HYDRUS numerically solves the Richards' equation for saturated–unsaturated water flow and convection–dispersion type equations for heat and solute transport. A sink term accounts for water uptake by plant roots as a function of water stress. The heat transport equation considers movement by both conduction and convection with flowing water. The transport models also account for convection and dispersion in the liquid phase as well as diffusion in the gas phase, thus permitting the models to simulate solute transport simultaneously in both the liquid and gaseous phases. HYDRUS has been extensively evaluated and applied to ET covers. HYDRUS has an energy balance module that can do bare soil evaporation and snowmelt; however, it is not available when vegetation is present. Diffusive transport of radon can be simulated. Dual-porosity models (Durner, 1994) are available; however, gas transport is limited to matrix diffusion. Daily meteorological input is not advised as HYDRUS uses net precipitation (total precipitation - potential ET) over each time step. These limitations can be overcome by using a separate snow melt model (e.g., SHAW) to create a new input file of liquid fluxes from snowmelt and solid water storage in snow water equivalent. Net precipitation can be avoided by separating each day into 12 hours of precipitation followed by 12 hours of potential ET.

HYDRUS 1D and HYDRUS 2D/3D at both available at https://www.pc-progress.com/en/Default.aspx?hydrus-1d. The model and code are freely available for HYDRUS 1D while 2D/3D is a commercial software package.

LEACHM

The Leaching Estimation And CHemistry Model (LEACHM) was developed for agricultural use. This model is similar to UNSAT-H (described below) as it uses a one-dimensional, finite-difference method to solve a Richards' based physical model (Hutson and Wagenet, 1995). However, it does not calculate surface runoff and uses a uniform nodal spacing, which was set to 20 mm (Bohnhoff and others, 2009). On the other hand, LEACHM can simulate weathering and clay migration related to pedogenesis, as well as bioturbation and soil mixing. LEACHM has also been used for long-term simulations involving soil formation, clay translocation, and carbonate formation (Finke and Hutson, 2008).

There are currently five versions of LEACHM model with different functionality including: LEACHP (pesticides), LEACHN (nitrogen, carbon, and phosphorous), LEACHC (major cations and anions), LEACHW (water only), and LEACHB (microbial growth and competition). There are also two-dimension and GIS-linked versions of LEACHP and LEACHN, which can be used for spatial simulations. The code and several versions of the model are available on request (J. Hutson, pers. comm., September 26, 2021).

SEEP/W

SEEP/W is a commercial, finite element model that solves Richards' equation in two dimensions for use primarily in slope stability and soil cover design under changing pore-water pressure conditions within earth slopes due to infiltration. SEEP/W is formulated only for flow that follows Darcy's Law – often applied for steady-state solutions. Surface evaporation and infiltration processes are better simulated using VADOSE/W (described below) – another commercially available software package from Geoslope. Limited information is available on SEEP/W in the literature.

Software details can be found at https://www.geoslope.com/products/seep-w.

SHAW

Simultaneous Heat and Water (SHAW) simulates the movement of water, heat, and solutes within a one-dimensional soil profile that includes the effects of plant cover, dead plant residue, and snow (Flerchinger and others, 2012). Soil water and heat flow are simulated using Richards' equation for water flow, Fick's law for vapor diffusion, and Fourier's law for conductive heat flow. Unique features of SHAW include simulating infiltration at the end of a time step using a Green-Ampt approach and allowing excess water to pond on the soil surface or runoff. The snowpack-, vegetation-, and soil-energy balance are solved at each iteration. Frozen soil moisture dynamics are also included. SHAW can simulate isothermal and thermal gas flow. SHAW has been extensively tested in many different environments but has less application to waste cover systems (Flerchinger and others, 1997).

Although no longer updated, the model and code are freely available at https://www.ars.usda.gov/pacific-west-area/boise-id/northwest-watershed-research-center/docs/shaw-model/.

SoilGen

SoilGen is a simulation model for the study of pedogenesis in slightly calcareous soils such as loess. The model takes an initial soil or parent material as a starting point and calculates the effect of various boundary conditions over long periods of time on soil development (Finke and Hutson, 2008). SoilGen is based on LEACHM and all inputs and calculations are the same; however, SoilGen requires one climate year of data, a bioturbation time series, climate, and vegetation evolution, and pedogenically relevant events, such as erosion, deposition, or fire. Additionally, atmospheric partial pressures of carbon dioxide levels can be specified along with the carbon-14 isotopic signature of soil organic matter.

Software details can be found at https://users.ugent.be/~pfinke/index_files/Page1167.htm.

STOMP

Developed at the Pacific Northwest National Laboratory, Subsurface Transport Over Multi-Phases Simulator (STOMP) is designed to solve a variety of nonlinear, multiple-phase, multi-dimensional flow and transport problems in unsaturated porous media. STOMP-W has a barrier module that provides capabilities for modeling partially vegetated surfaces, which are driven by atmospheric inputs; however, it is primarily a subsurface reservoir simulator but also used in more complicated vadose zone problems (Ward and others, 2006; Zhang and others, 2016). The application to ET-radon barrier systems would be challenging.

The code and documentation are available at https://www.pnnl.gov/projects/stomp.

SWAP

Soil, Water, Atmosphere and Plant (SWAP) model simulates transport of water (including ET), solutes, and heat using a finite difference solution to Richards' equation. Development began in the Netherlands in 1978 with SWATR that evolved to SWATRE, SWACROP, SWAP93, and eventually SWAP in 2009. SWAP has a robust plant growth module and macropore flow routine that can simulate soil shrinkage and cracking (van Dam and others, 2008).

Software details can be found at https://www.swap.alterra.nl/.

SWIM3

Soil Water Infiltration and Movement (SWIM3) was developed predominantly for studies into management options for water and solutes in agricultural systems (Huth and others, 2012). SWIM3 uses a simplified evaporation term derived from potential ET and surface and air humidity. SWIM3 simulates isothermal water vapor flow but has had minimal use for ET covers (Scanlon and others, 2002).

Model documentation and modules can be found at https://www.apsim.info/documentation/model-documentation/soil-modules-documentation/swim3/.

TOUGH3

Much like STOMP, TOUGH3 is multi-phase, reservoir flow solver that uses multiple equation-of-state modules, which define the components and phases and related thermophysical properties (such as density, viscosity, enthalpy) of the fluid mixture being considered (Pruess, 2004; Jung and others, 2018). Any application to ET-radon barrier systems would be challenging and require detailed knowledge of the modeling system.

The code and documentation are available at https://tough.lbl.gov/software/tough3/.

UNSAT-H

Unsaturated Water and Heat Flow (UNSAT-H) simulates the movement of water, vapor, and heat in one-dimensional soil profiles that include the effects of plants. The code was developed at Pacific Northwest National Laboratory to assess the water dynamics of arid sites and, in particular, estimate recharge fluxes for scenarios pertinent to waste disposal facilities (Fayer, 2000). This physically-based model solves for water vapor transport using soil-surface temperature gradients and Fick's law of diffusion. UNSAT-H has been extensively evaluated for ET covers and waste disposal (Table 5-1). UNSAT-H can over-predict surface runoff (and under-predict infiltration) when using daily time steps because precipitation is applied at a constant rate of 10 mm/h which generally exceeds the infiltration capacity of the soil (Benson, 2007; Ogorzalek and others, 2008). Hourly time steps for meteorological input are recommended. As of 2005, UNSAT-H is no longer being updated.

The model and code are freely available at https://github.com/pnnl/unsat_h.

VADOSE/W

VADOSE/W uses the finite element method to solve a one- or two-dimensional solution of Richards' equation. Vadose/W is the two-dimensional version of SoilCover. Like HYDRUS, VADOSE /W uses net precipitation (total precipitation – potential evaporation) at each time step. Snow accumulation and snowmelt are accounted for when temperatures go below zero or above freezing, respectively. Weather inputs are daily which can under-estimate runoff and over-estimate infiltration and ET (Adu-Wusu and others, 2007). Benson and others (2005) accurately modeled surface runoff, ET, and SWS using Vadose/W but under-predicted percolation, likely due to differences between lab and field hydraulic properties. Bohnhoff and others (2009) found Vadose/W, along with UNSAT-H, HYDRUS, and LEACHM, all under-predicted percolation. Vadose/W is perhaps the most popular commercially available software platform for ET covers. However, Vadose/W has been integrated into the SEEP/W software package and is no longer supported.

Documentation of the software is available at www.geo-slope.com.

VS2DI

Variably Saturated 2-Dimensional Interface (VS2DI) was developed by the USGS as a graphical software package for simulating flow and transport in variably saturated porous media in one or two dimensions (Hsieh and others, 2000). It consists of three components: VS2DTI, for simulating fluid flow and solute transport, VS2DHI, for simulating fluid flow and energy (heat) transport, and VS2POST, a standalone postprocessor. The current version, VS2DH 3.0, uses a finite-difference approximation to solve the Richard's equation for flow, and the advection-dispersion equation for transport of heat and solute. Plant transpiration and bare soil evaporation can be specified in atmospheric boundary conditions. VS2DI is mostly commonly used for infiltration and streamflow loss (Constantz, 2008). Scanlon and others (2002) found VS2DI poorly simulates evaporation and storage changes as the model sets potential evaporation to zero during days of rainfall.

The model and code are freely available at https://www.usgs.gov/software/vs2di-version-13.

Other models and considerations

Several predominant codes and software packages are missing from this list. Some commercial software systems have changed companies or migrated to other platforms. SoilCover (http://www.geo2000.com) which did vapor transport on covers (Scanlon and others, 2002) was converted to VADOSE/W and is no longer available. SoilVision (www.soilvision.com) was acquired by Bentley and SVFLUX (Benson, 2007; Albright and others, 2010) could not be further evaluated. Likewise, several agency codes are becoming unsupported as the developers have retired including SHAW, UNSAT-H and VS2DI. While much of the physics remains the same, computer operating systems continue to evolve, and older FORTRAN based codes may eventually fail to compile on newer machines. Thus, keeping these legacy codes in compliance is imperative to their future use.

Table 5-1 Available Numerical Models Applicable to ET Cover Design and Other Related Hydrological Processes

Model	Open-source	Current	PET	Hydr. Props.	Gas	Runoff method	Time step	Veg. Prop	ET Cover application	Notes
GLEAMS adapted from CREAMS	X	X	P, PT	RP		SCS/I	Daily/hourly	LAI	(Devaurs and Springer, 1988; Nyhan, 1990)	Soil erosion, simple snowmelt routine
EPIC Adapted from APEX	X	X	P, PT, H	RP		SCS	Daily	LAI, root growth	(Hauser and others, 2005)	Estimates root growth based on soil density and temperature. Also estimates wind and water erosion
HELP	X	X	P	RP		SCS	Daily	LAI, growth	(Khire and others, 1997; Scanlon and others, 2002; Hauser and others, 2005; Albright and others, 2013)	Quasi-two-dimensional, snowmelt routine
HYDRUS 1D HYDRUS 2D/3D	X	X	P, PM, H	B-C vG R-N D	X	I	Any	LAI, root density, CC, MLP	(Scanlon and others, 2002; Abichou and others, 2006; Benson, 2007; Ogorzalek and others, 2008; Bohnhoff and others, 2009; Albright and others, 2010; Byrne and others, 2017; Breitmeyer and others, 2018)	Dual-porosity, thermal and isothermal vapor flow, tortuosity models (Moldrup and others, 1997; Moldrup and others, 2000b)
LEACHM	X	X	PM	C		I	Daily	Crop cover fraction, root density	(Ogorzalek and others, 2008; Bohnhoff and others, 2009; Albright and others, 2010)	Some abilities to simulate pedogenesis
SEEP/W		X		vG-M	X				(Aubertin and others, 2009; GEO-SLOPE, 2012; Argunhan-Atalay and Yazicigil, 2018)	
SHAW	X		P	C B-C vG-M	water	I	Daily/hourly	LAI, growth	(Flerchinger and others, 1997; Scanlon and others, 2002)	Snow accumulation and melt, frozen soil hydraulics,
SoilGen	X	X	PM	C	CO_2	I	Daily	Crop cover fraction, root density		Model extension of LEACHM with pedogenesis

Table 5-2   Available Numerical Models Applicable to ET Cover Design and Other Related Hydrological Processes (cont.)

Model	Open-source	Current	PET	Hydr. Props.	Gas	Runoff method	Time step	Veg. Prop	ET Cover application	Notes
STOMP	X	X			X		Any			Multi-phase fluid flow simulator. Surface application to ET covers is limited.
SWAP	X	X	P	B-C vG-M		I	Daily	LAI, cover, root depth, MLP		Macropore module including cracks and shrink-swell soils.
SWIM3	X	X	PM	B-C vG-M	water	SCS	Daily	LAI, crop growth	(Scanlon and others, 2002)	
TOUGH3	X									More suitable for multi-phase subsurface flow
UNSAT-H	X		P	B-C vG-M R-N	water	I	Daily/hourly	LAI, CC, root density	(Fayer and others, 1992; Khire and others, 1997; Scanlon and others, 2002; Benson and others, 2005; Scanlon and others, 2005; Benson, 2007; Ogorzalek and others, 2008; Bohnhoff and others, 2009; McGuire and others, 2009; Albright and others, 2010)	Hourly timestep is preferred. Well-used code but future support is questionable.
VADOSE/W			P	vG-M	X		Daily	LAI, MLP, root depth	(Benson and others, 2005; Adu-Wusu and others, 2007; Benson, 2007; Bohnhoff and others, 2009; Albright and others, 2010; Walter and Dinwiddle, 2015; Argunhan-Atalay and Yazicigil, 2018; Stock and others, 2020)	Integrated into the Seep/W software package.
VS2DH	X						Any		(Scanlon and others, 2002)	

Potential evapotranspiration (PET) as Penman-Monteith (PM), Priestly-Taylor (PT) or Hargreaves (H).

Surface runoff based on Soil Conservation Service's (SCS) curve number method or physical model of infiltration capacity (I).

Hydraulic properties based on an empirical routing process (RP), Brooks-Corey (B-C), Campbell (C), van Genuchten-Mualem (vG-M), Rossi-Nimmo (R-N), Durner dual-porosity (D-P).

Vegetation properties for simulations include leaf-area index (LAI), crop coefficient (CC), moisture-limiting points of transpiration (MLP).

6 FINAL DESIGN PHASE

The final design phase begins once sufficient site-specific documentation has been assembled and provides reasonable assurance that the performance criteria can be achieved within the scope and budget of the project. The final design phase should specify the borrow material for each component, the logistics to transport and store the needed materials, a construction quality control plan, a revegetation plan detailing the vegetation type and density, and a performance monitoring plan with a performance goal to definitively meet or exceed the regulatory requirements.

6.1 Material Selection and Logistics

The edaphic properties of the borrow material for the ET cover will likely determine the success of the revegetation program and the performance of the water storage layer. The cover soil requires a balance of soil texture, nutrients, organic material, and biota. Most desert vegetation is uniquely hardy, but only once a mature root system is developed, which requires good aeration, low compaction, and sufficient moisture. Broadcast seeding and established seedlings are particularly vulnerable to drought. Nutrients are generally low in arid systems and supplemental nutrients may be required if the borrow source has a particularly low nutrient content or if it has been mishandled. Storage of the borrow material can compromise its quality. Piling soil can cause degradation of organic material and soil structure. Surface soils are generally preferred for the water storage layer as they inherently contain more biota. However, the choice and handling of the surface borrow soil is critical to the growth and sustainability of the vegetation, as is the placement of the material on the cover. The cost to construct an ET cover system is likely less than other covers if local materials, such as soil, can be utilized during construction, thus reducing transportation costs (EPA, 2011). Ideally, on-site riprap material and drainage sands can be reused directly in the adaptation to an ET cover (Gorakhki and Bareither, 2017), but the surface soil for the water storage layer must meet revegetation needs.

Noteworthy considerations should include material transportation, construction costs, and time, including the additional efforts needed to demonstrate performance and potential offsets in the LTSP. Regardless, the economic feasibility for any licensee are the costs of an ET-radon cover system versus the long-term maintenance and inherent risk associated with a traditional radon barrier. UMTRCA covers ranged in cost from $18,000 to $33,000 per ha in 1981 (Baker and Hartley, 1982). Albright and others (2010) estimate the construction of a RCRA multi-composite cover with a compacted clay liner at an Oregon landfill to be over $250,000 per ha, while a 1.5 m monolithic water balance cover was $100,000 per ha. Preliminary site design, refinement, and demonstration efforts further add to these costs. McCartney and Zornberg (2006) discuss the merits for using simple performance models of ET cover designs to assess potential cover failure (e.g., exceedance of some percolation threshold) with the implementation cost for thicker covers, longer transport distances of borrow sources, or compaction efforts for denser soils. Similar considerations could be taken to optimize LTSM costs of an ET cover over the in-place UMTRCA cover. Section 4.5.2 of ITRC (2003) provides some discussion on the issue of the feasibility of moving soil long distances and suggest that in semiarid and dry sites, a lower water-holding capacity soil (i.e., less than 0.15 m^3/m^3) may be acceptable if the cover can be made thicker, which could be achieved by using soils that are closer to the site.

6.2 Quality Assurance and Quality Control

Construction and quality control specifications provide a means to determine whether an ET cover has been constructed as designed and that it functions correctly. Most state regulators with ET cover guidance require potential licensees to submit a construction quality control plan (CQCP). For example, the State of Texas (RG-494, 2017) provides very detailed guidance on the material specifications and construction quality control procedures that need to be included in a CQCP. This information includes material testing and testing frequencies, agronomic soil evaluations (including any soil amendments, fertilization, or irrigation), and vegetation assessments. ITRC (2003) refers to this plan as a construction quality assurance plan (CQA) and Chapter 5 of that report provides detailed guidance regarding the construction specifications that should be included. ITRC (2003) emphasizes that achieving satisfactory long-term performance of an ET cover is directly related to the adherence to these construction specifications.

All materials used in cover construction should be described in detail using the Unified Soil Classification System (USCS) along with their basis for selection. Materials used for the low-permeability layers should be compacted to a saturated hydraulic conductivity of at least 1×10^{-7} cm/s. McGuire and others (2009) targeted a dry bulk density of 1.3 g/cm^3 for an ET cover system and found that soil placement in 30.5 cm lifts using a low ground pressure dozer and subsequent soil tillage was needed. The authors found post-construction bulk densities were slightly higher at 1.44 ± 0.16 g/cm^3. ITRC (2003) notes that root growth can be reduced by soil bulk density above 1.5 g/cm^3 and recommend this as the upper limit for an ET cover. In addition, a lower limit of 1.1 g/cm^3 is recommended to limit settlement of the cover.

Protection from burrowing animals, root penetration, and erosion in the near surface layers, as discussed in Chapter 2.3.4, also should be described. Additionally, for ET covers, water storage capacity of the rooting medium layer should be thoroughly quantified to the extent described in Chapter 4.1, and refined using site-specific weather, soils, vegetation, and potential extreme events (Chapter 5 for more detail). The field and laboratory investigations of borrow material should be summarized and include material property testing results as described in this Chapter. Design schematics with layer thicknesses and cover boundaries should be presented (Aitken and Berg, 1968). An analysis should be presented on the potential for development of cracks in the cover as a result of differential settlement and shrinkage.

6.3 Performance Monitoring Requirements

The goal of performance monitoring is to provide data to either directly and/or indirectly demonstrate ET cover and radon barrier (if present) compliance. The adaptation of an ET-radon cover system should directly or indirectly monitor the two key performance metrics (1) radon flux and (2) percolation. Chapter 8 discusses such methodologies and presents the monitoring infrastructure required for the cover design plans. Direct methods to monitor radon flux, (e.g., sampling ports or diffusion membranes) and percolation (e.g., pan lysimeters) should be installed during the construction phase. It is also advantageous to consider the infrastructure for indirect monitoring methods including horizontal and vertical access tubes (i.e., boreholes for geophysics), fiber optic cables for distributed temperature sensing and soil moisture, and rhizotron tubes to image root growth. Any horizontally buried in situ sensors (e.g., time-domain reflectometry (TDR) probes, or electrical resistivity tomography (ERT) electrodes) are ideally installed during construction when they are more easily incorporated between soil lifts. Surface monitoring equipment (e.g., weather stations or runoff plots) or proximal sensors or cameras should wait until construction is complete.

6.4 Revegetation Plan

Natural analogues or other relict sites in the region of a potential site should be evaluated for species occurrence and distribution, density and coverage, leaf area index, historical trends, and rooting depth and density. Strictly native plants or a mixture of native and nonnative plants may be preferred. A diverse mixture of cool and warm season species will ensure the cover will develop over a wide range of conditions and achieve desired transpiration rates (ITRC, 2003). Establishment of vegetation on an ET cover is rarely successful on the first attempt and monitoring and maintenance of the vegetation cover should be expected for a period of time (Caldwell and Reith, 1993). For example, the State of Texas (RG-494, 2017) requires the submittal of a vegetation establishment report on a semi-annual basis until the vegetation is established to design conditions. This plan is specified in the construction quality control plan, which is also required. RG-494 notes that this vegetation establishment report should describe the type and quantity of vegetation established and the overall percentage of coverage as well as root density and depth. Furthermore, corrective actions may be needed to improve vegetation if vegetation and root structure do not meet specifications.

Recent research has shown the potential in modifying soil conditions to encourage spontaneous revegetation on mine waste (Álvarez-Rogel and others, 2021); however, it is more likely that active soil and vegetation restoration methods are required. Soil manipulation and revegetation methods could enhance the natural soil-forming and ecological processes occurring on existing UMTRCA covers that are loosening compaction and creating a more favorable habitat for vegetation (Waugh and others, 2014). Soil amendments may be used to improve soil fertility and enable plant establishment; however, their beneficial properties will be temporary (ITRC, 2003). Conventional nitrogen, phosphorus, and potassium fertilizers may adequately amend unproductive soils. Compost or manure may be applied to alleviate micronutrient deficiencies and improve soil tilth.

Although not specific to ET covers, numerous revegetation manuals are available for most ecosystems, including shrub-steppe and grasslands of the Pacific Northwest (Benson and others, 2011b), arid deserts (Bainbridge and others, 1995; Anderson and Ostler, 2002), and western rangelands and wildlands (Monsen and others, 2004). Furthermore, local agricultural extensions, land grant universities, and Natural Resource Conservation Service personnel may provide additional guidance on appropriate revegetation techniques, timing, species selection, and density for cover systems. Lastly, any revegetation strategy in arid or semi-arid lands should address the challenges of the typically hot and dry climatic conditions that prevail where the soil microclimate is a particularly hostile environment (Caldwell and others, 2009). Modest irrigation, well below SWS capacity of the water storage layer, would likely be required for several years until the vegetation is fully established. It can be beneficial to plant only when there is ample soil moisture to sustain seedlings, for example, after a particularly wet spring. Unfortunately, most construction projects with vegetation requirements cannot wait for optimal conditions and instead plant and water as needed.

7 FACTORS AFFECTING DESIGN LIFE

Although ET covers are typically designed to last for a 30-year post-closure period, application of such covers at long-term disposals sites would require performance periods of more than 200 years. Most ET cover construction and research began in the early 1990’s and most studies were restricted to short-term evaluations (Ward and Gee, 1997; Albright and others, 2004; Scanlon and others, 2005). Long-term studies and follow up research have now collected data decades post-construction (Breshears and others, 2005; Fayer and Gee, 2006; Zhang, 2016). Nonetheless, there is still much uncertainty regarding a variety of potential impacts to ET cover systems over both short- and long-term periods after construction.

All engineered covers will evolve over time and as-built specifications and intrinsic properties will change. The risk of long-term catastrophic failure is low, but change is inevitable. Naturally designed ET covers are likely to be more resilient to these changes, but factors such as erosion, vegetation and ecology, and pedogenesis will threaten cover integrity through its performance period (Beedlow and Hartley, 1984; Suter and others, 1993).

7.1 Longevity, Design Life, and Performance Period

The longevity of an ET cover is based on both the design life and the expected performance period. The design life is the period during which the ET cover can protect the waste with acceptable certainty, whereas the performance period varies depending on each component of the ET cover. Long-term waste disposal, such as at UMTRCA sites, aims to have a minimum design life of 200 years, but strives for 1,000 years. Following Caldwell and Reith (1993), the design life can be broken down into the following periods:

1. The *construction* period covers approximately first 5 years, depending on the size of the project. This is the period when the waste cell is constructed, the waste is placed within it, and the cover is constructed to completion.
2. The *short-term* period directly following construction can be thought of as an operations and maintenance period that extends between 5 and 50 years. This will be the most hands-on period with the expectation of regular oversight, maintenance, and active repairs.
3. The *long-term* period extends beyond 50 years to the minimum design life of 200 to 1,000 years. This period is expected to have much less human oversight and only minimal maintenance. With little to no active maintenance, this period is when the ET cover co-exists with the natural environment and when “to the extent reasonably achievable” comes into play.

Many of the impacts that effect the short-term will persist into the long-term period. Thus, long-term success more likely relies on the emulation of natural topography and ecologic/pedologic processes, while addressing construction flaws and other impacts during the short-term will help limit long-term impacts.

7.2 Settlement, Erosion, and Landform Evolution

Settlement of the underlying waste material and localized erosion (gully formation) can quickly degrade the integrity of a cover system (NRC, 2007). Some settlement is expected over the short-term, however, mass wasting, or when significant geomorphic movement of the cover system layers occurs, is considered unusual, and unfavorable, damage (DOE/LM, 2012).

Depending on the severity of any mass wasting, the site integrity could be compromised requiring immediate action. Mass wasting and settlement generally lead to the onset of significant erosion and piping of water along such features as noted in case studies in Chapter 9. The surface and apron of an ET cover is subject to wind and water erosion. The water storage characteristics of ET covers are designed to infiltrate and keep precipitation on the cover, minimizing surface runoff and related erosion. Water storage layer erosion is largely controlled by vegetation density and any significant loss of vegetation to drought or fire could quickly erode the ET cover. Significant surface erosion would decrease water storage and reduce the amount of root zone, potentially increasing percolation. On the other hand, eolian deposition of dust can add material to the cover. Surface gravels can create surface roughness and pockets for eolian deposition. Important factors influencing water erosion are rainfall and rainfall intensity, vegetative cover, slope, and water velocity, whereas factors influencing wind erosion are wind velocity and direction and soil characteristics (Fischer, 1986). Field monitoring for erosion is critical for ensuring ET cover integrity. Installation of erosion control monuments can be a good way to quantify the extent of surface erosion (ITRP, 2003).

The geotechnical stability of a cover system is essential to its short- and medium-term functionality. Most existing site plans include a summary of regional and site-specific geomorphology and geomorphic processes to assess the nature and extent of major active processes that may modify the present-day topography of the geomorphic province(s) and the site area (NRC, 2003). Although rare, dramatic geomorphic events, associated with flooding or seismic activity, are always a possibility. When selecting the geographic location for an ET cover system, it is preferable to choose a location in the topographically higher parts of the basin far away from floodplains. However, Porro (2001) artificially flooded experimental ET cover systems and, after a two-year recovery period, found a capillary barrier still yielded less total percolation and had greater resilience to erosion and subsidence than a monolithic cover.

Over the long-term, some geomorphic change should be expected. Engineered surface barriers are essentially small mesas – flat elevated surface rising sharply above the surrounding area. However, the barrier was not naturally shaped by erosion leaving the remnant resistive materials behind. Engineered landforms will co-evolve with the surrounding geomorphology through natural but likely accelerated processes of weathering, surface water and wind erosion, mass wasting, and settlement. The surrounding geomorphology, such as slope, aspect, surface roughness, and drainage patterns, should be considered in the site design to better transition the site into the long-term period.

7.3 Extreme Events and Climate Change

Extreme events, such as floods, high intensity or amounts of precipitation, droughts, wildfire, and other large disturbances can trigger geomorphic change at the landscape scale; these events are indifferent to any performance period. Since precipitation is the primary mode of contaminant transport, areas that receive low precipitation are the most desirable for waste isolation. An ideal aridity index, or the ratio of precipitation to potential ET, would be <0.5 (Budyko, 1961). Ideally, precipitation would also fall evenly throughout the year. Few, if any, arid or semi-arid regions oblige. High intensity, short-duration summer precipitation events are the norm, which can cause pulses of infiltration and surface erosion. Long, wet winters, where there is continued moisture, including snow accumulation on the cover surface, requires more available storage since ET is out-of-phase with precipitation. Other extreme events can directly impact the vegetation on the cover. For example, Zhang (2016) found the ET cover on the Prototype Hanford Barrier to be extremely resilient to controlled fire; Ward and Gee (1997) found it equally resilient when subjected to a 1000-year storm with no increase in percolation.

The ideal cover system should be designed to withstand the most extreme events. However, such design methodology and performance requirements assume a stable climate. With confounding evidence of relatively rapid past climate change, and model predictions of future climatic variation, DOE/LM recognizes a need to incorporate future climatic scenarios and ecological change in the cover design process (Waugh and Petersen, 1995).

7.4 Soil Pedogenesis

Natural systems are commonly characterized by the duality of being both dynamically stable and chaotically changing (Lin, 2011; Phillips, 2017). Soils, and the ecosystems they sustain, are complex, open systems that are the accumulation of fast and slow environmental drivers (Lin, 2011). Some of these drivers can induce rapid changes, including freeze cycles and bioturbation, while others are much slower (e.g., soil structure and carbon accumulation). The water storage layer of an ET cover will have an acclimation period as wetting and drying cycles move materials, such as fines and organic and inorganic carbon, within the soil profile. As vegetation and roots grow, soil aggregates will develop that stabilize the soil and improve infiltration capacity. However, these changes are not necessarily detrimental to a water storage layer.

In engineered soils, freezing causes liquid water to expand as it turns to ice. Repeated freeze-thaw cycles change engineering properties of soil over time by increasing the vertical permeability through the formation of structural cracks (Chamberlain and Gow, 1979). In fact, a significant network of cracks in compacted clays can form in a single freeze-thaw cycle (Othman and Benson, 1993). Frost heaving or cryoturbation can cause distinct engineered soil layers to become mixed, thereby disrupting the integrity of critical layer interfaces (Bjornstad and Teel, 1993). Drainage from cover systems increases with time due to freeze/thaw causing formation of macropores which close after rewetting (Albright and others, 2006b). For compacted clay soils, 5 to 10 freezing cycles can increase K_s by orders of magnitude (Kim and Daniel, 1992; Benson and others, 1995). Loamy materials, instead of clays, are used for water layers; vegetation tends to keep them drier so there is less propensity for frost heaving.

The design frost depth is the theoretical maximum depth below the surface that temperatures go below freezing for a moist soil (DOE/UMTRCA, 1989; Smith and Rager, 2002). However, both climatic factors and soil properties including moisture levels, mineralogy, and density affect frost depth, as can subtle variations in micro-climates from solar aspect, gravel content, organic material, and vegetation cover. A relatively small amount of extreme cold events could have a disproportional impact to barrier properties. One technique for preventing frost penetration in colder regions is to simply have a thicker soil or fill layer within the ET cover to protect the radon barrier.

Soil development or pedogenesis is a long-term process that is generally investigated using natural analogues such as a chronosequence of similar soils evolving under similar vegetation, climate, and topography with only time varying (Harden, 1982; Phillips, 2015). A soil chronosequence essentially substitutes space for time. Soil formation begins when the geomorphic surface becomes stable and depositional or erosional rates are less than biotic and abiotic pedogenic processes (Caldwell and others, 2012). The transformation of these surficial sediment to soil over time is termed pedogenesis. Analogous transformations happen to engineered soils on waste covers.

Pedogenesis such as structure development and an increase in cation exchange capacity have been document on abandoned mine tailings soils. These site received no formal restoration but were spontaneously colonized by native vegetation, 20 years post mine closure (Álvarez-Rogel and others, 2021). Both deflation of the soil cover (Andraski and Prudic, 1997) and accumulation of dust in riprap can be substantial (DOE/LM, 2020a).

As soils in arid systems age, and dust is incorporated into the matrix (McFadden and others, 1987; Wells and others, 1995), infiltration tends to decrease while soil water retention increases (Young and others, 2004; Meadows and others, 2008), which causes roots to contract (Stevenson and others, 2009) and vegetation density and canopy to decrease (Hamerlynck and others, 2002). Bioturbation under shrubs tends to quickly reset pedogenesis and maintain higher conductivity than interspace soils, which can eventually form desert pavements (Caldwell and others, 2008; Caldwell and others, 2012). In fact, deserts are mosaics of soil-plant assemblages that have evolved through time from young hummocky alluvial deposits to old flat desert pavement surfaces (Pietrasiak and others, 2014). Desert pavements are particularly stable landforms (>10,000 years old); however, their survival depends on the resistance of the underlying bedrock, the presence of disk-shaped cobbles to promote dust accumulation, and microclimatological and ecological reasons for minimal bioturbation (Seong and others, 2016). While these pedogenic processes have operated over the past tens of thousands of years in natural settings, engineered soils are likely to evolve more quickly.

7.5 Vegetation Management and Succession

The composition of desert ecosystems results from the coupled biotic and abiotic processes of each individual plant resulting in a mosaic of vegetation cover that is changing with time. The goal of vegetation management on waste burial sites is to provide short- and long-term stability with minimal required maintenance (Anderson and others, 1993). However, the initial revegetation goal is to set the trajectory of succession by creating a favorable environment for the native system to populate (Albright and others, 2010). The end goal is to replicate the natural, undisturbed ecosystem observed at the analogue site. It may not be feasible to go directly to this final stage in one step. Following large disturbances, vegetation goes through a series of early occupying species that create more favorable habit for late successional species. Much of the guidance on succession ecology, as referenced in Chapter 6.4, was established from reclamation projects related to fire recovery, mining, disturbed military lands, and recreational impacts. Post-fire restoration plans also incorporate a successional vegetation strategy to first stabilize the surface, then allow a natural propagation of species to occur. While drought and fire may be inevitable, irrigation and an active monitoring program should be required to ensure vegetation remains functional and the stage is set for natural succession over the long-term.

The patterns of vegetation responses to environmental changes of the past provide important information on vegetation responses to present and future climate change (Tausch and others, 1993). In the short-term, the restoration goal is to have plants grow and minimize erosion but ultimately a trajectory towards a more complex and diverse ecosystem is required to assure vegetation performance in the future.

While vegetation is critical to the functionality of the ET cover, some plants can negatively impact the cover water balance. For example, shallow rooted invasive grasses, which tend to prefer disturbed, vacant soils, can lead to higher percolation rates (Smesrud and others, 2012). Furthermore, root intrusion into a radon barrier can increase radon emissions along internal uptake and transpiration pathways (Lewis and MacDonell, 1990), by creating preferential pathways in the soil (Fuhrmann and others, 2021), or physically damaging and desiccating the radon barrier. Burrowing animals such as mice, kangaroo rats, and badgers along with invertebrates such as harvester ants can potentially penetrate and disturb the radon barrier and potentially transport and disperse buried waste. However, Hakonson (1999) found gopher burrowing in the presence of vegetation reduced surface erosion by increasing infiltration which was later removed by ET.

The integrity of the ET cover (and radon barrier, if present) relies on the effectiveness of a biointrusion layer (Chapter 2.3.4 for more detail) to block plants roots, burrowing animals and invertebrates (Bowerman and Redente, 1998). Three years after construction, Waugh and Weston (1999) found a diverse woody plant community had invaded the Burrell, Pennsylvania UMTRCA site and rooted 90 cm into the compacted clay barrier. In another study, tree height was related to soil thickness over a compacted clay cap in England; however, no roots entered the cap or extended below 1.3 m in a period of ten years after construction (Hutchings and others, 2001). In water-limited areas, absolute rooting depth tends to increase with decreasing mean annual precipitation except for shrubs and trees, which tend to be wider and shallower in arid environments (Schenk and Jackson, 2002). In arid systems, roots follow water and as dust is incorporated into surface soils the hydraulic conductivity decreases and soil water retention increases (Young and others, 2004). In natural desert ecosystems, roots of shrubs can reach 2 m depth in young, sandy soils; however, rooting depths tend to become reduced as soils age and the wetting fronts become shallower (Stevenson and others, 2009). On the other hand, deep rooted shrubs can quickly take hold on covers reaching great depths and potentially increase radon flux from mill tailing waste (Williams and others, 2021).

7.6 Radon Barrier Desiccation, Gas Diffusion, and Soil Structure

Over the long-term, the cover's ability to maintain sufficient S_w will determine the effectiveness of a radon barrier. Williams and others (2021) found J_c at four UMTRCA sites met regulatory requirements 20 years after construction; however, a few locations were substantially higher and generally associated with the presence of large plants, ant colonies, and emergent soil structure. The as-built radon-222 fluxes at closure were measured on a systematic grid including at least 100 measurements across the surface of the radon barrier within one year of construction. As-built surveys are conducted using accumulation chambers containing activated charcoal that adsorbs radon-222 over a fixed area and exposure time. Using more advanced methods, Fuhrmann and others (2021) also found most radon-222 fluxes at UMTRCA sites were similar to as-built surveys; however, certain cover features maintained or induced low radon fluxes by retaining moisture or increased radon fluxes (4 to 30 times) after deep rooted vegetation was established. The combination of rooting vegetation, soil structure formation, and soil desiccation as covers age should be accounted for when considering radon flux over long-term. Soil structure or desiccation of the radon barrier will increase air-filled porosity, pore continuity, and gas diffusivity (Kreba and others, 2017), which would increase radon exhalation.

Any cracks or large continuous pores (i.e., macropores, bio-pores, preferential flow paths, etc.) can create either advective transport or increase diffusion rates (Holford and others, 1993). While steady-state models (Chapter 4.4) adequately fit laboratory experiments on repacked soils, Meslin and others (2010) found them inappropriate for modeling radon diffusion in intact, structured soils. Using undisturbed soil cores, Moldrup and others (2000b) incorporated soil-water retention parameters, including a measurement of air-filled porosity at -100 cm of tension (ε_{100}) in terms of m^3/m^3 as:

$D_c = D_0(2\varepsilon_{100}^3 + 0.04\varepsilon_{100})\left(\frac{\varepsilon}{\varepsilon_{100}}\right)^{2+3/b}$		Eq. 17

where *b* is the Campbell (1974) parameter related to the slope of the soil-water retention function. The model illustrates the effects of soil texture and pore-size distribution, not of heavy soil structure (e.g., cracks). A non-cracked but heavier soil with higher Campbell *b* can distribute the water better than a lighter soil, and thus a slightly higher D_c in finer-textured compared to coarser-textured soils within some ranges of air-filled porosity (Figure 7-1a).

More recently, Moldrup and others (2013) introduced a structure-dependent, linear reduction model for predicting the D_c of both repacked and intact soils. In Eq 18, C_m is the media complexity factor, where $C_m = 1$ represented repacked soils while $C_m = 2.1$ gave improved predictions for intact soils:

$$D_c = D_0 \varepsilon^{(1-C_m\varphi)} \left(\frac{\varepsilon}{\varphi}\right) \qquad \text{Eq. 18}$$

The difference between the repacked or structureless soil and intact undisturbed soil C_m values is related to bulk density and thus total porosity (φ); however, the model is unique because it inherently can represent both repacked and structured soils through one parameter, C_m. In either case, the D_c is considerably lower than the Rogers and others (1984) estimation regardless of soil moisture level (Figure 7-1b). Moldrup and others (2013) suggest the major reason is local-scale variations in soil bulk density creating a more heterogeneous volume and lower overall D_c. In fact, Hamamoto and others (2011) found the soils packed to >1.6 g/cm^3 also increased D_c because of improved alignment of larger air-filled pores.

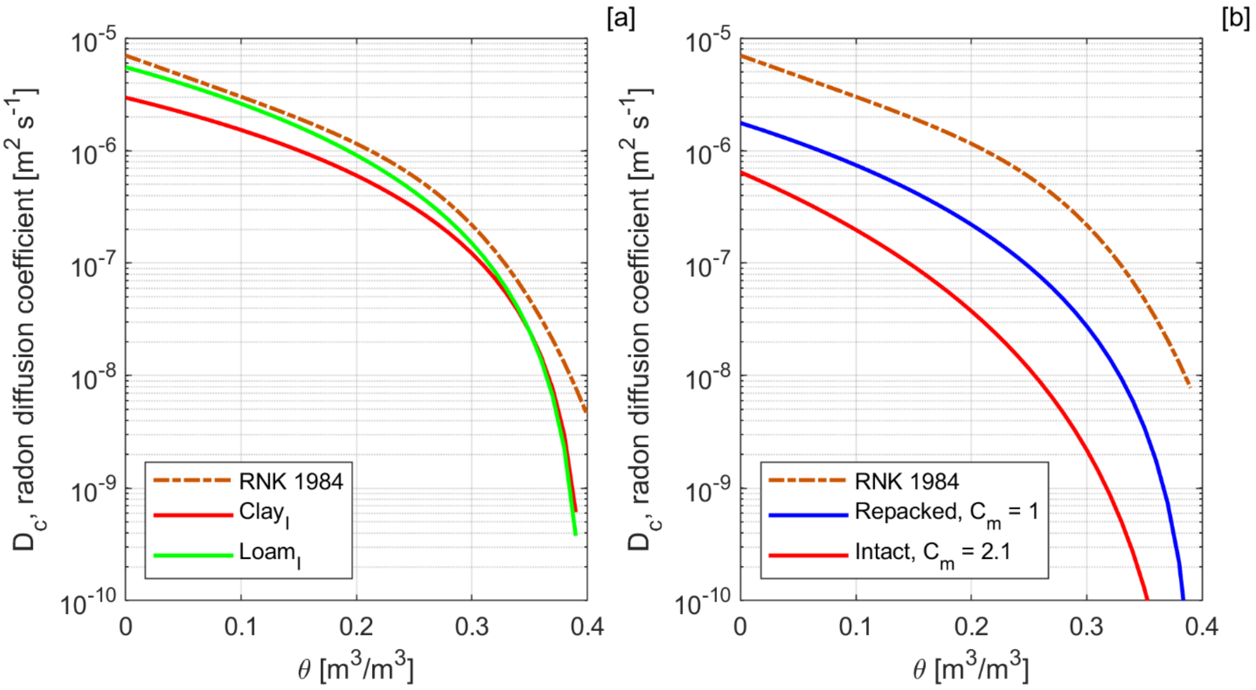

Figure 7-1 [a] Radon Diffusion Coefficient (D_c) for an Intact Clay (b = 14) and Loam (b = 7) Using Moldrup and Others (2000) Using Air-Filled Porosity at -100 cm Matric Potential (ε100). [b] The Dual-Porosity Model of Gas Diffusivity from Moldrup and Others (2013) Introducing a Complexity Factor (C_m) of 1 for Repacked Soil and 2.1 for Intact, Structured Soil. RNK 1984 Corresponds to Eq. 9 (Rogers and Others, 1984)

Fuhrmann and others (2019b) found that radon barriers generally retained the as-built S_W near 0.8; and met regulatory radon fluxes; however, some sites show more heterogeneity. Measurements of S_w at Bluewater and Falls City were often <0.5, while Shirley Basin was nearly saturated (Figure 7-2). Maintaining adequate moisture content over the long-term is critical to reducing radon-222 fluxes. In summary, radon barrier thickness guidance (Rogers and others, 1984; see Chapter 4.4 for more detail) is limited to simple cases as it assumes diffusive transport and homogenous S_w throughout the entire barrier. As covers age, S_w may decrease, and diffusion coefficients may increase. The long-term monitoring plan should consider methods to measure both the radon flux and the moisture content of the barrier.

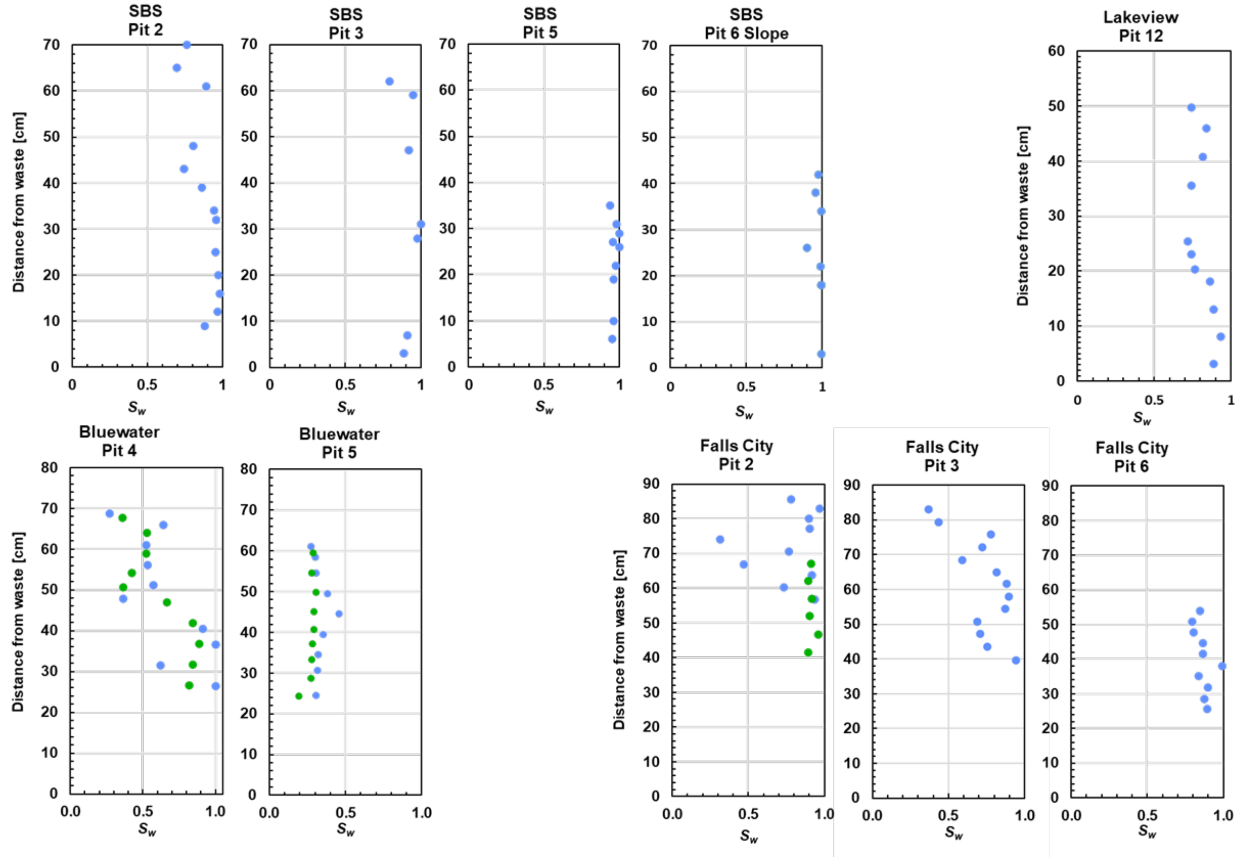

Figure 7-2 Profiles of Saturation Index (*S_w*) in the Radon Barrier Over UMTRCA Waste Disposal Cells at Shirly Basin South (SBS), Lakeview, Blue Water and Falls City. Data Adapted from Fuhrmann and Others (2019b)

7.7 Simulating Long-Term, Dynamic Factors Affecting ET Covers

The anticipated performance of an ET cover is highly uncertain over a 1,000-year performance period. However, the appropriate hydrological model with proper conceptualizations of future scenarios may provide some documentation of what dynamic factors are more important to cover performance. These dynamic factors, such as pedogenesis and vegetation succession, could be further researched with natural analogues. Such models would need to consider:

- What model parameters are likely to change over time? And how quickly are they changing?
- How are fluxes affected by these changes?
- How reasonable are the simulated outcomes represented in the natural analogues?

Long-term performance simulations provide insight into cover susceptibility to soil structural formation and its potential impact on ET, percolation, and gas fluxes, as well as changes species composition over time.

7.7.1 Vegetation Succession and a Changing Climate

Wilcox and others (2012) numerically investigated the conversion of shrublands to invasive grasslands in cold (i.e., Great Basin and Colorado Plateau) and warm (i.e., Mojave, Sonoran, and Chihuahuan Deserts) climates using HYDRUS and a hillslope erosion model, MAHLER. Exotic grass invasion of shrublands in either cold or warm deserts radically accelerates fire regimes due to the lack of diverse canopy and the tendency for them to be highly flammable, and alters rooting depth, canopy cover, soil-water use, and ET. To evaluate the impact of grassland conversion to recharge in cold deserts, LAI, percent vegetative cover, and rooting depth were manipulated in HYDRUS and simulated using a long-term synthetic weather dataset. The modelling results suggest a recharge rate of 50 mm/*y* that could result in deeper (10-m depth) groundwater recharge after only 40–50 years. Warm deserts were not evaluated because neither shrublands nor grasslands are expected to have any diffuse groundwater recharge. To evaluate the impact of grassland conversion to runoff and erosion, simulations were carried out across the range of slopes with variable grass cover and burn severity (by reducing or removing vegetation cover). In cold deserts, invasion by grasses significantly increases runoff and erosion by reduced infiltration capacity and increased bare soil following recurrent fires. In contrast, in warm deserts, invasive grasslands reduced surface runoff and erosion overall; even following fire, erosion increases only marginally over that of unburned native shrublands.

While the future climate trajectory is uncertain, long-term paleoclimate simulations over the Holocene (12,000 to 18,000 years before present) can be used to infer pedogenic development from wetter and drier periods in the historical record. For example, (Walvoord and others, 2002) used a steady-state, hydrostatic equilibrium, and unit gradient model to show that vadose zones of the desert southwest have been drying for thousands of years, as indicated by a net upward flow of water vapor, caused by a lagged response to drier climatic conditions and the vegetation transitioning from mesic to xeric. Even during pluvial (wetter) periods 13–9.5 thousand years ago, recharge was 2–5 mm/*y* and any liquid fluxes below the root zone have ceased since the establishment of desert vegetation several thousand years ago. Yin and others (2008) used HYDRUS to simulate dynamic changes in vegetation by changing ground cover percentage and LAI every century then comparing their results to solute (chloride) concentration in Holocene soil profiles in the Mojave Desert. Their results were highly sensitive to rooting depth and a few extremely wet years.

7.7.2 Pedogenesis

Macropore flow, preferential flow, nonequilibrium flow, and dual-porosity flow are commonly observed processes in natural soils (Beven and Germann, 1982; Beven and Germann, 2013); however, models have failed to keep up with field observations (Nimmo, 2021). Macropores are formed by soil fauna (e.g., worms, ants, even burrowing mammals), living or dead plant roots, cracks or fissures related to soil shrinkage from desiccation, and soil pipes resulting from erosion along subsurface flow paths. Macropore flow does not follow the assumptions of laminar flow used in Richards'-type equations (and most numerical models) and tends to be more rapid and turbulent. Some models can approximate these turbulent, preferential flow paths using two-domains with fast and slow regimes, similar to diffusive gas fluxes in fractures. For example, HYDRUS includes several physical nonequilibrium models like Mobile-Immobile Water Model, Dual-Porosity Model, Dual-Permeability Model, and Dual-Permeability Model with Immobile Water which consider the two systems of soil particles (slow) and soil aggregates (fast), each with their own set of hydraulic/chemical properties solved assuming laminar flow (Simunek and van Genuchten, 2008). For an ET-radon cover system, macropores would be relevant to the water soil layer and radon barrier, both of which may develop preferential paths over short- or long-term; however, the rate of development is not well understood.

In the very early stages of pedogenesis, the major factor controlling soil structure evolution is the action of gravity and rainfall, which compact the soil by increasing the number of pores while decreasing their size; during later stages, climate and biological activity are the controlling factors (Jangorzo and others, 2013). Benson and others (2007) collected undisturbed soil cores for over four years post-construction at ten ACAP field sites representing a broad range of environmental conditions. They found that changes in the as-built specification of van Genuchten hydraulic parameters (see Eq. 1 and 2) can increase K_s by a factor of 10^4, θ_s by a factor of 2, and α by a factor of 2.0, while n can decrease by a factor of 1.4. The more densely packed or the more plastic the fine-textured the soils, the greater the change.

Bodner and others (2013) quantified wet-dry cycles on pore-size distributions using repeated tension infiltrometer tests and inverse modeling. They determined that cycle intensity was strongly related to a temporal drift in median pore size and standard deviation in a tilled agricultural field. Dagois and others (2017) converted fluctuations of water content and temperature into "pedoclimatic events" accumulated over time as a function of climatic conditions, soil properties, and depth.

Pedogenesis over the Holocene has also been investigated using soil-water balance models. Soil carbonate profiles during episodic periods of wetter (pluvial) climate were simulated with the SHAW model using wetter and drier years extracted from historic data (McDonald and others, 1996). They found that dry and wet years strongly corresponded with the upper (75 cm) and lower (150 cm) zones of carbonate accumulation, respectively, and illustrated the use of a numerical model to evaluate to a natural analogue.

Finke and Hutson (2008) developed the SoilGen1 model, based on LEACHC, to model soil development over 15,000 years. As these authors note, the verification and calibration of process-based models of soil formation are challenging because often only the start (parent material) and current end stage of soil development can be quantified. Their results indicate that the incorporation of the bioturbation process was essential for the observed decarbonization of the topsoil and deeper clay migration.

Few studies, if any, have implemented either long-term paleoclimate/vegetation changes or short-term pedogenic effects into numerical simulations of a long-term ET cover or radon barrier system, nor is there a singular model that accounts for these. In many cases, simulation of multiple processes would require importing boundary conditions from one simulation or model into another, changing the necessary input tables, and restarting the simulation. Another approach is to use transient numerical simulations as input to the steady-state gas diffusion equations presented in Chapter 7.6.

7.7.3 Natural Analogues

Natural analogues provide useful data on the rates and effects of various geologic, pedologic, and biologic processes that can be applied to better predict the long-term performance and trajectory of engineered protective barriers (Bjornstad and Teel, 1993). While natural analogues are necessary to determine key elements of the ET cover design, these areas also make ideal locations to compare vegetation metrics to the ET cover. Drought, fire, extreme rainfall, pests, and invasive species may have different outcomes on the cover to those of the natural analogue and result in different vegetation indices between them. Periodic vegetation transects, as described in Chapter 8.2.2, may be necessary to ensure sufficient vegetation cover and biodiversity. Similarly, remotely sensed vegetation indices would allow direct comparisons between analogue locations and the cover while requiring minimal effort in the field. Natural analogues of cover systems can provide valuable insights into the future performance of an ET-radon barrier. Analogues can be thought of as long-term experiments. The soils and hydraulic properties of natural analogues likely differ considerably after being used for post-waste containment (Andraski, 1996). However, the natural soil-plant system provides an excellent model for design of surface barriers intended to limit deep percolation and transport of soluble contaminants to ground water in an arid environment (Andraski and Prudic, 1997). Long-term performance issues can be directly addressed using analogues that include ecological change, pedogenesis and climate change (Waugh and Petersen, 1995).

7.8 Implications to UMTRCA Covers

A cover system working with natural processes should be more resilient to the effects of soil development, climate variability, disturbance, erosion/deposition, and even ecological change than a conventional cover. Early UMTRCA covers relied on compacted soil to limit water percolation and attenuate the release of radon. Some of these covers inadvertently created habitats for deep-rooted plants, which increased the saturated hydraulic conductivity by several orders of magnitude above design targets (Waugh, 2004). The adaptation of ET covers should be indistinguishable from the reference analogue site if the trajectory for restoration was achieved over the long-term. In most cases, the annual inspection reports have noted little physical change to the disposal cell or the associated features over the ~30 year monitoring period (DOE/LM, 2020a). Minor issues included erosion control and stabilization (Canonsburg, Green River, Naturita, and Shiprock); vegetation management of deep-rooted shrubs or noxious invasive weeds (Ambrosia Lake, Burrell, Canonsburg, Durango, and Slickrock); and the stabilization, degradation, or accumulation of windblown sediment in the riprap (Canonsburg, Lakeview, Salt Lake City, Shiprock, and Tuba City). More recently, Title II sites tended to have more prolonged issues with groundwater contamination (Bluewater and Shirley Basin South) (DOE/LM, 2020b). No assessment of cover performance is required and there is no routine measurement of radon flux. Regulatory compliance is assumed by proper maintenance of the radon barrier cover system. The integration of a more natural ET-radon cover system could improve design life over the long-term; however, there is no data to support such conclusions at this time.

Rock durability is the ability of the riprap to withstand erosional (chemical or physical) forces. Rock durability is affected by water, temperature, and wind, which work to breakdown such materials at or near the surface (DOE/UMTRCA, 1989). Rock degradation has been noted in the annual inspection reports for several UMTRCA sites including Lakeview, Naturita, Rifle, and

Salt Lake City, (DOE/LM, 2020a). The burial of the surface riprap and possible addition of more gravel would likely reduce rock degradation from freeze/thaw cycles and solar-induced thermal fatigue (McFadden and others, 2005). However, moisture levels would be higher, increasing the potential for chemical weathering. The original riprap function was surface erosion resistance. In a multi-component ET cover, this layer would serve as a capillary break and drainage layer and its durability would have less impact on the overall ET cover functionality.

Refinement of the LTSP should be based on analogue sites and climate factors affecting erosion such as low-probability extreme storms or freeze/thaw events, channelized flows or piping, wind erosion or deposition, fire or vegetation succession/invasion, subsidence, and seismic activity.

While changes to the ET cover are inevitable over the, the goal is to have a maintenance-free site. The evolution through time of the ET cover should ideally enhance and preserve the cover system allowing it to exist in equilibrium with the environment. For example, dust deposition should enhance vegetation productivity, which should, in turn, increase soil development and resilience (Fischer, 1986). In this way, an ET cover system should have far lower long-term maintenance costs (Zhang and others, 2017).

8 MONITORING AND SURVEILLANCE METHODS

Monitoring approaches can be split into performance and process monitoring. For an ET-radon cover system, performance monitoring would include direct measurement of radon flux, percolation, and groundwater quality. Process monitoring, on the other hand, provides indirect means to assess cover performance. These indirect means can either directly inform numerical simulations (e.g., on-site weather data or vegetation cover) or be used to confirm output from a numerical model (e.g., SWS or ψ). Process monitoring involves sensors that are either continuously recording data or measured periodically during site visits.

8.1 Performance Monitoring

Performance monitoring provides a direct measure of the performance criteria, outlined in Chapter 4.7, for ET-radon cover systems at long-term disposal facilities such as UMTRCA sites. There are some limitations associated with performance monitoring. Radon flux is heterogeneous at the surface and measurement volumes are typically small in comparison to the area of the cover. Vegetation, settlement, and pedogenesis can create macropores, which have been associated with areas of elevated fluxes. Drainage lysimeters can create an artificial lower boundary (i.e., seepage face), which artificially increases SWS and reduces percolation. Lastly, groundwater monitoring at UMTRCA sites (Title I, in particular) has for the most part been abandoned because they either have extremely thick unsaturated zones or their aquifer and water quality are of poor quality.

8.1.1 Percolation and Drainage Rates

Percolation rates can be estimated from analytic expressions using measurements (e.g., θ and ψ) and steady-state assumptions (Gee and Hillel, 1988), or measured using water collection systems or lysimeters beneath the cover. Benson and others (2001) used analytical methods using measured states and lysimeters. They found θ data alone provided the least precise estimate of percolation, while the addition of ψ improved precision by two orders of magnitude.

Early evaluations of protective barrier designs were performed using lysimeters (Kirkham and others, 1987). Lysimetry is defined as the use of buried containers with open tops that collect or measure soil water flux providing a direct measurement of percolation (Gee and Hillel, 1988; Benson and others, 2001). Lysimeters can be either drainage lysimeters or weighing lysimeters. Drainage lysimeters collect the volume of water reaching the cover base. Weighing lysimeters are more commonly used to measure changes in SWS. For vegetated covers, a drainage lysimeter must fully enclose the entire root system and not create artificial boundary conditions. Lysimeters generally collect drainage water over a smaller part of a cover to reduce installation costs. The bottom of a lysimeter is an impermeable geomembrane or metal sheet that diverts any water to a collection point or drain. Generally, the membrane or collection pan is emplaced during construction and leachate is pumped or allowed to drain freely into a monitoring device.

Lysimeters create an artificial, no-flow boundary condition. Similar to a capillary break, percolating water in the soils above the lysimeter must equilibrate to atmospheric pressure before it will drain into a collection device (Benson and others, 2001), i.e., the bottom boundary becomes a seepage face, the ψ must approach saturation before water will drip into the lysimeter. This buildup of moisture at the seepage face can cause water above to divert around the lysimeter, if they are small, or be removed by transpiration. In either case, percolation measured by the lysimeter would be less than the actual. Abichou and others (2006) recommend using pan lysimeters of sufficient size (i.e., > 7 by 14 m) and height (i.e., >0.35 cm) to minimize these boundary effects. The lysimeters developed by ACAP can estimate percolation rates with a precision between 0.00004 to 0.5 mm/y; the study recommended that the lysimeter precision be an order of magnitude smaller than the percolation criteria (Benson and others, 2001). Some states require lysimeter studies to be conducted before the final cover design is approved (e.g., a pilot study). For example, Washington State requires a pan lysimeter and quarterly reporting (Valceschini and Norris, 1997).

8.1.2 Radon Flux

Measuring radon-222 flux to the surface can be achieved by direct measurement of radon-222 using passive accumulation chambers and/or active continuous monitors, or indirectly by determining lead-210 distributions in the soil profile of the radon barrier. Accumulation chambers use a canister of activated charcoal to passively measure radon-222 flux. A canister of known area is placed on or in the soil usually for a 24-hour period, then the accumulated concentration is measured by counting gamma rays emitted from short-lived progenies of lead-214 and bismuth-214 (Alharbi and Akber, 2014). Such methods are used within one year of the completion of a radon barrier to ensure regulatory compliance. Active detectors include the RAD-7 solid-state alpha detectors (Chao and others, 1997), which are commonly used for continuous radon flux monitoring (Stefani, 2016), and scintillation cell or semiconductors (Alharbi and Akber, 2014). Recently, Fuhrmann and others (2022) used accumulation chambers with a RAD-7 active continuous monitor at four UMTRCA covers and found most fluxes were within the range of their as-built specifications.

Passive accumulation chambers are generally left in the radon barrier for short periods of time and may not represent the long-term average (Fuhrmann and others, 2019b). Lead-210 distributions in the radon barrier soil profiles provide a long-term measure of accumulation since lead-210 is a daughter product of radon-222. Elevated lead-210 in upper barrier soil profiles, therefore, can be used to evaluate long-term radon-222 transport in clay barriers (Fuhrmann and others, 2019b); however, this method requires destructive sampling of the radon barrier.

8.1.3 Groundwater Contamination

Legacy groundwater contamination at existing disposal sites is unlikely to be affected by the addition of an ET cover with no amendment to any existing LTSM protocols. An ET cover may add some protection by further reducing percolation. At UMTRCA sites, groundwater contamination has been limited primarily to processing sites, whereas most disposal sites have water tables more than 200 feet below land surface (Table 8-1). Most Title I disposal sites have aquifers of limited use (e.g., Ambrosia Lake, Falls City, Grand Junction, and Shiprock) and have ceased groundwater monitoring, which is limited to processing sites (e.g., Gunnison, Lakeview, and Rifle). Title II disposal sites groundwater efforts would also remain unchanged by any ET cover additions.

Where required, groundwater samples should be collected from permanent well-constructed monitoring wells surrounding and downgradient of the ET cover site. Sampling protocols, similar to those described in the USGS National Field Manual for the Collection of Water-Quality Data (USGS, 2015), should be used so that proper equipment, well purging, cleaning procedures, and sample processing is consistently used to collect each set of samples.

Table 8-1 Groundwater Contamination Summary for UMTRCA Title I and II Sites

Site Name	Site type	Wells	Depth [ft]	Contaminant	Notes
Title I Sites					
Ambrosia Lake	Disposal	3		None	low yield aquifer, exempt
Burrell	Disposal	8	30		Sampling for Pb, Mo, Se, and U but below contaminant thresholds
Canonsburg	Disposal	5	10	Mn, U	
Durango	Disposal & Processing	7		Se	
Falls City	Disposal	26	30	None	Groundwater is classified as limited use; ambient contamination, exempt
Grand Junction	Disposal & Processing	3	>30	None	Limited use aquifer, widespread, non-milling related contamination, exempt
Green River	Disposal	22		Ar, NO_3, Se, and U	Lower Cedar formation is only aquifer of concern
Gunnison	Disposal & Processing	19		U	U contamination at processing site, not disposal
Lakeview	Disposal & Processing	12	30	U	U contamination at processing site, not disposal
Lowman	Disposal	0	30-80	None	Unique milling site, used mechanical extraction, no processing chemicals or waste
Maybell	Disposal	0	35-300	None	
Mexican Hat	Disposal	17	>200	None	All monitoring wells dry and abandoned
Monument Valley	Processing			NO_3, SO_4, and U	Most waste transported to Mexican hat
Naturita	Disposal & Processing	5	200-800	Ur, Va	
Rifle	Disposal & Processing			Ar, Mo, NO_3, Se, U, and V	Most remediation at Old Rifle processing site
Riverton	Processing		3-5		All 1.8M tons relocated to Gas Hills East in 1988
Salt Lake City	Disposal & Processing			Ar, Mo, U	
Shiprock	Disposal	186		NH-, Mn, NO_3, Se, St, SO_4, U	Uncapped artesian well opened in 1961; contaminants flushed into terrace alluvial aquifer
Slick Rock	Disposal & Processing		None		
Spook	Disposal	6		Cr, NO_3, Ra, Se, U	
Tuba City	Disposal	38	60-75	Mo, NO_3, Se, U	
Title II Sites					
Bluewater	Disposal	19		None	Pump and treat show no reduction in Mo, Se, or U, exempt
Edgemont	Disposal	0		None	Underlain by 300-700' of low permeability shale, exempt
L-Bar	Disposal	12	50-100	Cl, NO_3, Se, SO_3, U	
Maybell West	Disposal	0	200	None	
Sherwood	Disposal	7	20-200	None	
Shirley Basin South	Disposal	14	100-200	Cd, Cr, Pb, Ni, Ra, Se, Th, U	

In summary, performance monitoring provides a direct measurement of ET-cover performance, but not without limitations. Drainage lysimeters can create an artificial boundary and must be of sufficient size to fully encapsulate the vegetation and minimize these effects. Radon flux is heterogeneous and measurement volumes are typically small in comparison to the area of the cover. Vegetation, settlement, and pedogenesis can create macropores prone to elevated fluxes.

8.2 Process Monitoring

While direct performance monitoring provides a physical measurement of the potential regulatory criteria (e.g., percolation), process monitoring can provide indirect evidence of a functioning ET cover. For example, vegetation annually depletes SWS. Measurements of water balance components in the cover can also be used to the verify fluxes and states from simulations. In most situations, some form of process monitoring is beneficial to assess ET cover performance. Precipitation data can predict drought conditions or event magnitudes that cause erosion. Measurements of ET or SWS can verify a functioning ecosystem and water storage layer.

8.2.1 Water Balance Monitoring

8.2.1.1 Precipitation and other weather data

Precipitation is the solitary input to the water balance. Tipping bucket gauges funnel rain into small, calibrated buckets that tip when full, generating an electrical pulse that is counted over some period time. Small rainfall events maybe not register a tip and large events may overflow between tips. They do not measure solid precipitation, like snow and hail. Weighing gauges measure both solid and liquid precipitation using an electronic balance. Weighing gauges are more difficult to maintain and winds can result in data variability and noise. Both methods are likely to under-catch rain during high winds. In regions where snow is significant, a weighing gauge is more appropriate but will not correspond to melting periods. Alternatively, snow depth sensors and snow pillows are available. The uncertainties associated with the measurement of precipitation can be large, particularly in areas of high rainfall intensity and blowing snow (Sieck and others, 2007).

The collection of standard weather variables is encouraged at any ET cover location. Most water balance models need standard weather data as input including precipitation, solar radiation, air temperature, relative humidity, and wind speed. These values can be obtained from gridded weather products (Chapter 3.1), which may present some bias and not fully represent on-site weather. On-site data can be used to adjust any bias in meso-scale products (Breitmeyer and others, 2018). Weather data collection does require dedicated staff to perform maintenance and data quality control. Bad data can be worse than no data. Weather data standards are available and should be followed (ASABE, 2015; AASC, 2019; Fiebrich and others, 2020).

8.2.1.2 Evapotranspiration Monitoring

Monitoring ET continues to be a challenge and includes field-scale measurements, remote sensing, and empirical relationships between satellite data and field measurements. Field-scale measurements using micrometeorology, such as Bowen ratio-energy balance and eddy covariance methods, provide direct measurement of ET, but also require substantial effort and rely on assumptions of energy balance closure, corrections and gap filling, expensive and delicate equipment, and routine maintenance visits (Allen and others, 2011). The eddy covariance method uses the statistical covariance (correlation) between vertical fluxes of water vapor or sensible heat within upward and downward legs of turbulent eddies (McMillen, 1988). The eddy covariance method provides an integrated measure of ET ranging from 50-200 m, which no other method can provide. The upwind fetch is generally 50-100 times the height of the instrument, which must be located several meters (>15%) above the vegetation canopy. The ET measurement footprint also depends on surface roughness and thermal stability (Schuepp and others, 1990). For example, a three-meter-high sensor would measure flux from ~150 to 300 m area.

Remotely-sensed ET is typically estimated from land surface temperature that is derived from thermal infrared imagery which often requires significant atmospheric and emissivity corrections. Land surface temperature is sensitive to ET because the solar radiation or available energy is consumed by evaporation and the land surface is cooler. Satellite data are suited for deriving spatially continuous ET (Moran and Jackson, 1991; Bastiaanssen and others, 1998; Allen and others, 2007). Mapping ET from satellite data is done at a moderate resolution of ~100 m using Landsat thermal infrared imagery (Anderson and others, 2012). Coarser spatial resolution (1 km) thermal infrared imagery is available from instruments like the Moderate resolution Imaging Spectrometer (MODIS) and the Advanced Very High Resolution Radiometer (AVHRR), which is available at a daily time step. Most robust remote sensing models are based on land-surface temperature which is used to constrain and scale potential ET from meteorological data. All satellite and airborne imagery provide an instantaneous snapshot of ET and additional methods are needed to temporally integrate ET to daily totals between overpasses (e.g., 8 days for Landsat).

Most satellite-based methods scale potential ET between a cold-to-hot pixel which is particularly relevant in irrigated agriculture that transpires at or near crop reference ET, but less applicable to native vegetation under water-limited conditions where actual ET is far below potential ET. Thermal imagery in arid lands without any active irrigation lack a reasonable range of thermal signatures needed to effectively scale potential ET without substantiating uncertainty in the actual ET. The scale of an ET-radon cover likely requires some combination of remote sensing and ground-based methods, if ET is to be effectively monitored (Glenn and others, 2007).

Other methods use empirical relationships between satellite vegetation indices and field measurements, generally using eddy covariance, to estimate large-scale ET (Nagler and others, 2005; Beamer and others, 2013; Glenn and others, 2016). However, recharge or percolation are assumed to be the difference between precipitation and ET. These methods are mostly developed in riparian areas or other areas with groundwater-dependent phreatophytes. The field is rapidly advancing and data is becoming more accessible through the use of open-source software and open data sources like OpenET at https://etdata.org/. For now, monitoring ET cover performance using remotely sensed data is likely more applicable to assessing vegetation performance rather than using greenness indices such as the normalized difference vegetative index (NDVI; refer to Chapter 8.2.2 for more detail).

8.2.1.3 Soil water storage monitoring

Soil water storage is calculated by integrating discrete samples of θ over the total depth of the profile, component layer, or cover system. Recent advances and the state-of-the-art of remote sensing, proximal detectors, and in situ techniques for measuring θ are reviewed in Babaeian and others, 2019. While remotely sensed methods have advanced significantly in recent years (Chan and others, 2016; Kerr and others, 2016), measurements of passive microwave emissions are shallow (<5 cm) and the sensitivity of large aperture antennas to these emissions results in coarse spatial resolutions of ~ 30-40 km. Active radar backscatter can improve spatial resolution to ~1km but there are many compounding factors that impact the soil moisture retrievals (Das and others, 2019). Optical techniques that use changes in surface reflectance are more of a proxy for relative soil moisture status than actual θ. Non-invasive, proximal detectors have more recent applications for soil moisture monitoring including Global Navigation Satellite System Reflectometry (GNSS-R), Nuclear Magnetic Resonance (NMR), and Cosmic Ray Neutron Sensing (CRNS) technologies (see Chapter 8.3 for more detail). However, buried, in situ sensors or removable borehole sensors are more commonly used for SWS at the scale of an engineered cover.

Gravimetric sampling is a direct measurement of θ and is based on the physical weight of water loss from oven drying. Soil sampling should be done using volumetric samplers that can be manually or mechanically driven into the soil. These samples can either be across the entire soil profile or collected at specific depth intervals. Gravimetric sampling is destructive and requires at least four sampling locations to get one aggregate measure at that time. Gravimetric sampling is more commonly used to calibrate or verify dielectric soil moisture sensors in the field.

There are many technologies available to estimate θ from dielectric properties of the soil (Vereecken and others, 2008; Ochsner and others, 2013). Electromagnetic sensor technologies operate at various frequencies that tend to parallel the sensor's cost: higher frequencies are typically more accurate and more expense. Impedance and capacitance sensors operate at frequencies between 20–300 MHz, while TDR and transmission line oscillators (TLO) operate in the GHz frequency range (Vaz and others, 2013). There is no standardization for in situ soil moisture sensors (Cosh and others, 2021), but they do have a long legacy of measurements for model calibration and validation on engineered barriers although most tend to use TDR (Ward and Gee, 1997) or TLO (Albright and others, 2013). However, in situ sensors and the electrical components and wiring have finite lifespans. Replacement of broken sensors using either the same or a new technology is challenging, laborious, and can affect data continuity (Wilson and others, 2020). In situ sensors are appropriate for short-term (<10 year) process monitoring, but they may not be reliable for long-term performance evaluations.

Removable sensors set in access tubes may be more robust for long-term monitoring because cross-sensor calibration can be done with reference materials (Ward and others, 2000). The most common access tube sensor, and the oldest, is the neutron probe (NP). The thermalized NP consists of a fast neutron source (50 mCi ^{241}Am-Be) and a slow neutron detector (^{3}He); both are lowered into the access tube (IAEA, 2002). As fast neutrons from the source collide with hydrogen in water, they are thermalized (i.e., slowed) and detected. The number of thermalized neutrons over time is a direct measure of hydrogen within a given cross section that includes the access tube, access tube material (e.g., aluminum, or polyvinyl chloride), the surrounding disturbed fill material, and the undisturbed sediment. An accurate calibration is required to remove these conflicting factors. While the only standard method for θ is destructive gravimetric sampling, the NP remains the most accurate and precise method for θ determination in the field (IAEA, 2008). The disadvantages of NP include operation and maintenance of a radioactive source and readings must be manually taken – there is currently no automated, remote NP system, so field personnel must physically lower and measure the sensors.

Weighing lysimeters, as described in Chapter 8.1.1, can be used to monitor SWS using an enclosed soil monolith placed on a scale (Young and others, 1997), provided the encapsulation system does not impose any artificial boundary conditions to the hydrology (Scanlon and others, 2005). The SWS of weighing lysimeters and the actual cover can be relatively close, but there can be subtle differences which can affect the inferred gradient of soil water flux (Mijares and Khire, 2012). Weighing lysimeters provide the most precise measurement of SWS but they require a lot of maintenance to ensure that the scale system is functioning and any drainage water (percolation) is usually pumped out and weighed.

Finally, in situ ψ sensors provide measurements of pore-water pressure and hydraulic gradient. Tensiometers measure ψ in the wetter range from 0 to -70 kPa while thermocouple psychrometers and heat-dissipation sensors work primarily in the dry range (<-500 kPa). Long-term deployment of a tensiometer requires some manual means to refill the reservoir after the cavitation of the porous ceramic cup. Polymer tensiometers, a newer technology, use a hydrophilic polymer in place of water and do not cavitate (Degre and others, 2017). When collocated with soil moisture sensors, ψ measurements can provide substantially more information for model calibration and validation than either alone (Caldwell and others, 2013).

8.2.2 Vegetation Performance Monitoring

The monitoring of vegetation attributes and performance requires knowledge of the plant species and quantity that are present. Measurements can be field based, remotely sensed, or more likely a combination of both. The general measurement attributes include vegetation cover, density, frequency, structure, and species composition. The transect method is perhaps the most common and repeatable method to assess vegetation cover (Elzinga and others, 1998; Coulloudon and others, 1999). Vegetation cover is calculated as a percentage of the transect intersected by any shrub that crossed the vertical plane of the transect. More advanced methods, such as Generalized Random Tessellation Stratified design, are also applicable (Stevens and Olsen, 2003; Barabesi and Fattorini, 2013). A survey is one static measurement in time and vegetation is constantly changing and evolving. Field measurement of shrublands at the plot-level including LAI, total fractional cover, and green fractional cover collected from digital cameras, multi-spectral cameras, and other field sensors can be useful for relative within-site plant area index long-term monitoring (White and others, 2000). Alberton and others (2017) provide a review of these methods.

Airborne sensors and drone-based technologies are also advancing quickly (Yao and others, 2019; de Castro and others, 2021). Unmanned aerial systems (UAS) are now capable of fine-scale, spatially explicit estimation of the above-ground biomass for a variety of vegetation types (Poley and McDermid, 2020). For example, Young and others (2017) used airborne light detection and ranging (lidar) and multi-spectral imaging to estimate percent vegetation cover and species richness of dominant perennial plant species in the Mojave Desert. Vegetation indices derived from multi-spectral satellite imagery can provide an indication of greenness, plant health, and canopy cover. One of the most common indices is the normalized difference vegetation index (NDVI), which uses the near-infrared and red bands (Rouse and others, 1974). The soil adjusted vegetation index (SAVI) adds a constant soil-brightness correction factor (Huete, 1988), the modified soil adjusted vegetation index, which improves SAVI by using a recursive soil-brightness function (Qi and others, 1994). The enhanced vegetation index also includes an atmospheric resistance term and a blue band that accounts for background noise, atmospheric noise, and saturation (Liu and Huete, 1995).

The multi-band Landsat satellite has the longest historical record, dating back to the early 1970’s making long-term records of landscape change easily observable through API platforms like Google Earth Engine. However, the moderate resolution remotely-sensed imagery (30 m) lacks sufficient resolution to accurately measure vegetative cover in more arid environments because the plant density is generally too low to significantly influence spectral reflectance. The required spatial resolution is dependent on the abundance and size of species of the plant community; however, 1.0 m resolution was found to be adequate (Frank and Tweddale, 2006). For ET covers, such resolution would require lightweight UAS that can deliver fine spatial resolution data of ecologic structure to function at a temporal resolution defined by the user (Anderson and Gaston, 2013). New systems have and will be launched that may provide sufficient resolution for vegetation mapping at the cover-scale.

Preventative measures like biointrusion barriers are designed to keep plant roots from penetrating the radon barrier. Root depth is also a critical parameter for most numeric models or ET covers. Periodic, nondestructive documentation of subsurface rooting distributions, root lengths, and depths is possible using minirhizotron imaging (Johnson and others, 2001). The technique uses a clear acrylic tube inserted at an angle into the soil. A micro-imaging system on an indexed survey wheel captures a full, wrapped high-definition picture or video from within the tube. Image processing software and algorithms convert the images or series of images into quantitative measures of root properties. Tube installation must minimize disturbance and avoid compaction which can create micro-environments that may preferentially attract or deter roots. In a two-year study in the Mojave Desert, Verburg and others (2013) imaged a significant amount of roots to 90 cm depth in the interspaces between shrubs despite less than 25% cover. Installing a horizontal access tube (Dubach and Russelle, 1995), either on top or within the radon barrier, would allow direct detection of any root growth into the clay.

8.2.3 Geophysical Techniques

Geophysical techniques allow non-invasive imaging of patterns in the subsurface. They do not directly supply either performance or process monitoring, but they can be inferred from geophysical data. Current technologies generally fall into one of two categories that measure (1) ground conductance or (2) electromagnetic wave propagation time (Robinson and others, 2008). Ground conductance includes ERT, electrical magnetic induction (EMI), frequency-domain electromagnetics (FDEM), and time-domain electromagnetics (TDEM). Radar systems, like ground-penetrating radar (GPR), infer the dielectric properties of the subsurface from travel-time of an electromagnetic wave similar in theory to that of TDR sensor. Most electrical methods can be used either in boreholes or as surficial surveys conducted in one-, two- and three-dimensions. None of these methods are a direct measure of soil moisture or flux. However, nuclear magnetic resonance (NMR), which is a newer technology, does provide a direct measurement of θ.

Electrical conductance of soils and sediments is a proxy for the spatial and temporal variability of many other soil physical properties including soil moisture, structure, and fluid composition (Samouelian and others, 2005). Electrical resistivity methods have been available for a long time and recent advances in multi-electrode systems and data processing software have increased its popularity in environmental applications (Van Dam, 2012). Electrical resistivity is a geophysical imaging tool that uses buried electrodes and inverse modeling to create subsurface electrical structure in two- or even three-dimensions. While difficult to interpret the exact structures below-ground, repeated surveys can allow for the inference of changes in soil moisture – the key dynamic factor affecting electrical resistance (Sailhac and others, 2004). The infrastructure is relatively simple, requiring multiple buried stainless-steel electrodes connected to individual cables attached to the measurement system. Current is induced in the ground using two current electrodes at a time until all combinations have gathered sufficient data to estimate lateral and vertical variations in ground resistivity values using an electrical inversion model. The depth of investigation and resolution is controlled by the electrode spacing and there are many different electrode array configurations available. This technique is more commonly used in the saturated zone (Daily and Ramirez, 2000). Repeated surveys in the unsaturated zone have been less successful due to higher uncertainty in the inversion models (Linde and others, 2017; Carey and others, 2019). Permanently embedded electrodes are inexpensive; however, the cabling is not. Electrodes are small (~12 inches) and can be temporarily installed on the surface for repeated surveys, but this does add uncertainty to the inversion models and interpretation.

Electrical magnetic induction (EMI) uses an energized transmitter to create a primary magnetic field in the ground that produces a secondary magnetic field which is proportional to ground conductivity (McNeill, 1980; Corwin and Lesch, 2003). Different loop separation distances and orientations create different integrated measurements with depth based upon the instrument's configuration (e.g., EM38 or Dual-EM). Repeated EMI surveys can identify subtle changes in subsurface soil patterns (Abdu and others, 2008; Zhu and others, 2010; Franz and others, 2011) and be used to predict soil moisture in waste covers (Reedy and Scanlon, 2003). Frequency-domain electromagnetics (FDEM) is like EMI; however, the distance remains fixed while the transmitted frequency is varied over a specified range of steps (Huang and Won, 2003; Huang, 2005). This configuration is more common to airborne EMI surveys (Minsley, 2011). While these multifrequency systems are easier to operate on the ground, they offer little improvement over single frequency EMI sounding (Doolittle and others, 2001). Alternatively, TDEM induces a secondary field then measures its decay; however, these surveys are generally for deeper investigations (Christiansen and others, 2006). Auken and others (2006) provide an extensive review of electrical geophysical methods for near-surface investigations.

Ground penetrating radar (GPR) is an electromagnetic method that uses the transmission and reflection of high-frequency (typically 1 to 1,000 MHz) radio waves. An overview of the technology is presented by Knight (2001) including surface and borehole techniques. The depth of investigation is controlled by the GPR frequency and conductance of the substrate. Higher frequency improves surface resolution but at an expense to depth of investigation. Similarly, increased conductance due to clays or high soil moisture can decrease depth of investigation. Distinctly different dielectric properties in subsurface materials is the critical component in radar imaging, for example, the contrast between a moist radon barrier and a dry capillary barrier (Lunt and others, 2005). Borehole systems use similar technology with the transmitter and receiver place in different holes with each move iteratively at different depths (Eppstein and Dougherty, 1998; Kowalsky and others, 2005). Many multi-frequency, multi-channel systems are now commercially available.

All geophysical techniques require some ancillary data, numerical modeling, parameter estimation, and some preconceived conceptualization of the system. As these technologies continue to improve, there is potential to non-invasively detect changes in barrier properties, but perhaps only semi-quantitively.

In summary, process monitoring of states (i.e., SWS, ψ, leaf-water potential) is also challenging due to the spatial heterogeneity of the soil/vegetation cover and the small representative volume of most measurements. Furthermore, the uncertainty in the measurement of these water balance components can often overwhelm any estimate of percolation, which is the smallest remaining component. The next subchapter details some new techniques that may improve process-based monitoring in the near-future.

8.3 Novel Techniques for Future Consideration

Over the performance period of long-term disposal cells, new developments will likely advance monitoring systems and sensors. There are advantages in having open boreholes, access ports, fiber-optic cable and other infrastructure emplaced during barrier construction. The systems below are novel and perhaps not at the technical readiness level for full consideration today but may prove useful in the upcoming years.

8.3.1 Distributed Temperature Sensing

Fiber-optic distributed temperature sensing measures temperature at a resolution of 0.01 degrees Celsius and spatial resolution of 1 m along standard cables of lengths to 30 km (Selker and others, 2006). The system sends discrete laser pulses down a continuous optical fiber. The light scatters and returns to the detector where the incidental Ramen and Brillouin backscattering measure temperature along the entire cable length. Fiber optic sensors have many other geotechnical applications including axial strain along the cable (Pei and others, 2014), slope stability (Zhu and others, 2015), and vertical displacement (Zhang and others, 2018). Recently, distributed acoustic sensing along telecommunication fiber allowed geophysicists to use passive seismic signals from trains to image shallow geologic structures and groundwater depths at 2 m spacing over 27 km of fiber (Ajo-Franklin and others, 2019).

Actively-heated fiber optic θ detection is based on the thermal response and decay of soil temperatures along the fiber. Electrical current is discharged through the protective stainless-steel cladding around the fiber. The time varying response and decay following heating are measured and inverted to estimate soil moisture content every meter along the fiber (Sayde and others, 2010). This technique was originally proposed to anticipate the intrusion of moisture into mixed waste repositories (Weiss, 2003). More recently, it is being investigated for its potential use in capillary barriers at landfill sites (Wu and others, 2020). Advantages include spatially explicit θ measurements; the fiber is relatively inexpensive and easy to install during construction. Sourbeer and Loheide (2016) found a hysteretic response of the heat pulse as soil structure healing that resulted in air gaps around the cable. Other disadvantages are the “relative” nature of the soil moisture measurements, significant computational processing, and general maintenance of the system.

These technologies all use standard fiber optic cable common to the communications industry making it inexpensive and readily available. The various instrument and technologies simply connect to the fiber. For a barrier under construction, the simple addition of a horizontal fiber between or within layers could make an ideal monitoring device with unlimited potential in the short- and long-term.

8.3.2 Nuclear Magnetic Resonance

Nuclear magnetic resonance (NMR) characterizes the pore-scale environment of hydrogen-bearing fluids, such as water, by inducing rotation in hydrogen nuclei and quantifying its angular momentum during relaxation (Walsh and others, 2013; Walsh and others, 2014). Surface and borehole NMR consists of a permanent magnet and an array of radio-frequency induction coils, which excite and measure the NMR response to the induced magnetic field (Behroozmand and others, 2015; Knight and others, 2016). A series of magnetic pulses causes a weak oscillating radio signal that is detected by the tool. The relaxation of the water molecules after each pulse allows the NMR to determine the soil water content approximately 10 cm away from the borehole, noted as the shell radius of measure. The relaxation of bound and moveable water provides an estimate of hydraulic conductivity, as well. While NMR has distinct advantages over other geophysical imaging techniques by directly measuring water content, the instruments are currently cost-prohibitive for routine monitoring.

8.3.3 Cosmic Ray Neutron Sensors

Cosmic Ray Neutron Sensors are a non-contact, proximal sensor that measures low-energy cosmic-ray neutrons generated within soil, moderated mainly by hydrogen atoms, which diffuse back to the atmosphere (Zreda and others, 2008). A neutron detector is mounted above the surface and the moderated neutrons are counted and converted to θ. The measurement represents a large area with a 200 m radius (0.20 km^2) around the sensor. The depth of measurement is variable and dependent on total hydrogen-content, decreasing when wet (~0-5 cm) and increasing when dry (0-50 cm). The sensor operates in similar fashion to a neutron probe but cannot differentiate between hydrogen pools bound in clays, in soil moisture, in vegetation, or in snow without calibration (Desilets and others, 2010; Franz and others, 2012). The senor can be fixed or used on a mobile platform for large scale soil moisture mapping (Franz and others, 2015). The biggest advantage of this technology is operation and maintenance which is relatively easy since nothing is buried in the ground.

8.3.4 New Remote Sensing Technologies

Remotely sensed imagery from airborne or satellite platforms can detect and monitor ground settlement, erosion, and landslides on macro- and micro-levels using differential synthetic aperture radar (SAR) interferograms (Berardino and others, 2002; Wasowski and Bovenga, 2014). European Space Agency imagery from ERS-1/ERS-2 was used to monitor erosion and settlement of earthen covers on uranium mill tailings impoundments using SAR coherence analysis, differential radar interferometry (DInSAR), and multi-temporal interferometry (Necsoiu and Walter, 2015). DInSAR methods can measure differential settlement of tens of mm. Soil micro-topography changes on fragile hillslopes have been detected using UAS photogrammetry and structure-from-motion image processing (Jiang and others, 2020) and/or terrestrial LiDAR devices (Telling and others, 2017; Eltner and others, 2018). Periodic UAS imagery, even simply optical data, can provide valuable data and sensors keep improving along with the UAS platforms.

Space-borne soil moisture measurements from passive L-band microwave emissions produces coarse, yet accurate soil moisture maps. Active L-band radar systems improve spatial coverage but with lower precision. The Soil Moisture Active Passive (SMAP) combines the two to produce 9 km soil moisture with a 2-to-3-day revisit time (Chan and others, 2016). Microwave emissions generate from shallow soil (<5 cm) and do not have much direct use for monitoring an ET cover system. Unfortunately, the SMAP active radar became inoperable about 3 months into the mission. However, Sentinel-1 SAR satellite uses C-band radar (and shallower emissions depth) and has recently started soil moisture retrievals at 1 and 3 km (Das and others, 2019; Peng and others, 2021). In 2023, NASA and the Indian Space Research Organization plan to launch a joint SAR mission called NISAR combining an L-band microwave radiometer and S-band SAR that is expected to provide surface soil moisture maps at 200 m spatial resolution with12-day revisit times. Other systems are under development to use L-band scattering from global positional systems (Chew and Small, 2018; Kim and Lakshmi, 2018) and micro-satellite constellations (https://spire.com/) to increase spatial and temporal coverage. Microwave radiometers are being developed for permanent installation on tall masts and downsized platforms for UAS. For now, we can only speculate that these technologies will improve our ability to remotely monitor shallow soil moisture, vegetation, and surface subsidence.

9 CASE STUDIES AND LESSONS LEARNED

The following section summarizes applicable field studies available in the literature. First, recent UMTRCA cover performance is noted from annual site inspection reports to determine the primary long-term surveillance and maintenance (LTSM) issues noted. Second, several key takeaways from the ACAP assessment of ET covers are presented. Third, three case studies are examined from national laboratories that have facilities at DOE hazardous sites. In addition, several other relevant studies are presented.

9.1 UMTRCA Cover Performance

In accordance with site-specific Long-term Surveillance Plans (LTSP), LTSM activities by DOE/LM include: inspecting and maintaining sites, monitoring environmental media and institutional controls, conducting any necessary corrective actions, and other regulatory stewardship functions at UMTRCA Title I and Title II sites (DOE/LM, 2020a). All these sites require some degree of routine monitoring and maintenance, which may include water quality monitoring, erosion and vegetation control, routine maintenance of perimeter controls, and general custodial duties. In most cases, the annual inspection reports have noted little to no change to the disposal cell and the associated features over the ~30 year monitoring period (DOE/LM, 2020a). Minor issues included erosion control and stabilization (Canonsburg, Green River, Naturita, and Shiprock); vegetation management of deep-rooted shrubs or noxious invasive weeds (Ambrosia Lake, Burrell, Canonsburg, Durango, and Slickrock); and the stabilization, degradation, or accumulation of windblown sediment in the riprap (Canonsburg, Lakeview, Salt Lake City, Shiprock, and Tuba City). Title II sites tended to have more issues with groundwater contamination (Bluewater and Shirley Basin South) related to on-site processing (DOE/LM, 2020b).

A Title I disposal site in Burrell, Pennsylvania closed in 1987 (Table 1-1). Three years after the construction of a 4-acre disposal cell containing about 86,000 tons of mill tailings, a varied plant community established on the cell's rock cover (Waugh and Weston, 1999). Plant root intrusion can create macropores, which in turn can increase water infiltration through the compacted clay soil layer and the potential for radon-222 to travel to the land surface. Saturated hydraulic conductivity measurements at the Burrell site showed a two orders of magnitude increase over the design standard in water flux through the compacted clay layer (Waugh and Weston, 1999). It was concluded that ecological evolution on the landfill cover must be considered during the design phase to ensure compacted clay layers, intended to act as low-permeable barriers, do not degrade (Waugh and Weston, 1999).

An early field study at Shirley Basin by Morris and Fraley (1989) measured radon-222 flux from two plots of uranium mill tailings, each buried under 30 cm of overburden and 20 cm of topsoil with both bare and vegetated measurement areas. One of these plots also had a 30 cm clay cap above the tailings. The study concluded that radon-222 flux on the vegetated clay cap plot was over three time greater than the vegetated plot without a clay cap, and 18 times greater than the bare plot with a clay cap. This increased radon flux is due to the growth of plant roots in the moist clay, which in turn enhanced radon transport to the surface.

The "Radon Barriers Project" is a research program to study the effects of changes in the properties of in-service engineered earthen covers over uranium mill tailings as these covers aged. Field studies were conducted at four UMTRCA sites: Falls City in Texas, Bluewater in New Mexico, Shirley Basin South in Wyoming, and Lakeview in Oregon. Small areas were excavated, radon fluxes were measured, observations were made, and samples were taken for parameters including saturated hydraulic conductivity, root counts, moisture, density, lead-210 concentrations, soil texture, structure, chemistry, and nematode counts. The results of the project, which are compiled in Fuhrmann and others (2019a) and a NUREG/CR report by (Williams and others, 2022), indicate variable radon fluxes, much higher radon diffusion coefficients than prescribed in Rogers and others (1984), and accelerated radon travel times through the covers.

At the Grand Junction Disposal Site in Colorado, Waugh and others (2014) and Waugh and others (2015) tested the idea of natural conversion of a radon barrier to an ET-radon cover system by enhancing natural soil-forming processes and ecological change on sections of the existing radon barrier. They used furrowing and ripping as means for creating depressions parallel to the slope contour, bringing soil up into the rock riprap layer, and loosening and blending compacted fine soil with coarse sand and gravel layers to evaluate soil manipulation and revegetation methods. Ripping with an oscillating plow decreased soil bulk density but also created large soil aggregates and voids that may create preferential flow paths and reduce water storage capacity.

Smith and Benson (2016) modeled one-dimensional erosion for a period of 1,000 years at the Grand Junction Disposal Site. Landform evolution modeling was performed using the SIBERIA landform evolution model (Willgoose and others, 1991), which considered the following four main factors affecting fluvial erosion: (1) climate, (2) soil, (3) vegetation, and (4) topography . The following types of surface covers were simulated: riprap, topsoil, and gravel admixture. Vegetation decreased the amount of erosion by 1.5 m and 4.0 m in semi-arid and humid climates, respectively. Overall, riprap was the most effective at minimizing erosion; however, it also increased percolation. A gravel admixture surface had slightly higher erosion but minimized percolation regardless of climate.

The cover system at the Monticello, Utah, Superfund site, constructed in 2000, employs a RCRA cover Subtitle C design for hazardous waste. The cover is comprised of the following components: a sand drainage layer capillary barrier, a geomembrane, a compacted soil layer, and a thick vegetated SWS layer (Waugh and others, 2009). The surface layer (0-20 cm) consists of a mix of gravel and topsoil to mimic conditions leading to the formation of a stable desert pavement over time (Waugh and others, 2006). Later, a large (3 ha) lysimeter was embedded in the cover system which collected data over a 9-year period (Waugh and others, 2009). The data showed that the cover system successfully limited percolation to less than 3 mm/y, and that SWS was 80-90% of the laboratory-derived values. This study confirmed that field measurements should be used for evaluating cover performance. The study also showed that that development of weak soil structure had little influence on the overall performance of the cover, and that converting a conventional cover to a more native plant and ET-dominated cover may increase the cover's long term performance and therefore minimize maintenance costs and risks to human health (Waugh and others, 2009).

9.2 The Alternative Covers Assessment Program

The EPA created the Alternative Covers Assessment Program (ACAP) in 1998 to focus efforts on understanding the differences in water balance dynamics between conventional and alternative ET covers at 11 field sites across a range of climates (Albright and others, 2002; Albright and others, 2004). These studies generally concluded: 1) surface runoff was small (i.e. 0-10% of the water balance) and was not sensitive to cover slope, design, or climate, 2) conventional covers with a geomembrane were mostly successful in limiting percolation while conventional soil-only covers were the least successful, 3) alternative ET covers in humid climates did not perform well, although covers utilizing grasses instead of trees did better, and 4) alternative ET covers in arid, semiarid, and subhumid climates performed similar to conventional covers with geomembranes (Albright and others, 2004).

A series of field performance evaluations on compacted clay barriers in Georgia, Iowa, and southern California found that over the course of 2-4 years, the infiltration rates at all sites were observed to have increased by several orders of magnitude. This change from as-built specifications was attributed to cracks creating preferential flow paths in the clay barrier from repeated freezing/thawing and desiccation (Albright and others, 2006a; Albright and others, 2006b).

A study evaluating field hydrology of seven composite barrier sites in varying climates observed that the average infiltration was less than 2.8 mm/*y* on average (Albright and others, 2013). The Hydrologic Evaluation of Landfill Performance (HELP) model was used to predict water balance parameters. The modeling exercise concluded that measured soil hydraulic properties were superior to default values in HELP, which consistently overpredicted percolation (Albright and others, 2013).

Benson and others (2001) compared five different method s for measuring the percolation rates in earthen covers: trend analysis, tracer methods, water balance methods, Darcy's Law calculations, and lysimeter measurements. They concluded lysimeters were the most accurate, although results will vary depending on how the collected water was measured. The lysimeter used in that study was capable of estimating infiltration rates between 0.00004 to 0.5 mm/*y*.

Benson and others (2011a) concluded that cover soil properties change from as-built values with time in a cover, regardless of the climate, cover design, or service life, and when evaluating long-term performance, these new soil properties should be used for model inputs. These soil properties include saturated hydraulic conductivity, saturated volumetric water content, and air entry potential.

Apiwantragoon and others (2015) evaluated 12 ET covers across a variety of climates ranging from arid (~120 mm/*y* of annual precipitation) to humid (1,300 mm/*y* of annual precipitation) and found that percolation ranged from 0 to 225 mm/*y* or 0–34% of the annual precipitation.

9.3 Hanford Site

The Hanford Site occupies over 1,400 km^2 in southeastern Washington on the southern banks of the Columbia River. It was the epicenter of nuclear materials refinement during the beginnings of the atomic age and is now a nuclear legacy management site managed by the DOE. For over 50 years, ET covers with capillary barriers have been under development at Hanford in order to isolate single-shell tanks containing transuranic contaminated solid waste for permanent in-place disposal (Wing and Gee, 1994). Original model results and lysimeter studies showed the importance of vegetation and capillary barriers to control and even eliminate percolation (Fayer and others, 1992; Gee and others, 1992). Bjornstad and Teel (1993) did pioneering work on natural analogues to evaluate long-term cover performance noting deflation by wind, soil compaction, soil eluviation/illuviation, bioturbation, and cryoturbation in the geologic past. Revisiting vegetated lysimeters 17 years later, Fayer and Gee (2006) found no loss in performance, except where plants were completely eliminated and when experimental precipitation was tripled. The recommended test configuration was the Hanford Barrier Design of 1.5 m of Warden silt loam, in which the top 20 cm was amended with 15% pea-sized gravel, over sand and gravel filter layers. Using small tube lysimeters, Sackschewsky and others (1995) concluded that a non-vegetated gravel surface will result in percolation, but the addition of vegetation and ET eliminated percolation even with the experimental application of 450 mm or three-times the mean annual precipitation.

Based on this prior research, a field-scale, multi-layered Prototype Hanford Barrier was constructed in 1994 to test the performance of an ET cover with a capillary barrier design and various side-slope configurations (Ward and Gee, 1997). During construction, U-shaped neutron probe access tubes were installed horizontally at depth above the capillary barrier which was underlain by an asphalt pad that routed any percolation to a dosing syphon, essentially a very large drainage lysimeter. On the surface, Waugh and others (1994b) showed that mixing gravel into the surface soil (i.e., gravel admix), as opposed to armoring the surface riprap, did not negatively affect surface erosion or vegetation establishment over a 5-year monitoring period. Ward and Gee (1997) tripled precipitation using a linear-move irrigation system (including a 1,000-year storm) and found no percolation on any soil-covered plot. A controlled fire to simulate vegetation loss on the barrier resulted in an early summer ET rate that was slightly less in the burned area; however, vegetation quickly reestablished and was able to remove the stored water over a slightly longer period and no change in percolation was noted for five years following the fire (Zhang, 2016). For 20 years, the barrier exceeded RCRA criteria by limiting drainage to well below the 0.5 mm/*y* regulatory rate. Furthermore, the ET cover effectively limited runoff and minimized erosion and biointrusion (Zhang and others, 2017).

9.4 Los Alamos National Laboratory

A series of field and modeling studies (Nyhan and others, 1990; Nyhan and others, 1997; Nyhan, 2005) at the Integrated Test Plot cover demonstration compared the water balance of a conventional trench cap design with an “improved” cap. The conventional trench cap design used at Los Alamos for low-level radioactive waste disposal consists of 20 cm of topsoil over 100 cm of crushed volcanic tuff. The “improved” design incorporates 70 cm of topsoil on top of 46 cm of gravel for a capillary barrier, and ~20 cm of cobble to protect the waste from biointrusion. The surface of both caps was sloped at 0.5%; however, the boundary between topsoil and gravel sloped at 5% to increase lateral interflow in the capillary barrier of the “improved” design. Both cover designs were seeded and allowed to naturally revegetate. Results found that increased ET and an embedded capillary barrier reduced percolation through the “improved” cover by a factor of more than four over the conventional design.

Breshears and others (2005) revisited the Integrated Test Plot cover demonstration more than 10 years after construction. Both cover designs showed similar increases in vegetation biomass and species diversity, although the “improved” cover had fewer invasive species, and rooting was more pronounced with roots noted in the gravel layer. With the exception of soil moisture, there were no discernable differences in soil properties between the two cover designs. Furthermore, there was no observed development of soil horizonation or development; however, macropores along roots were present in both designs. Additionally, the conventional cover was drier and lost ~98% of precipitation to ET while the improved design lost ~95% of precipitation to ET. This difference was mainly due to the 5% slope of the capillary barrier surface causing interflow to increase SWS in the biointrusion barrier. The authors noted that burrowing animals can negatively impact infiltration. They observed an order of magnitude increase in infiltration depth following intense thunderstorms due to the presence of burrows.

They recommended incorporating biointrusion layers of gravel or cobbles into the topsoil, as well.

The Protective Barrier Landfill Cover Demonstration also added a RCRA cover and two capillary barrier designs to the cover demonstration. Nyhan and others (1997) found 10% of precipitation on the conventional design became percolation, while seepage did not occur in either of the other designs. Water balance data collection continued for an additional four years to give a larger 7-year dataset to allow for more robust statistical testing to determine how cover performance varied as a function of slope (Nyhan, 2005). Resulting recommendations from this larger dataset were to choose a slope which minimized long-term runoff and infiltration and maximized evaporation. Site specific slopes could be matched to the sun's altitude and angle; however, a 15% slope is thought to be generally ideal.

9.5 Idaho National Laboratory

Radioactive waste has been disposed at the Idaho National Engineering Laboratory Subsurface Disposal Area in southeastern Idaho since 1952. Small mammals, including mice, rats, and ground squirrels were observed to burrow through and excavate contaminated soils. A study by Arthur and Markham (1983) was aimed at determining the long-term effects of the upward movement of radionuclides through contaminated soils. It was determined that mammal population density was a key factor when assessing disturbed contaminated soils and there was also an increased potential for water infiltration. However, since radionuclide concentrations in contaminated soils were only 0.05% of the amount estimated to be contained in the study site, it was not determined to be a significant risk (Arthur and Markham, 1983). Anderson and others (1987) conducted an analogue study of four monocultures of native vegetation and determined that a thickness 1.4 m of soil was sufficient storage for the maximum precipitation received outside the growing season, although they later increased this depth to 2 m of soil (Anderson and others, 1993).

9.6 Case study summary

Conventional resistive covers with a geomembrane are the most effective cover design to limit percolation; however, the K_s of the barrier and integrity of the geomembrane would likely degrade with time. Several studies noted that K_s of compacted clay layers can increase several orders of magnitude, particularly after repeated wet/dry or freeze/thaw cycles. Many of these studies conclude that vegetation will decrease percolation in more arid regions without the reliance on engineered properties. However, no single ET cover design is universally applicable to all locations.

The performance of ET covers is generally improved when a capillary barrier is used to increase water storage in the rooting zone. The natural combination of a stratified soil (compared to a monolithic cover) and native plants is an effective surface barrier design that will limit deep infiltration (Andraski and Prudic, 1997). Field studies involving monitoring and modeling in arid Texas and semiarid New Mexico concluded that cover thickness, a capillary barrier, and vegetation productivity are very important in ET cover design and performance (Scanlon and others (2005). In arid and semiarid regions, study results indicated that a 1-m-thick ET cover underlain by a capillary barrier would likely be enough to minimize drainage to less than 1 mm/*y* and that vegetation was critical in reducing water stored in the SWS layer (Scanlon and others, 2005).

Models and monitoring data can improve ET cover design. For example, McGuire and others (2009) evaluated a 6.1 ha ET landfill cover at a semiarid site near Colorado Springs, Colorado, over a five-year period. Preliminary simulations using UNSAT-H showed negligible percolation rates of less than 1 mm/*y*. The final cover was a 120 cm thick clay loam compacted to less than 80% Proctor density (1.3 g/cm^3) and seeded with native grasses. Over the study period, lysimeter-measured annual drainage was <0.4 mm/*y*. In general, field measurements should be used for evaluating cover performance.

Lastly, decadal studies and natural analogues have illustrated the resilience of ET covers to extreme storms and wildfire with little impact to their performance.

10 SUMMARY AND CONCLUSIONS

The largest component of the hydrologic cycle, after precipitation, is evapotranspiration or ET. While many conventional cover systems use hydraulic barriers to deflect percolation away from waste, the store-and-release process of ET cover systems takes advantage of ET and the natural water balance cycle, particularly in arid and semiarid environments. This cycle has essentially created the deep unsaturated zones common to southwestern U.S. where interfluve soils on vast alluvial fans have not recharged groundwaters since the episodic periods of wetter (pluvial) climate during the early Holocene 15,000 years ago (Phillips, 1994). Over the long-term, the soil-plant-atmospheric system of arid and semi-arid systems provides an excellent analogue for the design and function of surface barriers intended to limit deep percolation and transport of soluble contaminants to groundwater.

Conventional waste covers, such as UMTRCA covers with radon barriers, are designed to meet specific regulatory requirements. Alternative covers, such as ET or water balance covers, must meet performance criteria by demonstration. Before implementing ET covers at long-term disposal sites, it is prudent to clearly define acceptable performance standards such that any proposed alternative cover can be evaluated (Valceschini and Norris, 1997). A combined ET-radon cover system may include the following performance criteria:

1. Limit surface radon-222 flux to less than 0.74 Bq m^{-2} s^{-1},
2. Limit any increase in the annual average concentration of radon-222 in the air around the disposal site to no more than 0.02 Bq/l, and
3. Limit percolation below the drainage layer to less than 3 mm/y, or 6% of mean annual precipitation.

The preliminary design should adequately document that the ET cover meets or exceeds these performance metrics; first through steady-state analysis of radon and ET cover component thickness calculations, and then through numerical simulations using more site-specific climate, borrow soils, and vegetation data from natural analogues. The refinement process should include alternative scenarios, uncertainty analyses, and pilot studies to document performance ranges of the full-scale cover. The borrow sources that may be needed include topsoil capable of supporting vegetation, sand sources for drainage layers, and gravel and rock for capillary and biointrusion layers. The long-term societal benefit should also meet or exceed the costs to acquire, transport, and properly store these materials, as well as the costs of final construction. The final cover design should balance performance and monitoring with risk reduction and economic benefit over the short- and long-term. The revegetation of the cover surface should consider the correct plant species occurrence and distribution, density and coverage, leaf area index, historical trends, and rooting depth and density to ensure long-term performance is maintained.

Based on this report's technical review of literature on both radon barriers and ET covers, the following conclusions can be summarized:

- Vegetation reduces percolation through the cover to the waste and also limits erosion of the cover surface compared to a bare cover.
- Properly designed and evaluated ET cover systems effectively limit percolation in arid, semiarid, and subhumid regions.
- ET covers are less effective in humid areas.

- ET covers are more effective in regions where precipitation is ‘in-phase’ with the growing season.
- Capillary barriers significantly improve the effectiveness of ET covers by increasing SWS in the overlying layer, providing lateral drainage, and limiting biointrusion.
- ET covers can be resilient to fire and extreme precipitation (rainfall and snowmelt).
- Stable and representative geomorphic surfaces, in the region of the proposed ET cover, provide a natural analogue to aid in cover design (e.g., soils and vegetation) and long-term monitoring comparison.

The implementation of ET-radon cover systems at uranium mill tailings disposal sites should provide the following beneficial improvements over the existing requirements in UMTRCA Title 40 CFR 192.02:

(a) Be effective for up to 1,000 years, to the extent reasonably achievable, and, in any case, for at least 200 years:
    i. Stable geomorphic surfaces in arid and semiarid environments are vegetated, not barren.
    ii. Compared to ET cover soils, compacted, engineered barriers will tend to naturally diverge from their as-built specifications with time.
    iii. Covers with vegetated surfaces should require less ongoing maintenance.
    iv. In time, vegetated covers would more naturally blend into the background and be less prone to disturbance and dispersion by anthropogenic forces.
(b) Provide reasonable assurance that releases of radon-222 from residual radioactive material to the atmosphere:
    i. Water storage layers would provide some additional tortuosity to radon-222 flux, even at lower moisture levels.
    ii. The additional soil thickness provided by the water soil layer of the ET covers also provides additional biointrusion and freeze-thaw protection to the radon barrier.
    iii. Compacted, moist radon barriers are likely to desiccate and fracture over time with or without vegetation on the surface.
(c) Provide reasonable assurance of conformance with groundwater protection provisions:
    i. Vegetated, layered soils in arid and semiarid lands naturally limit recharge (i.e., percolation) through ET.
    ii. Reduced percolation due to the ET cover will increase the isolation of contaminants from the groundwater.
    iii. ET covers rely less on engineered soil properties and more on vegetation to reduce percolation.

The following aspects of an ET-radon cover system should be carefully considered:

- Site-specific cover designs and required documentation of beneficial improvement.
    - Performance standards for each cover design need to be clearly defined before an alternative cover design can be evaluated.
    - Review guidance should be flexible enough to evaluate alternative designs.
- Performance is based primarily on models with highly uncertain parameters and simplified physics
    - Models can provide a basis to optimize soil thickness and target soil hydraulic parameters of the final cover.
    - Models can inform design despite significant uncertainties.

    - Performance, to some degree, can be predicted but needs some verification with monitored data.
- ET covers are bioengineered systems; the design standards are less clearly defined than for conventional covers.
    - Plants will eventually invade any bare, earthen cover. Invasive plant species may also invade an ET cover if is not properly maintained, particularly in the vegetation establishment phase.
    - Vegetation can and will die, but the cycle may improve the resilience of the cover as it evolves with time.
    - Plants provide erosion control through interception and roots bind soil aggregates. However, roots will seek moisture, such as the moist clay-rich radon barrier; they may disrupt the waste if the soil water storage layer dries out and if the plant root penetration depths exceed the cover thickness.
    - An effective vegetated cover will also host macro-fauna that can cause large disturbances from burrowing animals.
- Performance-based monitoring is challenging
    - Longevity of instruments and technologies is not known.
    - Measurements may not fully represent cover processes or miss significant yet discrete events.
    - Access tubes, boreholes, fiber optics, and electrodes have current uses; novel methods may evolve that can use this infrastructure, which could be put in place during cover construction.
- Alternative covers may require more extensive performance monitoring and modeling than conventional covers.
    - Vegetated covers take time to become established and stable.
    - Event-based monitoring is particularly important for ET covers. The water balance system is vulnerable to extreme events (including drought, fire, heavy precipitation), which are unpredictable in nature.
- Borrow materials capable of supporting vegetation may be difficult to find and difficult to revegetate.
    - Not all soils or geologic deposits, particularly in arid regions, are capable of supporting life.
    - Borrow soils should ideally mimic the physical and chemical properties of the natural analogue.
- Construction quality control requirements for ET covers are more challenging than for conventional covers: the design has additional agricultural and restoration components.
    - Traditional approaches to clay and compact soil lifts may not work for water storage layers.
    - Lighter equipment is needed to keep bulk densities lower, which will encourage infiltration and root propagation.

The negative aspects of ET covers are ideally be outweighed by the positives, particularly when considering the long-term benefits of an ET-radon cover system. However, beneficial improvement should not rely solely on predictions from numerical models; data obtained from analogue sites or pilot-scale studies is essential.

10.1 Model Standardization and Best Practices

Due to the epistemic uncertainty associated with model selection, model parameterization, model structure, and modeler, standardization of methodology and modeling tools is necessary to allow an approach that is representative of the consilience of approaches. Modeling tools could be developed to impartially assess the performance design and performance of proposed covers. Such tools could effectively develop climate input datasets and general hydraulic and vegetation parameters to efficiently model proposed cover systems. However, no singular model currently available incorporates all the processes related to percolation and gas flux related to such covers, which leaves further discrepancy when ET cover proposals are presented.

The ideal, and most cost effective, water-gas-pedogenic model for long-term performance evaluations would require integrating several models. None of the available vadose zone models were designed to account for pedogenic processes or climate/vegetation changes for both short- and long-term effects. Pedogenic processes generally operate over long times scales on natural soils, but engineered soils are likely to evolve more quickly. Quantitative rates of soil development on cover components are not known. Similarly, constraints and estimates of vegetation growth, root development, and succession, in the short- and long-terms, should be integrated into performance assessment models for ET covers.

10.2 Site Data for Models and Monitoring Methods

Regardless of the model used, benchmark datasets are needed for model and modeler evaluations. Open-data allows new models to be developed and tested against a quality-controlled dataset to verify reasonable results before being applied to new sites or extreme cases. Furthermore, direct, or indirect performance monitoring methods should endure changing technologies. In situ sensors provide high temporal resolution data but at limited spatial extent, and the buried electronics will eventually fail. Tube-access sensors and fiber optics may be a better route for long-term monitoring. Access tubes and fiber can be emplaced vertically or horizontally during construction. Several sensors work in access tubes, including the neutron probe which remains the most accurate and precise field method for soil water storage. Clear, acrylic tubes can image roots and structural cracks. Standard fiber optics can be used with a variety of technologies to measure temperature, stress, and moisture. With the simple addition of a horizontal fiber, boreholes are wired geophysical electrodes and could make an ideal monitoring device in the near- and far-term as technologies improve. Initially, testing and evaluations of such systems could begin.

Monitoring ET cover performance using remotely sensed data is likely more applicable to assessing vegetation performance using greenness indices like NDVI than direct monitoring of ET. Field measurements of ET using eddy covariance errors average 84% of energy balance closure (Stoy and others, 2013). These water-balance methods assume percolation is the difference between precipitation and ET; however, the errors and uncertainty remain considerably higher than the percolation which is likely far less than 10% of annual precipitation. Direct observations of short- and long-term performance are ideal, but observational data of any kind can improve models and refine conceptual approaches. Additionally, new sensor technologies (in situ and proximal), and improved algorithms to process such data, should be tested and evaluated. As covers age, soil moisture in clay barriers may decrease and radon diffusion coefficients may increase. Given such large uncertainties and risks related to exposure, the long-term monitoring plan should consider methods to periodically measure both percolation and radon flux.

10.3 Closing Considerations

The final design of ET-radon cover systems is rooted in selecting suitable soils and materials for each component, adding amendments where needed, and ensuring that the thickness of each layer optimizes ET while minimizing desiccation of the restrictive layers (i.e., radon barriers and infiltration barriers). ET covers have been successfully implemented at numerous sites. For example, the EPA's alternative cover database at https://clu-in.org/products/altcovers/ (accessed September 29, 2021) lists 187 Monolithic ET covers and 28 Capillary Barrier ET Covers project profiles. While ET covers are generally becoming accepted at landfill sites with 30-year closure periods, the following questions remain for their application at sites requiring substantially longer closure periods:

1. Can unacceptable levels of infiltration of water through the waste be averted by using ET covers (i.e., beneficial use)? Furthermore, if a radon barrier, or other types of cover components (i.e., geomembranes) are present above the waste, can their degradation be averted or delayed?
2. To what extent can degradation of the ET cover be tolerated (i.e., regulatory compliance) over its short- and long-term life cycle?

Any technical solutions that can be applied in a restoration/remediation context should balance public expenditures (i.e., cost) with societal benefit. The performance of any cover, particularly those designed as ET covers, is a complex interaction between climate, weather, vegetation, cover components, and component thicknesses. None of these elements will remain static over the long-term as climate, vegetation succession, and pedogenesis progress and the cover evolves as open systems do in the natural environment. By looking to nature (i.e., stable natural site analogues) for design guidance, some of the negative effects of nature on a cover system may be minimized.

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report evaluates evapotranspiration (ET) cover designs with an emphasis on applications to long-term disposal sites such as Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA) sites. ET covers reduce percolation by storing precipitation then allowing vegetation to cycle it back to the atmosphere. For long-term waste isolation, ET covers may provide significant benefits over conventional, resistive covers that rely on engineered components, such as compacted clay barriers and geomembranes, to divert precipitation. UMTRCA covers were designed to impede and attenuate radioactive radon-222 gas flux from the underlying tailings, while minimizing percolation of any contaminants to groundwater. Such covers have implicit regulatory compliance post-construction. Alternative cover systems, such as ET covers, must explicitly meet some anticipated performance, and demonstrate beneficial use. While all engineered structures will change over time, an ET cover evolves with nature rather than resisting it, which may perpetuate a more reliable waste isolation system. The design of an ET cover is far more dependent on mesoscale meteorology, native vegetation, and edaphic soil properties, which are site-specific. Therefore, the design and anticipated performance of an ET cover should be demonstrated through a combination of modeling, natural analogue and pilot studies, and then verified with monitoring data.

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