Evapotranspiration covers at uranium mill tailings sites

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UPDATES

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Abstract
Waste isolation is a key strategy for mitigating risk from municipal solid waste (MSW) and hazardous waste streams. Conventional covers at MSW facilities are designed for a 30-yr post-closure period where compacted soils and geosynthetics are used to minimize percolation into buried waste. Recently, evapotranspiration (ET) covers have shown beneficial use for MSW management. Evapotranspiration covers encourage infiltration, storage, and transpiration of precipitation to minimize percolation. Such covers may also have beneficial use for long-term waste issues, such as at Uranium Mill Tailings Radiation Control Act (UMTRCA) sites. These sites were covered by a clay radon barrier to create tortuous flow paths that allow radioactive decay and attenuation of short-lived, radon-222 gas. For long-term waste isolation, an ET-radon cover may provide greater resilience by exploiting natural processes instead of resisting them. This update presents a review of the current state-of-the-science regarding ET covers and considerations for long-term applications.

1 INTRODUCTION

Waste residing on the land surface poses 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 the waste and the transport of contaminants to receiving water bodies. Conventional earthen cover systems use combinations of materials of low saturated hydraulic conductivity ($K_s$), geosynthetic liners, and geomembranes to isolate municipal solid waste (MSW) and hazardous waste streams from the environment. Conventional MSW covers are designed to meet regulatory requirements at the time of construction and for a post-closure period of 30 yr (USEPA, 1989). However, the engineered properties of the restrictive layers, created by compacting fine-textured soils, can change rapidly over time. Specifically, pedogenic processes acting on the cover soils leads to the formation of soil structure, fractures, and macropores (Albright et al., 2006; Benson et al., 2007, 2011; Breshears et al., 2005; Fuhrmann et al., 2021; Jangorzo et al., 2013; Williams et al., 2022).

In more arid environments, vegetation has been successful at limiting groundwater recharge through evapotranspiration (ET) (Gee et al., 1992). Beginning in the 1990s, MSW management pivoted from conventional to alternative cover systems (USEPA, 2011), such as ET covers. Evapotranspiration covers, also referred to as water balance or store-and-release covers, use a noncompacted, soil water storage (SWS) layer to retain precipitation and allow vegetation to remove it during the growing season, thereby naturally minimizing percolation (Scanlon et al., 2005). Unlike

Abbreviations: ET, evapotranspiration; MSW, municipal solid waste; NRC, U.S. Nuclear Regulatory Commission; RCRA, Resource Conservation and Recovery Act; SWS, soil water storage; UMTRCA, Uranium Mill Tailings Radiation Control Act of 1978.
conventional covers with implicit regulatory compliance, ET cover designs are site specific and need to meet or exceed certain performance criteria, which complicates the implementation of their design (Albright et al., 2010; Ho et al., 2002; Khire, 2016; Khire et al., 1997). Evapotranspiration covers have been successfully used for MSW management in all environments across the United States. The USEPA manages an alternative cover database located at https://clu-in.org/products/altcovers/ (accessed 29 Sept. 2021), which currently lists 187 monolithic ET covers that use a single fine-textured soil layer to support vegetation and 28 capillary barrier ET covers that add a coarse-textured layer underneath creating a discontinuity in pore sizes.

Uranium production produced large volumes of waste, some of which contain long-lived radionuclides, particularly across the southwestern United States (Figure 1). 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. Unlike MSW facilities, UMTRCA disposal sites rely on vegetated or rock-armored covers to effectively minimize disturbance and dispersion for the permanent isolation of tailings and associated contaminants for a minimum of 200 yr, and to the extent achievable, for 1,000 yr. The UMTRCA covers have started to show signs of post-closure change. The “Radon Barriers Project” evaluated four UMTRCA disposal sites 20 yr post-closure and found that natural processes, including ecological succession and soil formation, were changing engineered covers in ways that could negatively affect percolation and radon flux requirements (Fuhrmann et al, 2021; Williams et al., 2022). Evapotranspiration covers may provide a more resilient solution to a long-term environmental problem.

This update reviews technical information and the necessary considerations to implement ET covers at disposal sites with long-term regulatory requirements, such as UMTRCA

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**Core Ideas**

- Conventional cover designs assume that engineering properties are static in time.
- Evapotranspiration (ET) covers integrate natural hydrologic and ecologic processes into the design.
- ET covers may provide improved resilience at long-term disposal sites with radon barriers.
- Scientific basis and regulatory implications of using ET covers at long-term disposal sites.

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**FIGURE 1** The USDOE currently manages 19 Title I and five Title II disposals sites under the Uranium Mill Tailings Radiation Control Act (UMTRCA). Effective mean annual groundwater recharge rates were adapted from Reitz et al. (2017)
disposal sites. We refer readers to Caldwell et al. (2022) for a more detailed technical guidance. Regulatory guidance on implementing ET covers is now under development by the U.S. Nuclear Regulatory Commission (NRC).

2 | URANIUM MILL TAILINGS AND UMTRCA

Beginning in the 1940s, uranium production generated enormous quantities of mill tailings as the by-product of the uranium enrichment for the development of nuclear weapons and energy. Mill and disposal sites pose an indefinite risk due to the quantity and concentration of radioactive materials in the tailings and associated waste, including uranium-238, which has a half-life of 4.5 billion yr. In response to growing public health concerns about exposure to radiological waste materials, Congress enacted the UMTRCA of 1978 to limit long-term gas emission and groundwater contamination by requiring earthen covers over tailings. Groundwater contamination has been effectively mitigated at most UMTRCA Title I disposal sites (Caldwell et al., 2022). Today, the most serious radiological health concern posed by uranium decay is radiation from radon-222 gas emitted from the tailings.

The primary objectives of an UMTRCA cover are 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. This was achieved using either a radon barrier of highly compacted fine-grained native soil or a bentonite-amended soil of sufficient thickness and moisture content to attenuate the flux of radon-222 from the cover ($J_r$) to less than 0.74 becquerels per square meter per second (Bq m$^{-2}$ s$^{-1}$) and an average concentration of 0.002 Bq L$^{-1}$ above background. These radon standards are design standards in which compliance is determined on the basis of predicted rather than measured emission rates or concentrations (USDOE/UMTRCA, 1989).

3 | WASTE COVER SYSTEMS

Conventional waste covers are engineered to meet regulatory requirements at the time of construction. At MSW facilities, the annual percolation must not exceed some specified limit. Percolation is the amount of drainage or flux below the cover base. Conventional covers consist of a hydraulic barrier of a fine-grained, compacted soil having a prescribed maximum $K_s$ at construction, or a composite barrier that also uses synthetic, impermeable geomembranes (Albright et al., 2004). When constructed properly, percolation can be limited to 2.8 mm yr$^{-1}$ or 0.4% of the mean annual precipitation across a range of climates (Albright et al., 2013).
et al. (1984). They developed an empirical relationship for radon transport using sieved and repacked (i.e., unstructured) soil cores over a range of saturation ratios ($S_w$, volume per volume) and compaction densities:

$$D_c = 0.07 \exp \left[-4S_w \left(1 - \frac{\varphi}{S_w} + \frac{4}{S_w}\right)\right]$$  \hspace{1cm} (1)$$

where $\varphi$ is the total porosity ($m^3 m^{-3}$), which is estimated from the dry bulk density. In Equation 1, $S_w$ is related to the air-filled porosity, $\varepsilon$ ($m^3 m^{-3}$), by

$$S_w = \frac{\varphi}{\varepsilon}, \text{ and } \varepsilon = \left(1 - S_w\right) \varphi$$  \hspace{1cm} (2)$$

**TABLE 1** Uranium Mill Tailings Radiation Control Act (UMTRCA) disposal site details including cell design and barrier components (USDOE/LM, 2020)

| Site          | Radium-226 Ci | Site Cell | Height m | Grade Surface cm | Component thickness |
|---------------|---------------|-----------|----------|------------------|---------------------|
| **Title I sites** |               |           |          |                  |                     |
| Ambrosia Lake | 1,850         | 117       | 37       | 15               | 2.5                 |
| Burrell       | 4             | 29        | 2        | 15               | 20                  |
| Canonsburg    | 100           | 14        | 3        | 20               | 30                  |
| Durango       | 1,400         | 49        | 24       | 30               | 45                  |
| Falls City    | 1,277         | 93        | 51       | 75               | 15                  |
| Grand Junction| 571           | 146       | 38       | 30               | 60                  |
| Green River   | 30            | 10        | 2        | 20               | 30                  |
| Gunnison      | 175           | 37        | 12       | 15               | 15                  |
| Lakeview      | 42            | 16        | 6        | 10               | 45                  |
| Lowman        | 12            | 7         | 3        | 30               | 15                  |
| Maybell       | 455           | 102       | 27       | 20               | 120                 |
| Mexican Hat   | 1,800         | 48        | 28       | 20               | 20                  |
| Naturita      | 79            | 11        | 4        | 15               | 15                  |
| Rifle         | 2,738         | 83        | 29       | 30               | 15                  |
| Salt Lake City| 1,550         | 40        | 22       | 15               | 120                 |
| Shiprock      | 746           | 42        | 31       | 20               | 30                  |
| Slick Rock    | 149           | 25        | 5        | 20               | 60                  |
| Spook         | 125           | 6         | 2        | 20               | 15                  |
| Tuba City     | 940           | 59        | 20       | 45               | 15                  |
| **Title II sites** |           |           |          |                  |                     |
| Bluewater     | 1335          | 143       | 1335     | 20               | 30                  |
| L-Bar         | 299           | 40        | 299      | 20               | 120                 |
| Maybell West  | 73            | 24        | 23       | 30               | 15                  |
| Sherwood      | 154           | 40        | 154      | 15               | 490                 |
| Shirley Basin South | 612 | 57    | 11 | 25 | 60 |
| **Median** | | | | | |
| **Min.** | | | | | |
| **Max.** | | | | | |
| **Number** | | | | | |

- Where $S_w$ is related to the air-filled porosity, $\varepsilon$ ($m^3 m^{-3}$), by
- $S_w = \frac{\varphi}{\varepsilon}$, and $\varepsilon = (1 - S_w) \varphi$
where soil water content \( (\theta) \) is in \( \text{m}^3\ \text{m}^{-3} \). Several other gas diffusion equations, presented in greater detail in the supplemental material, are noted here as P-1940 (Penman, 1940), MQ-1961 (Millington & Quirk, 1961), and RN-1991 (Rogers & Nielson, 1991), which is an updated empirical model to Equation 1 using more data.

The steady-state diffusion models for radon are shown as a function of \( S_w \) (Figure 3a). Radon barriers have a \( S_w > 0.80 \) at construction (USDOE, 1989) with \( D_c \) ranging from \(~4 \times 10^{-7}\ \text{cm}^2\ \text{s}^{-1}\) using Penman (1940), to \( 1 \times 10^{-8}\ \text{cm}^2\ \text{s}^{-1}\) using Millington and Quirk (1961). The largest differences between models are observed at \( S_w > 0.6 \). Thus, the choice of diffusion model and estimated \( S_w \) will alter the required cover thickness. Rogers et al. (1984) estimate the radon flux at the cover surface \( (J_c) \) for a one-layer cover over a thick waste material:

\[
J_c = J_t \exp \left( -\sqrt{\frac{\lambda}{D_c}} x_c \right)
\]

where \( J_t \) is the radon flux directly from the tailings and waste, \( \lambda \) is the radon decay constant of \( 2.1 \times 10^{-6}\ \text{s}^{-1}\), and \( x_c \) is the radon barrier thickness. As such, the sensitivity of \( D_c \) to \( S_w \) directly affects \( J_c \) and the required \( x_c \) (Figure 3b). The compaction levels, shown ranging from 1.4 to 2.00 g cm\(^{-3}\) and at a constant \( S_w \) of 0.80, show less effect on \( J_t \) (Figure 3c). Lastly, radon-222 half-lives (3.8 d) are calculated using \( D_c \) from Equations 1 and 3 as a function of travel time for a moist radon barrier \( (S_w = 0.8) \) and dry water storage \( (S_w = 0.2) \) assuming 

\[
t = \frac{x_c^2}{D_c}
\]

(Figure 3d). Despite the long half-life of uranium-238, the earthen cover need only be of sufficient thickness to contain the radon-222 throughout several half-lives to minimize the flux, which ultimately escapes into the atmosphere (Nielson & Rogers, 1982). For a 0.5-m-thick radon barrier at \( 0.8 S_w \), the higher \( D_c \) from Penman (1940) attenuates only one half-life, whereas Rogers et al. (1984) attenuates three half-lives. For drier (e.g., \( S_w = 0.2 \)) components, such as 1 m of a water storage layer in an ET cover, there is potentially one half-life of added protection.

### 3.3 ET covers

Unlike conventional covers, the design of an ET cover is site-specific. ET covers can be a single layer (monolithic) cover, a two-layer system using a capillary break, or a multi-component system using geosynthetics (Albright et al., 2010; USEPA, 2011). All ET covers function similarly by storing water in wet periods, then releasing it through ET to the atmosphere during drier periods (Albright et al., 2004). 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. Beneath the water storage layer, ET covers commonly use a coarse-textured capillary barrier to help retain moisture in the root
zone. Generally, USEPA (2011) recommends that ET covers be constructed with water storage layers ranging from 60 to 300 cm in thickness; the thickness can be reduced to 15 to 60 cm when a capillary barrier is used (Section 3.3.2). The primary design considerations for an ET cover include the cover thickness and slope, soil edaphic properties and hydraulic properties, vegetation properties, and expected meteorological conditions (McCartney & Zornberg, 2006). However, ET covers do not have a prescribed formula based on regulatory requirements. Instead, the cover design is first conceived from simple approximations then refined through numerical models and pilot studies (Albright et al., 2010).

### 3.3.1 Water storage layer

Percolation can be controlled to an acceptable limit by selecting a soil that provides adequate infiltration capacity to minimize surface runoff (and erosion), sufficient SWS to retain the water, and a rooting media to sustain vegetation (Apiwantragoon et al., 2015). Gravel-admix is often added to the top of the water storage layer to minimize erosion while vegetation is becoming established (Waugh et al., 1994). The revegetation goal is to set the trajectory of succession by creating a favorable environment for the native system to populate (Albright et al., 2010).

In the preliminary conceptual design phase, the SWS must be sufficient to accommodate the expected precipitation even under extreme conditions. A first approximation of total SWS assumes the difference in soil-water content ($\theta$) at a matric potential ($\Psi$) of $−33$ kPa where capillary forces counteract gravity termed field capacity $\theta(\Psi_{fc})$ and wilting point $\theta(\Psi_{wp})$, which is generally assumed $−1,500$ kPa. Note that drought-tolerant vegetation in warm deserts can survive xylem water potentials of nearly $−5,000$ kPa (Hamerlynck et al., 2002), and evaporation can also reduce soil moisture to below $\theta(\Psi_{wp})$. The SWS can be estimated by integrating over the total depth ($x$) of the soil layer as

$$SWS = \int_0^x \theta(\psi) dx = x [\theta(\psi_{fc}) - \theta(\psi_{wp})]$$

Both values are obtained from the soil-water characteristic curves of the borrow soils that will be used to construct the layer at the appropriate dry bulk density. Figure 4a shows the SWS ($0.27–0.07 = 0.20$ m$^3$ m$^{-3}$) of a hypothetical silt loam water storage layer, compacted to 1.4 g cm$^{-3}$. Assuming the layer is 0.9 m thick, the simplest approximation of SWS is 180 mm; however, 2 m is generally recommended to provide adequate protection for wet years (Anderson et al., 1993).

### 3.3.2 Capillary barrier

A capillary barrier or break in an ET cover is the coarse-textured layer underneath the fine-textured water storage layer. The continuity of interface pore-water pressures ($\psi^*$) and contrast in unsaturated hydraulic properties [$K(\psi)$] between the layers restricts the movement of water into the

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**FIGURE 3** (a) Radon diffusion coefficients ($D_c$) using four analytical expressions presented in Equation 1, and supplemental materials. Using Equation 3, surface radon attenuation ($J_c$) as a function of barrier thickness ($x_c$) over (b) a range of saturation levels ($S_w$) at a constant bulk density of 1.6 g cm$^{-3}$, (c) a range of compaction densities (from 1.4 to 2.0 g cm$^{-3}$) at a constant $S_w$ of 0.80, and (d) the transport time, calculated as number of radon-222 half-lives, for a moist radon barrier ($S_w=0.8$, solid lines) and drier water storage layer ($S_w=0.2$, dashed lines). These scenarios assume 10 Bq m$^{-2}$ s$^{-1}$ from uranium tailings (Rogers et al., 1984). Dashed blue line (b, c) denotes the maximum regulatory compliance $J_c$ of 0.74 Bq m$^{-2}$ s$^{-1}$.
capillary barrier (Khire et al., 2000). The large pores of capillary barrier have an air-entry water potential ($\alpha^{-1}$) closer to saturation ($\psi = -0.25$ m) than the overlying water storage layer ($\psi = -0.50$ m), and moisture will be retained in water storage layer until $\psi^*$ exceeds $\alpha^{-1}$ of the capillary barrier (Figure 4a). At this point, the hydraulic conductivity [$K(\psi^*)$] of the capillary barrier is extremely low ($10^{-12}$ m s$^{-1}$) as the flux is limited to a small number of very small pore-sizes (Figure 4b). As $\psi^*$ approaches $\alpha^{-1}$ of the capillary barrier, the water storage layer maintains a much higher $\theta$ ($\sim 0.25$ m$^3$ m$^{-3}$) and moisture remains in the water storage layer longer, increasing the effective SWS and allowing more time for ET.

Combining Equation 4 with the soil-water retention function (van Genuchten, 1980), Stormont and Morris (1998) created an analytical expression of SWS with more realistic depth integration that also accounts for the capillary barrier (see Supporting Information). Assuming $\psi$ is $-4$ m and the cover is 0.9 m thick, the SWS increases from 177 mm (Equation 1) to 214 mm in the presence of a capillary barrier. Note that USEPA (2011) generally recommends the thickness of a capillary break be 15–60 cm.

**4 PERFORMANCE CRITERIA FOR AN ET-RADON BARRIER COVER**

While conventional covers with radon barriers were designed to meet specific regulatory requirements, alternative covers, such as ET covers, must meet or exceed these performance criteria through demonstration typically accomplished with modeling exercises and pilot studies. To begin the adoption of ET covers at long-term disposal sites, it is prudent that acceptable performance standards be clearly defined in order for any proposed alternative cover to demonstrate beneficial use (Valceschini & Norris, 1997). Regulatory compliance at UMTRCA sites was based on the implicit assumption that the radon barrier remains intact. Adding or retrofitting an ET cover would imply the radon barrier was unaffected by vegetation. However, vegetation can create preferential pathways for gas transport (Fuhrmann et al., 2021), uptake radionuclides and potentially make it bioavailable (Oufni et al., 2013), and even remediate radium from contaminated soils (Kozak et al., 2003). To prevent the migration of hazardous constituents in solution during the active life and post-closure period, RCRA 40 CFR (Code of Federal Regulations) 264.301 specifies at least 1 m of compacted soil with a $K_s$ less than $10^{-9}$ m s$^{-1}$ or 30 mm yr$^{-1}$. For ET covers, the most common performance criterion is less than 3 mm yr$^{-1}$ of percolation from the base of the capillary barrier (Smesrud et al., 2012).

Covers at UMTRCA sites were 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 cover, however, would enhance the overall geomorphic stability of the cover surface. Furthermore, ET covers are also 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 at a site, over a set requirement such as less than 3 mm yr$^{-1}$ for RCRA covers. The beneficial
TABLE 2  Mean annual precipitation (PRISM, 2021), groundwater recharge (Reitz et al., 2017), and the ratio of recharge to precipitation at Uranium Mill Tailings Radiation Control Act (UMTRCA) disposals sites

| Site          | State   | Precipitation (mm) | Recharge (mm) | Recharge/precipitation (%) |
|---------------|---------|--------------------|---------------|----------------------------|
| Title I sites |         |                    |               |                            |
| Ambrosia Lake | NM      | 262                | 0             | 0                          |
| Burrell       | PA      | 1,100              | 265           | 24                         |
| Canonsburg    | PA      | 988                | 253           | 26                         |
| Durango       | CO      | 525                | 43            | 8                          |
| Falls City    | TX      | 710                | 0             | 0                          |
| Grand Junction| CO      | 299                | 23            | 8                          |
| Green River   | UT      | 181                | 7             | 4                          |
| Gunnison      | CO      | 286                | 31            | 11                         |
| Lakeview      | OR      | 349                | 0             | 0                          |
| Lowman        | ID      | 669                | 72            | 11                         |
| Maybell       | CO      | 359                | 47            | 13                         |
| Mexican Hat   | UT      | 165                | 5             | 3                          |
| Naturita      | CO      | 330                | 0             | 0                          |
| Rifle         | CO      | 460                | 45            | 10                         |
| Salt Lake City| UT      | 222                | 6             | 3                          |
| Shiprock      | NM      | 187                | 1             | 1                          |
| Slick Rock    | CO      | 343                | 31            | 9                          |
| Spook         | WY      | 327                | 0             | 0                          |
| Tuba City     | AZ      | 157                | 2             | 1                          |
| Title II sites|         |                    |               |                            |
| Bluewater     | NM      | 243                | 5             | 2                          |
| L-Bar         | NM      | 286                | 0             | 0                          |
| Maybell West  | CO      | 359                | 45            | 12                         |
| Sherwood      | WA      | 349                | 29            | 8                          |
| Shirley Basin South | WY | 300                | 34            | 11                         |
| Median        |         | 328                | 15            | 6                          |
| Mean          |         | 394                | 39            | 7                          |
| Min.          |         | 157                | 0             | 0                          |
| Max.          |         | 1,100              | 265           | 26                         |

Use of an ET-radon barrier cover would imply percolation is at or below analogous levels to the surrounding environment. For example, Reitz et al. (2017) used a water budget approach to calculate effective mean annual recharge at 800 m assuming recharge was the remainder of precipitation, ET and runoff from 2000 to 2013 (Figure 1). The recharge values (Reitz et al., 2017) for each UMTRCA disposal site, along with 30-yr (1980–2010) mean annual precipitation from PRISM (2021), are shown in Table 2. Eight sites are situated in areas that have an annual recharge value below the 3-mm yr$^{-1}$ performance criterion noted above. The median natural groundwater recharge value at UMTRCA disposal sites is 15 mm yr$^{-1}$ or 6% of 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.

4.1  A combination ET-radon cover could infer five 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 no more than 0.02 Bq L$^{-1}$.
3. Limit percolation below the drainage layer to less 6% of mean annual precipitation.
4. Remain effective for up to 1,000 yr, to the extent reasonably achievable and, in any case, for at least 200 yr.
5. Provide reasonable assurance of conformance with groundwater protection provisions.

The 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 long-term surveillance plan is necessary to ensure 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 monitoring or models to verify regulatory compliance.

5. CONCLUDING REMARKS AND OPEN QUESTIONS

The USEPA evaluated the performance of conventional and ET covers with the Alternative Cover Assessment Program. The goal of that program was to develop guidance on ET covers at RCRA Subtitle C (hazardous waste) or Subtitle D (MSW) landfills across the United States over a period of 4–8 yr (Albright et al., 2002). Regardless of climate, conventional covers with composite barriers (i.e., a geomembrane over fine soil) were most effective at limiting percolation to 0.4–1.4% of annual precipitation. Percolation rates for conventional covers using resistive barriers were the least effective with percolation ranging from 6 to 17% of precipitation (Albright et al., 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 yr\(^{-1}\) but less effective in humid environments. Albright et al. (2004) concluded that detailed, site-specific designs are critical to the success of any ET cover design. Alternative ET cover systems are less dependent on engineered properties, such as low permeability barriers and geosynthetics, and more reliant on the soil physics and ecohydrology.

However, ET covers for MSW are typically designed for a 30-yr post-closure period. The application of ET covers at long-term disposals sites with performance periods over 200 yr are certainly a more complex effort. Most ET cover construction and research began in the early 1990s, and most studies were restricted to short-term evaluations (Albright et al., 2004; Scanlon et al., 2005; Ward & Gee, 1997). Longer-term studies and follow-up research have since been collected (Breshears et al., 2005; Fayer & Gee, 2006; Zhang, 2016). Nonetheless, there is still much uncertainty regarding a variety of potential effects to ET cover systems over both short- and long-term periods after construction.

All engineered covers will evolve over time and the as-built specifications and intrinsic properties will change, with compacted earthen barriers the most likely to fail (Suter et al., 1993). The nature-based design of ET covers means that they are likely to be more resilient to such changes. The original factors affecting long-term stability of UMTRCA covers, including surface erosion, biointrusion, soil moisture and geomorphic hazards (Beedlow & Hartley, 1984), now have compounding factors of climate change, invasive species, and soil pedogenesis to consider. Conventional waste covers, such as radon barriers, were designed to meet specific regulatory requirements. Alternative covers, like ET or water balance covers, must meet performance criteria by demonstration. To begin any adoption of ET covers at long-term disposal sites, it is prudent that acceptable performance standards be clearly defined in order for any proposed alternative cover to be evaluated.

The final design of an ET-radon cover system is rooted in selecting suitable soils and materials for each component, adding amendments where needed, and providing adequate soil layer thickness to optimize ET while minimizing desiccation of restrictive layers like radon barriers and infiltration barriers. While ET covers are generally becoming accepted at landfill sites with 30-yr closure periods, the following questions remain for their application at sites requiring substantially longer closure periods:

1. Can unacceptable levels of infiltration 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 or remediation context must balance public expenditures (i.e., cost) with societal benefit. The performance of any cover, particularly those relying on ET, is a complex interaction between meteorology, vegetation, component properties, and layer thicknesses. None of these elements will likely 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 for design guidance, some of the negative effects of nature on a cover system may be minimized. This update provides a broad synopsis of ET covers for long-term management of uranium mill tailings. More detailed discussions can be found in Caldwell et al. (2022) and Williams et al. (2022).

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Todd Caldwell: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Visualization; Writing – original draft; Writing – review & editing. Sarah Tabatabai: Funding acquisition; Project administration; Writing – original draft; Writing – review & editing. Jena M Huntington: Methodology; Writing – original draft; Writing – review & editing. Gwendolyn E. Davies: Conceptualization; Writing – original draft; Writing – review & editing. Mark Fuhrmann: Conceptualization; Resources; Writing – review & editing.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

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