**Landfill Cover Design**

Evapotranspiration Landfill Cover Systems Provide a Natural, Cost-Effective, High-Performance Solution

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The cost-effective and environmentally sound management of waste generated by a growing population is a significant topic for engineers and government officials. While a majority of solid waste landfills are designed to isolate waste with an impermeable landfill cover, experience has shown that long-term management of waste in a dry tomb environment may not be the best landfill design approach. This dry environment results in very slow waste degradation and stabilization rates.

Evapotranspirative (ET) covers are increasingly being considered for use at waste disposal sites, including municipal solid waste (MSW) and industrial waste landfills, because the ET cover system is a more natural and cost-effective solution for landfill closure. ET covers are also being considered for landfill bioreactors where water is applied directly to the waste mass to enhance waste degradation. The EPA has allowed regulatory flexibility for these new approaches to stimulate the development and use of new alternative technologies (www.epa.gov/wastes/nonhaz/municipal/landfill/mswlficr/rdd-fs.pdf).

**Background**

Final cover systems at landfills are designed and constructed to mitigate long-term risk that landfilled waste poses to the environment. These cover systems serve a variety of specific purposes, including controlling infiltration and percolation, promoting surface water runoff while minimizing erosion, preventing direct human and ecological exposure to the waste, and controlling gas emissions and odors.

Conventional landfill covers for sites regulated under U.S. Environmental Protection Agency’s (EPA) 40 CFR Part 258 use materials with low permeability to minimize downward migration of water through the cover to the waste. When coupled with a conventional flexible membrane liner, these cover systems are generally effective in minimizing atmospheric water percolation into the waste. While conventional landfill cover designs effectively limit cover percolation and the emission of landfill gas to the atmosphere, they do little to mitigate the long-term risk the waste poses because water is necessary for biodegradation and stabilization (see photo below).

ET cover systems use a water balance and storage approach to control percolation (Figure 1). The cover acts as a reservoir instead of a barrier, storing moisture during precipitation events until it either transpires through vegetation or evaporates from the soil surface.

This newspaper was 33 years old when it was excavated from a landfill, putting it beyond the 30-year post closure period identified in 40 CFR Part 258.
Burns & McDonnell

In a monolithic soil cover, a single vegetated soil layer is used to retain water and support the vegetation, which is essential to the performance of the cover system. A monolithic cover can be modified through the addition of a capillary break. A coarser material, typically a sand or fine gravel, is placed under the monolithic fine-grain soil. The differences in the unsaturated hydraulic properties between the two layers minimize percolation into the coarse layer. Generally, the difference in pore sizes between the finer and coarser material forms a capillary break at the interface of the two layers. Capillary forces hold the water in the fine-grained layer until the soil near the interface approaches saturation.

The fine-grain material serves the same purpose in the capillary barrier design as it does in the monolithic layer: It stores water until it is naturally removed by the environment. If saturation occurs, the water is transferred into and through the coarser layer to the waste below.

In addition to potentially being less costly to construct than conventional cover systems, ET covers could also deliver equal or even superior performance. This is particularly true in arid and semi-arid environments. Within
these environments, ET covers are less prone to weakening through dehydration, cracking and freeze/thawing cycles.

The capillary barrier design has an added benefit in that the lower coarse material can serve as an effective horizontal landfill gas collection layer when operated at low vacuum. Landfill gas collection lines can be placed in the lower coarse material to collect landfill gas for beneficial use or combustion.

**General Considerations**

The design of ET cover systems is based on sufficient data associated with water storage capacity and evapotranspiration, which controls moisture and water percolation. Design consideration categories involved in the design of ET covers include climate, soil properties, vegetation types and software inputs.

**Climate**

Precipitation and other atmospheric factors — such as humidity, temperature, wind speed, cloud cover and solar radiation — strongly affect the performance of an ET cover. Ultimately, the success of an ET cover depends on the precipitation and evapotranspiration cycle. This cycle varies greatly from site to site. For example, the cover may need to accommodate a spring snowmelt event that causes high runoff over a short period of time, or conditions during cool winter weather with persistent, light precipitation. Ideally, the majority of precipitation will occur during the periods of greatest transpiration.

**Soil Properties**

The storage capacity of the soil is governed by soil texture, which defines the particle size, shape and gradation of the soil. The bulk density of soil is impacted by compaction, which affects the storage capacity of the soil and plant root zones. Minimizing the amount of compaction during placement is a key aspect of ET cover construction. Higher bulk densities may reduce the storage capacity of the soil and inhibit root growth. The required thickness of each soil type depends on the required storage capacity. The soil layers are designed to accommodate extreme precipitation conditions during both dormant and flourishing plant conditions.

**Vegetation Types**

Transpiration is one of the primary mechanisms for removing water from the ET cover. Plant roots uptake water from the soil and convey it to the atmosphere, which helps stabilize the soil moisture content. Established vegetation also helps minimize erosion by stabilizing the cover.
Several factors should be considered when choosing vegetation for an ET cover:
- Historical establishment of seed mix
- Experience with borrow soils
- Growing season
- Ground cover
- Root structure and depth
- Leaf area index
- Evapotranspiration
- Soil amendment requirements

Technical guidance documents and engineering best practices have shown that the benefit of early, strong vegetation establishment is one of the most important factors for cover performance.

**Software Inputs**

WinUNSAT-H, created by the University of Wisconsin, is Windows-based software used to evaluate the effectiveness of varying depths of final ET cover using site-specific data. WinUNSAT-H simulates water balance quantities for runoff, evaporation, transpiration, soil water storage and percolation.

Key attributes of the WinUNSAT-H model:
- Simulation of the removal of water throughout the soil profile via plant transpiration
- Surface boundary driven by site-specific meteorological data that simulates interactions among the soil, plants and atmosphere
- Lower boundary accounting for interactions between the cover and underlying waste
- Soil profile divided into nodes with derivatives approximated by slopes between adjacent points

Some WinUNSAT-H input parameters for soil and vegetation are described in Table 1.

**Cost Considerations**

ET covers have not only demonstrated environmental integrity, but are also a cost-effective alternative to conventional landfill caps. Significant construction cost savings were documented by the Air Force Center for Engineering and the Environment survey, “Survey of Air Force Landfills, Their Characteristics, and Remediation Strategies.” Results of this survey indicated construction costs for ET covers were approximately $119,000 to $321,000 less per acre than for traditional landfill caps at Air Force base landfills across the United States. Additionally, less-intricate repairs further reduce long-term operations and maintenance costs.

**ET Cover Design Potential Limitations**

ET covers can have site-specific limitations owners and designers should consider. In a traditional landfill cover design with a flexible membrane liner, the membrane controls the transmission of gas through the cover. This gas transmission control is useful to limit both the emission of landfill gas to the atmosphere and the introduction of atmospheric gas into the landfill by the gas collection system. Landfill gas collection systems are operated under vacuum. The operation of gas collection systems with conventional covers can be less operator-intensive when compared with an ET cover design because, when coupled with a flexible membrane liner in the cover, the flexible membrane liner prohibits the mixing of landfill gas and atmospheric air. The sensitivity of a particular landfill gas collection system is site- and design-specific. Owners and designers are encouraged to evaluate this potential limitation when considering an ET cover, especially for landfills regulated under EPA 40 CFR, Part 60, Subpart WWW.

![Figure 3: Measuring cover percolation performance.](image-url)
**Table 1:** Key model input parameters for WinUNSAT-H software for ET cover modeling and design.

<table>
<thead>
<tr>
<th><strong>Key WinUNSAT-H Model Inputs</strong></th>
<th><strong>Comments/Explanation</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Soil Input</strong></td>
<td></td>
</tr>
<tr>
<td>Tortuosity</td>
<td>Comparison of the direct path (straight-line distance) to the increased path length due to porous media. Provides a comparison of diffusion in a porous media to an open area.</td>
</tr>
<tr>
<td>Saturated Water Content (θ_s)</td>
<td>Condition occurs when there is no suction. Suction takes place when the soil is unsaturated and water clings to the soil pores (negative soil water pressure).</td>
</tr>
<tr>
<td>Residual Water Content (θ_r)</td>
<td>Condition occurs when there is no additional water which can be removed from the soil in a realistic setting.</td>
</tr>
<tr>
<td>Coefficient of van Genuchten Function (α)</td>
<td>Inversely related to the suction at which the largest soil pores drain of water. As “α” decreases, the point at which the hydraulic conductivity begins to decline occurs at a higher suction.</td>
</tr>
<tr>
<td>The “n” Exponent</td>
<td>Affects the slope of the Soil Water Characteristic Curve (SWCC). As “n” increases, the hydraulic conductivity more rapidly declines as the suction increases and vice versa.</td>
</tr>
<tr>
<td>Saturated Hydraulic Conductivity</td>
<td>Defines the rate at which water is able to move through the soil when the soil pores are completely filled with water.</td>
</tr>
<tr>
<td>Exponent of Pore Interaction Term (γ)</td>
<td>Directly influences how the unsaturated hydraulic conductivity (rate at which water is able to move through the soil when the soil pores are completely or partially filled with air) changes with respect to suction. As γ decreases, a more gradual decrease in unsaturated hydraulic conductivity occurs as suction increases.</td>
</tr>
<tr>
<td><strong>Plant Information Input</strong></td>
<td></td>
</tr>
<tr>
<td>Initial Suction Head</td>
<td>Typically defined as the wilting point or reassigned based on multiple year simulation using average year meteorological data for the Site. Represents initial conditions existing at the Site.</td>
</tr>
<tr>
<td>Day of the Year on which Seeds Germinate</td>
<td>Affects the time period when water can be removed via transpiration throughout the year. Site specific planting/growing dates are used.</td>
</tr>
<tr>
<td>Day of the Year on which Plants Cease Transpiring</td>
<td>Affects the time period when water can be removed via transpiration throughout the year. Site specific planting/growing dates are used.</td>
</tr>
<tr>
<td>Fraction of Soil Surface that is Bare of Plants</td>
<td>The amount of soil surface without vegetative cover. Provides a conservative estimate of vegetative cover based on site-specific plant data.</td>
</tr>
<tr>
<td>LAI Values throughout the Year</td>
<td>Leaf Area Index (LAI) is the area of leaves relative to the area of soil surface. The LAI varies throughout the year and defines the amount of leaf area available for transpiration.</td>
</tr>
<tr>
<td><strong>Root Growth Exponential Relationship Input</strong></td>
<td></td>
</tr>
<tr>
<td>Root Density Function (Coefficient a, b, &amp; c)</td>
<td>Indicates the distribution of roots versus depth. Directly affects the dispersion of transpiration through the root zone.</td>
</tr>
<tr>
<td><strong>Plant Water Intake Input</strong></td>
<td></td>
</tr>
<tr>
<td>Head Corresponding to Water Content below which Plants Witt and Stop Transpiring, cm</td>
<td>Suction at which transpiration no longer occurs.</td>
</tr>
<tr>
<td>Head Corresponding to Water Content below which Plant Transpiration starts to Decrease, cm</td>
<td>Suction at which water flow through the plant is impeded.</td>
</tr>
<tr>
<td>Head Corresponding to Water Content below which Plants do not Transpire because of Anaerobic Conditions, cm</td>
<td>Suction at which oxygen diffusion to the root zone is obstructed due to water.</td>
</tr>
<tr>
<td><strong>Daily Meteorological Input</strong></td>
<td></td>
</tr>
<tr>
<td>Meteorological Data</td>
<td>Site specific daily data for maximum air temperature, minimum air temperature, dew point temperature, solar radiation, average wind speed, and precipitation.</td>
</tr>
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</table>

**ET Cover Instrumentation and Monitoring**

Considerable research has been applied to the design and numerical modeling of cover performance. When considering that ET covers are a relatively new approach, the installation of a lysimeter in the cover system is encouraged — especially if the cover is designed to transmit a certain quantity of water to the underlying waste to promote waste degradation.

A lysimeter collects the cover percolation water and enables the cover flux to be quantified (Figure 3). The installation of a lysimeter in a cover pilot project is an excellent way for owners and designers to evaluate the long-term performance of a full-scale ET cover in advance of full-scale cover construction. Instrumentation that provides moisture sensing coupled with automatic data logging represents an enhanced instrumentation approach to evaluate a site-specified design.

**Summary**

ET cover systems represent a significant landfill design enhancement in the practice of solid waste engineering. The increasing popularity and continued success of monitored ET covers indicate that ET cover design is here to stay.

Instead of using conventional materials with a low permeability to keep moisture out, ET cover systems use a water balance approach to limit percolation. Site-specific borrow soil sampling and characterization followed by numerical modeling of cover performance is critical to developing a successful ET cover system design. This early investment in design effort pays a dividend because ET covers cost less to construct compared with traditional covers.

The construction of an ET cover pilot with an underlying lysimeter is an excellent way to evaluate a site-specific design prior to building a full-scale cover. Lysimeters also provide an opportunity for owners, engineers and regulators to fully understand how a particular cover will perform and provide for a level of comfort that modeling alone may not provide. As interest grows in exploring alternatives different from the dry tomb application, ET covers offer a modern approach to provide limited moisture to the waste, enabling controlled waste degradation and the associated reduction in long-term risk.