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An Application of Event Tree Analysis to Ecological Systems: Understanding the Long Term Performance of Engineered Covers

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Abstract

An approach that is often taken to contain and isolate contaminants in the environment and minimize human and ecological risks is to apply engineered covers over contaminated soil and landfills used for disposal of radioactive, hazardous chemical and municipal solid waste. However, the hazards and potential risks associated with the waste frequently persist well beyond 100 years. Yet, cover design and performance evaluation guidelines frequently fail to consider consequences of inevitable changes in ecological processes and settings. Cover systems, that can perform effectively for very long times (100s to 1000s of years) with minimal monitoring and maintenance are needed at U.S. Department of Energy (DOE) and other sites to assist in isolating contaminants from the biosphere at near-surface landfills, waste-disposal sites, and tanks from which high-level radioactive waste has been removed. Furthermore, rigorous method that includes all of the processes that will affect performance is needed to evaluate long-term performance of covers with quantification of risk and uncertainty.

This research uses lessons learned from experience gained through monitoring existing covers and designing alternative covers that accommodate ecological change to develop a screening method that can assist in identifying covers that my be prone to failure and candidates for renovation. This investigation into the role of ecological monitoring of isolation containment systems includes ways to identify parameters and processes for performance confirmation and monitoring using event-tree analysis. It is becoming apparent that we will need to use a combination of monitoring, modeling, and natural analog studies to evaluate long-term performance of covers. Furthermore, the screening method developed incorporates a performance-based approach that is essential to identify the covers at risk for failure to meet the design performance objectives.

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STUDY SCOPE AND BASIC CONCEPTS

This paper will address three areas of need that have been identified for engineered covers: 1. Need rigorous method to evaluate long-term performance of covers with quantification of risk and uncertainty; 2. Need way to identify parameters and processes for performance verification and monitoring; 3. Need more rigorous methods to compare alternative designs and approaches. With respect to these needs, the scope of this study is to develop a risk-based performance-assessment approach for selection, design, modeling, and monitoring of long-term covers.

PERFORMANCE ASSESSMENT FOR LONG TERM COVER DESIGNS

Regulatory guidance addresses design life both directly and indirectly. The minimum technical requirement is that covers should provide long-term minimization of migration of liquids and that the integrity of the cover should be maintained. RCRA regulations require a minimum post-closure care period of 30 years; however, the design life of the cover system may be much longer and is primarily defined by the service life characteristics of the material used to construct the cover system. EPA (2002) states that the design life goal for RCRA and CERCLA cover systems is to minimize infiltration into the waste for “as long as possible.”

The safety of disposal is evaluated by comparing predicted disposal facility performance to the performance objectives specified in NRC regulations for the disposal of low-level waste (10 CFR Part 61 Subpart C). The performance objectives contain criteria for protection of the public, protection of inadvertent intruders, protection of workers, and stability of the disposal site after closure. Performance assessment provides an estimate of the degree to which performance estimates will be met; quantification of uncertainty in the simulated performance metrics; identification of parameters and processes most important to performance for prioritization of site characterization and long-term monitoring activities; and a comparison of alternative designs to optimize cost and performance while ensuring that regulatory requirements are met (NRC, 2007).

POTENTIAL IMPACTS OF NATURAL PROCESSES ON COVER PERFORMANCE

With time, engineered barriers are subject to modification by environmental processes, particularly after institutional control has ceased. Engineered landfill covers are influenced by a myriad of natural processes that may eventually lead to failure of the barrier. While it is generally accepted that “all waste encapsulation schemes will ultimately fail (Caldwell and Reith, 1993, National Research Council, 2000, J. H. Clarke et al., 2004),” the nature of influence by natural processes is poorly understood. The definition of failure here is that an aspect of the engineered barrier is not performing as

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designed, in other words, a "non-compliance" of the design, which, without intervention could lead to loss of control. A non-compliance does not necessarily have immediate harmful effects, but compounded non-compliances may create a path to a major failure.

Kostelnik and Clarke reported the results of several case study evaluations that led to the identification of thirteen (13) types of controls both engineered and institutional (Kostelnik and Clarke, 2008). They defined failure as "loss of control" irrespective of consequences and developed event trees that enabled the identification of "precursors to failure" (Kostelnik, Clarke and Harbour, manuscript in preparation).

For risk assessment and development of maintenance and repair strategies, it is essential to understand the modes and probabilities of potential failure due to natural processes. The following general categories of natural processes are the most important to consider: wind and water erosion, water infiltration, and plant and animal intrusion.

A primary function of most cover systems is minimization or control of infiltration into the cover and percolation into the underlying waste. Measured percolation rates through covers can provide a variety of insights on the performance of the cover system, including the effectiveness of the surface at promoting runoff, the effectiveness of soil layers above or within the barrier at storing the removing moisture, the effectiveness of drainage layers at minimizing the hydraulic head on the underlying barrier layers, and the effectiveness of evapotranspirative barrier layers at minimizing leakage. Percolation rates for cover systems containing single compacted soil layers have been measured using pan lysimeters in test plots in different climatic regions for durations up to 7 years (Benson, 2001). Percolation through the cover systems increased at all test sites during the respective test periods. These data were consistent with other work showing that dessication, freeze/thaw, root penetration, animal intrusion, and pedogenic processes were major factors affecting the performance of covers with compacted clay layers (Bonaparte et al., 2002).

The need for permanent isolation for extended periods of time means dispersal factors need to be carefully considered in the design of barriers. Elements that can disperse wastes into the environment include water, wind, plants, and animals. Plants will have significant effects on upper layers and can, potentially, compromise a barrier (Bonaparte et al., 2002). Thus, it is important to determine how plants will affect the soil water balance, the stability of the surface subjected to wind and water erosion, and the potential for biointrusion into the waste. Plant communities will establish and change on soil covers in response to climate, soil development, and disturbances such as fire, grazing, or noxious plant invasion. Changes in plant abundance, evapotranspiration (ET) rates, root intrusion, and animal habitat may alter the soil water balance and stability of a cover (VanHorn, Fordham, Haney, 2004). One recent study drew evidence of possible future ecological changes using successional chronosequences (a mosaic of plant communities that represent different stages of recovery following a disturbance).

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The vegetation community on engineered covers will likely change over time. Predicting community dynamics on engineered surfaces that are expected to function for hundreds to thousands of years becomes an important consideration. The plant community may change in response to climate or to disturbances such as fire or human disturbance. Climate change and disturbances can alter the numbers, types, and diversity of species, and may be accompanied by changes in water extraction rates. Even under the present climate, and without disturbances, species abundance, biomass production, and transpiration rates vary seasonally and from year to year in response to precipitation and temperature. Plant community dynamics describe changes in the abundance of various plant species as well as the introduction and extinction of species (Lopez, et al., 1988). Short-term changes in species composition are related to disturbance and alien introductions. Long-term changes in plant communities in response to climate change could significantly alter long term barrier performance, especially if the new conditions are outside of the design criteria of the barrier. For example, if the climate were to become wetter, deep-rooted plants could become established that might intrude into the buried waste in a barrier designed for shallow-rooted plants in the arid West.

Biointrusion of the engineered cover is difficult to eliminate. Animals and plants entering the landfill area create a perpetual cycle. Vegetation entices animals, and as animal population increases, more vegetation seeds are transported to the location by the animals. Small burrowing mammals are of greatest concern because the animals' movement through the cover can compromise its design. Furthermore, burrows throughout the cap can increase the hydraulic conductivity of the soil, allowing water to infiltrate more quickly and more deeply. The burrows can create passages for air and thereby dry out the soils (Suter, et al,. 1994). Therefore, the structure, bulk density, and effective permeability of cover layers can be altered through time by pedogenic processes and related disturbances by plants and animals.

Environmental changes with time can result in rooting patterns, evapotranspiration, and erosion that are quite different from initial conditions. Climate changes may affect a site's water balance directly through increased or decreased precipitation and indirectly through influences on pedogenic and ecological factors. Numerous reports have pointed out the potential for environmental processes to modify landfill covers and liners.

Important questions emanating from the aforementioned environmental impacts include how soon and to what magnitude natural processes will occur, and what other confounding effects can be expected. Any changes in plant cover, burrowing animal behavior, precipitation and temperature, and wind regimes, may influence the stability of the barrier surface.

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ALTERNATIVE ENGINEERED CONTAINMENT SYSTEMS

Final covers serve to isolate the waste materials from human and ecological receptors. In addition, landfill covers serve to reduce the amount of infiltration and minimize the generation of leachate. Minimizing the generation of leachate reduces the need to manage the liquids and reduce the potential of contaminants from the landfill to impact the environment whether soils, groundwater, or surface water.

Conventional covers are designed to use low-permeability materials (i.e., compacted clay or geomembranes) to reduce or eliminate the infiltration of precipitation into the waste layers, thereby reducing the head on the liner and potential for leaching contaminants into the surrounding environment. While the concept is sound, practice has demonstrated that some of the existing requirements may be detrimental to achieving the goal of waste isolation, which may lead to a myriad of complex problems.

Often regulations and guidance require use of low-permeability compacted clay material to isolate the waste layers. One problem may be that acceptable clay borrow materials for construction purposes may not be readily available. Clays have the potential to dry and fracture. Then water (precipitation) may migrate through the fractures, compromising the intended matrix flow of low-permeability compacted clay. Desiccation as well as freezing, intrusion by plant roots, or burrowing animals, can result in the development of preferential flow paths in clay barriers, thus compromising long term performance.

Conceptually, the simplest type of alternative cover consists of a vegetated soil layer. An evapotranspiration (ET) cover is a specific type of vegetative cover. The ET landfill cover is designed to work with the forces of nature rather than attempting to thwart them. It uses a layer of soil covered by plants, and it contains no low-permeability barrier layers. The ET cover uses two natural processes to control infiltration into the waste: the soil provides a water reservoir, and natural evaporation from the soil plus plant transpiration empty the soil water reservoir. It is an inexpensive, practical, and easily maintained biological system that will remain effective over extended periods of time, perhaps centuries, at relatively low cost.

The principle upon which an ET cover works is that the soil layer holds incoming precipitation until it is removed by evapotranspiration. If the soil layer has sufficient storage capacity to hold the water until it can be removed by evapotranspiration, then no deep percolation will penetrate past the cover (Johnson and Urie, 1985). Despite the apparent simplicity of the design, proper performance of an ET cover depends on careful and robust analysis of the site variables and a thorough design procedure.

Performance of an ET cover, explicitly the health of the vegetative community as measured by percent ground cover and species richness, is strongly driven by four fundamental processes of the operating environment: soil water storage,

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evapotranspiration, vegetation and climatic factors. These processes are comprised of highly coupled parameters that must be characterized in order to develop an appropriate screening tool. It is important to note that these processes can vary significantly between sites; therefore, it is essential to understand how these processes may vary under range of possible conditions.

U.S. Environmental Protection Agency (EPA) has a database tracking alterative cover demonstration projects and full-scale operating facilities in locations representing the range of physical environmental across the country. Annual rainfall associated with these alternative landfill cover projects ranges from a low of approximately 3.5 to a high of 56 inches per year. Twenty-four of the Alternative Final Covers (AFC) are demonstration projects, and 11 are full-scale covers at operating facilities.

USE OF MODELS FOR PERFORMANCE ASSESSMENT

Predictive hydrologic models have been used for landfill applications since the early 1980's. Complex simulation models of ecological processes are increasingly constructed for use in both the development of models and the analysis of environmental questions (Ho et. al., 2004). However, such models can never be validated due to the limited observation of system dynamics. They can, however, be used to investigate deficiencies in the relationships they define between ecological theory, model structure, and assessment data.

Many cover performance models have the capability to incorporate long-term seasonal information into a water balance model approach but this is not typically done. Furthermore none of the models typically used incorporate important short-term and long-term ecological processes into the analysis.

There are four potential sources of failures in an ecological process model, each associated with a different phase of the modeling activity.

- inadequate selection of the component ecological hypotheses (an incorrect process structure)
- inadequate mathematical representation of these hypotheses (an incorrect mathematical structure)
- inadequate fitting procedure (a faulty parameterization)
- and, inadequate selection and formulation of the assessment criteria (an insufficient model assessment context).

MEASURING PERFORMANCE OF EVAPOTRANSPIRATION COVERS

The design and subsequent performance of conventional covers relies on the use of low-permeability materials (i.e., geomembranes or compacted clay) and the assumption that

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these materials will impede the downward flow of water over large areas and for extended periods of time. In contrast, performance of an ET cover depends on combining soil layers, plant species, and atmospheric conditions to form sustainable, functioning ecosystems that tend to maintain the desired water balance (Albright et. al., 2004). The ET cover design must focus on performance by evaluating each component of a design individually and with respect to its interaction with the other components. Performance of an ET cover is strongly driven by three fundamental processes: soil water storage, evapotranspiration, and climatic factors.

Soil water storage

Soils vary in ability to absorb and retain moisture according to pore structure, which is largely a function of grain size (i.e., fine-grained soil can store more water than coarse, sandy soils) (Holling, 1973). The soil column that composes an ET cover must be capable of storing the required quantity of water and supporting the vegetation community required to remove the water from the cover.

Determination of the soil water-storage capacity of available soils is fundamental to performance forecasting of an ET cover. This quantity represents the difference in volumetric water content between wilting point and field capacity of the soil in relation to plants. Wilting point is the water content at which transpiration ceases and thus represents the driest state of the soil layer when plants lack sufficient water to transpire. Field capacity is the water content at which no additional water can be added to the soil profile without significant drainage. The difference between these two points represents the storage capacity of the soil.

The vegetative community is influenced by the edaphic properties of the soil, especially calcium carbonate, moisture content, and total soluble salts. Although, these factors exhibit wide range of variation between different sites, field studies show that variation in these edaphic features tends to be greatest under differing climatic regimes. Therefore, soil edaphic properties will interact with plants differently in arid versus humid environments.

Evapotranspiration

The movement of water from the soil column to the atmosphere by bare-soil evaporation and transpiration by plants is crucial to ET cover function. While evaporation is a component of ET, in most environments the largest fraction of ET is provided by transpiration. Therefore, the performance will be heavily influence by the cover plant community. Several variables must be considered when evaluating a design plant community (Levin, 1976):

- the plants must be capable of rooting through the entire depth of the soil column;

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- the plants should be capable of transpiring throughout the growing (warm) season;
- native species, though not required, may be best suited to the environmental factors at the site; and
- agronomic factors at the site should be carefully considered to ensure optimal rates of transpiration.

It is necessary to determine the quantity (depth) of water for which storage in the cover will be required during periods when precipitation rate exceeds evapotranspiration rate. It is also essential to determine the depth of soil required to store the quantity of water that represents the difference between precipitation and evapotranspiration. This can be achieved by dividing the quantity of water storage required (depth of water) by the soil water-storage capacity (depth of water per unit depth of soil). In cold climates where transpiration is essentially nonexistent for several months each year, this may be fairly simple to determine. In such locations one might conservatively expect the cover to store all precipitation between onset of freezing temperatures in the fall and the time of active transpiration during the spring. Locations where significant precipitation occurs during a season when some transpiration occurs can require a more detailed analysis.

Climatic factors

Climate is one factor that cannot be controlled or engineered by the designers of alternative landfill covers. The most important factors are precipitation and the atmospheric parameters that influence evapotranspiration. Other factors (temperature, humidity, etc) influence the rate of transpiration, but the amount and timing of precipitation is most important to proper design of an ET cover. The design precipitation event or events to be considered in ET cover design is a site specific determination. In cold climates where transpiration is essentially nonexistent during the winter, a cover should be capable of storing all or most of the precipitation that occurs during that period.

The decision to use average or extreme event precipitation data for that period may be a topic of discussion between design engineer and regulator. The timing of precipitation events is critical to ET cover design. For example, two sites with equal annual precipitation and annual potential ET may have very different cover requirements if one site receives the majority of precipitation during the winter (nontranspiring) season while the other experiences predominately summer precipitation (Richter et. al., 1996). Site-specific climatic factors that are important to the performance of alternative landfill covers include daily precipitation values, maximum and minimum temperature, relative humidity, total solar radiation, and daily wind run. Of particular interest to ET covers is the relative timing of precipitation and transpiration.

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The diversity in climatic conditions, available soils, and plant communities in addition to differences in performance criteria preclude the establishment of a rigid design process for ET covers that is essentially prescriptive.

Vegetation community

Plant transpiration is the primary mechanism in removing water from an ET cover. Through transpiration, plants move water from the root zone to the atmosphere. Plant species selection can vary depending on climate, long-term land use, waste type, cover design limitations, etc. A mix of plant species may be appropriate to maximize the number of days, as well as the total amount, of transpiration by plants.

A variety of plant species should be growing both in the cool and warm seasons. A succession of species may be planted to enable early-start plants to begin the ET process while the later succession of plant population, which may provide higher transpiration rates, gets established. ET is effective soon after plants initiate growth and development, but for success criteria, a more mature plant community should be allowed to establish. A mature plant community can take 3–5 years or more to develop.

Plants and transpiration are active only during the growing season of the established plant community. However, evaporation from the soil continues year-round. Changes in transpiration potential occur at the seasonal scale and are associated with precipitation, wind, atmospheric pressure, and temperature fluctuation. Within a growing season different species initiate and achieve peak growth at different times.

In some locations, the transpiration season may be year-round. At most sites, however, the growing season begins when air and soil temperatures are high enough to allow plant growth and ends when day length and temperatures decrease below a metabolic threshold for vegetation. This project model is designed to start and end plant growth based on air and soil temperature experienced or estimated for each day of each year. Exact dates are not necessary for this model, and in fact dates will vary with yearly weather patterns. It may be prudent to estimate a conservative start and completion date that would apply in most years.

Percent ground cover can be composed of live plant material, mosses, lichen, standing dead plant material, litter, rock, and even miscellaneous debris. Total percentage of ground cover summed with percentage of bare ground should equal 100%. Estimates for percentage cover can be obtained through many approaches. For the purposes of this model, an average number with a low standard deviation should be determined.

Site specific data for root structure, density, and depth may be difficult to obtain. Actual rooting depth is usually controlled by soil properties and not by potential for the plant; therefore, it is most appropriate that the model accounts for actual root growth as limited

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by soil properties. EPA's Alternative Cover Assessment Program is gathering data from sites being monitored and may be a source for root density profile information. In general, grass species have the majority of roots in a dense network of fibrous roots in the top ½ meter of soil. Grasses also send a lower proportion of roots 2–3 meters or more into the soil profile.

NATURAL ANALOGS

Natural analogs of cover systems can provide valuable insights into the future performance of an ET cover and can assist in refining the conceptual model used to for the performance assessment. Analogs can be thought of as long-term experiments (Waugh, 1997) that are not subject to some of the limitations of theoretical evaluations (Fayer and Gill, 1997). Besides being helpful in evaluating the appropriateness of an alternative cover system, analogs may also be helpful in communicating the results of the performance assessment to the public (Waugh, 1997). An assessment of natural analogs may provide useful information regarding rates of deep percolation, the effects of long-term climate variability, vegetative succession, pedogenesis (soil development), and disturbances by animals. Natural analogs have been used in this study to assist in refining the conceptual models used to create event trees.

6.0 EVALUATING ECOLOGICAL PROCESSES THROUGH EVENT TREES

One way to account for variability in performance drivers is through event tree analyses. An event tree is a visual representation of all the events which can occur in a system. For the purposes of this project, event trees are used to understand potential ecological processes that act on a cover system. An event trees is a tool to analyze dynamics of one component of the cover (e.g., species diversity) while the system is continuously operating. The starting point, referred to as the initiating event (e.g., drought), may or may not change the normal system operation. The event tree expresses all potential pathways the system can take due to the initiating event by displaying the sequence of events involving success and/or failure of the system components. The purpose of utilizing event trees is to determine the probability of an event based on the outcomes of each event in the sequence of events leading up to it. By analyzing all possible outcomes, you can determine the percentage of outcomes which lead to compromising cover performance. Furthermore, event trees provide a tool capable of being easily adapted to include site-specific considerations. For example, a site manager who has knowledge of the prevalent climatic conditions can easily look up potential scenarios in an appendix of event trees most relevant to that area.

CONCLUSIONS

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Effective long-term containment of wastes is difficult and presents a myriad of complex challenges. Evidence to date reveals some previously constructed conventional covers are not performing as intended and may need to be renovated. Therefore, it is necessary to evaluate conventional cover sites to determine if renovation is needed. This paper presents important ecological processes that should be accounted for in screening potential sites for renovation, along with the subsequent design of an alternative cover. Effective containment requires insightful comprehensive design that takes ecological processes into account, carefully controlled construction, continual monitoring, and maintenance as required. Over the long-term, multiple scales of ecological processes must be incorporated in performance models. The large scale ecological drivers include soil water storage, evapotranspiration, vegetation and climatic factors. Central questions include how soon and to what magnitude do ecological processes occur, and what other confounding effects can be expected. This study takes a step toward understanding the extent to which the natural range of variability of these processes can change predicted degradation rates of the cover.

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