Monitoring the Long-Term Performance of Engineered Containment Systems: Role of Ecological Processes - 9418

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ABSTRACT

Engineered covers have been widely used to minimize water infiltration into landfills used by U. S. Department of Energy (DOE) for the disposal of radioactive and hazardous chemical waste. The degradation of engineered covers over time is a complex process that is influenced by site specific characteristics, the structure and dynamics of the indigenous plant community, and the interplay of physical and biological factors at contaminated sites. It is necessary to develop a rigorous method to evaluate long-term performance of covers and other engineered barriers with quantification of risk and uncertainty.

Because many of the contaminants of concern are long-lived, this methodology must consider changes in the environmental setting (e.g., precipitation, temperature) and cover components for long time periods (>100 years). Current monitoring approaches focus solely on hydrologic properties of the cover system. Additionally, cover design guidelines, such as those from RCRA, are not performance based and do not consider long-term site-specific influences such as climate, vegetation, and soils. Fundamental ecological processes such as succession are not even factored into current models, yet they directly affect the integrity of landfill covers through biointrusion, erosion, and water balance. Therefore, it is useful to identify ecological parameters and processes most important to performance for prioritization of site characterization and long-term monitoring activities. This investigation into the role of ecological monitoring of isolation containment systems utilizes the software platform GoldSim to identify important parameters and processes for performance verification and monitoring

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INTRODUCTION

A common approach used to isolate contaminants in the environment and mitigate associated human and ecological risks is to apply engineered covers over landfills used for disposal of radioactive, hazardous chemical and municipal solid waste. Long-term cover systems, composed of various layers of engineered barriers, are needed at U.S. Department of Energy (DOE) sites to assist in isolating contaminants from the biosphere at near-surface landfills, waste-disposal sites, and high-level radioactive waste tanks (Albright et al., 2004). The duration for monitoring and maintenance of landfill covers after closure varies but is generally not expected to exceed more than 30 to 50 years for cases in which institutional controls are applied (Suter et al., 1993). However some regulatory agencies, e.g., the Nuclear Regulatory Commission, specify 100 years of institutional control and require performance over 200 to 1000 years with minimal monitoring and maintenance (DOE Order 435.1). Furthermore, the hazards and potential risks associated with the waste frequently persist beyond even 100 years of institutional control; hence, the longer-term integrity and associated performance of landfill covers is of concern.

The degradation of engineered covers over time is a complex process that is influenced by site specific characteristics, the structure and dynamics of the indigenous plant community, and the interplay of physical and biological factors at contaminated sites. Landfill covers can range from a one-layer system of vegetated soil to a complex multi-layer system of soils and geosynthetics. In general, less complex systems are required in dry climates and more complex systems are required in wet climates.

A literature review of recent work in landfill cover design reveals the emergence of two major themes: 1) there has been an overemphasis on regulatory compliance, which has inhibited innovative and creative cover design and associated framework. Greater emphasis needs to be placed on how the design will affect cover performance over necessary long time periods, and 2) there are few published data on field performance of constructed cover systems. Research efforts have primarily been focused on the physical measurement of percolation through the cover and are often site-specific in scope; these efforts habitually neglect the measurement of important environmental parameters. These parameters include the variables of climate, plant community activities, soil physical properties, and biointrusion by both animals and plants. This is exemplified in the case of vegetation impacts on alternative covers. While the burden of performance for alternative covers rest on the vegetation, little work has been done to assess the longevity of the vegetation on alternative cover sites. This lack of performance data makes it difficult to compare the performance of ET covers and capillary barriers against the RCRA (e.g., compacted clay) cover systems (Johnson and Urie, 1985). Therefore, in order to enhance guidance for the design of new ET covers, it is imperative to develop an integrated computational framework to simulate the impact of dynamic ecological processes on cover performance over time. A computational framework will both highlight the most important components for long-term monitoring plans and assist in determining necessary data to collect from existing ET cover.

It is necessary to develop a rigorous method to evaluate long-term performance of covers and other engineered barriers with quantification of risk and uncertainty. A risk-informed performance-assessment methodology considers regulatory requirements, site-specific parameters, engineering-design parameters, and long-term verification and monitoring requirements. The development and implementation of environmentally protective and cost effective designs for alternative landfill covers are currently hampered by a number of issues including: 1) lack of field data; 2) absence of rigorously tested models for predicting the hydrologic performance of landfill facilities; and 3) lack of regional or national design guidance that integrates cover design options with the relevant environmental variables (Albright, et. al., 2001).

PURPOSE OF PERFORMANCE ASSESSMENT

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 (IAEA, 2001).

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 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 perdolation 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).

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 (Landeen, 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.

COMPONENTS OF PERFORMANCE ASSESSMENT CURRENTLY NEGLECTED

As defined by DOE, a performance assessment is an analysis of a radioactive waste disposal facility conducted to demonstrate there is a reasonable expectation that performance objectives established for the long-term protection of the public and the environment will not be exceeded following closure of the facility (DOE, 1997). Probabilistic, risk-based performance-assessment methods are available to assist DOE site managers in the selection, design, and monitoring of long-term containment isolation systems, but are typically not used. Current landfill-cover design guidelines, such as those stated in the RCRA, are not performance based and do not consider long-term site-specific influences such as climate, vegetation, and soils. These design guidelines may not address important long-term features, events, and processes at the site that may contribute to the long-term risk of groundwater contamination and human exposure. In addition, traditional design guidelines for covers often rely on deterministic models of flow and transport processes that neglect uncertainty inherent in actual contaminant transport.

While observational data have been extensively collected for the performance of engineered barrier systems, including liner systems, cover systems, leachate collection systems, and vertical barriers, unfortunately, few direct observational data on performance are available for most of these systems and none of the data extend beyond three decades. Predictive models have been established with the goal of forecasting overall performance of containment systems. The best-available information on the overall performance of cover systems comes from monitoring data for the environment surrounding the cover system (Lopez et al., 1998). Therefore, model verification is dependent on review of groundwater monitoring.

While many studies have documented parameters related to cover performance (soil moisture content, precipitation, runoff), these measurements by themselves do not directly address the central issue, namely deep percolation through the cover. In most cases, the collection of soil moisture, runoff, and precipitation data has been performed to meet regulatory compliance requirements. The performance of individual landfill cover systems has been evaluated by groundwater monitoring methods, and various soil moisture monitoring schemes (Weand and Hauser, 1997). Methods that utilize these data to estimate the ability of a cover design to limit the flux of water have inherent uncertainties. The difficulty in measuring the ability of an engineered cover to limit deep percolation is one aspect of the more general problem of quantifying water balance in any setting, engineered or natural. Methods of determining deep percolation include those based on fixed fractions of annual precipitation, water balance models, soil-water flow models, environmental tracer models, and lysimetry (Albright, 2004).

Despite the clear importance of designing landfill covers that will perform adequately over long time periods, most field-based studies of landfill liners and caps provide just a few years of data. Modeling environmental processes provides a means of projecting landfill performance further into the future, but the validity of such projections is limited by the quality and quantity of field data used for parameterization and testing of the models (Ho et al., 2001). Fundamental ecological processes such as succession are not even factored into current models, yet they directly affect the integrity of landfill covers through biointrusion, erosion, and water balance (Johnson and Urie, 1985). Waugh and Smith (1996) have illustrated that natural analogs can sometimes be used to help project the effects of possible changes in climate, soil morphology, and ecology. Additionally, maintenance requirements to ensure long-term performance have been neglected.

THE USE OF ECOLOGICAL MONITORING TO BUILD CONFIDENCE IN PERFORMANCE ASSESSMENT MODELS

A risk-based engineered cover design will rely heavily on validated and calibrated models to minimize uncertainties in predicted performance and must be accompanied by field monitoring to confirm performance (Bonaparte et al., 2002). A probabilistic, risk-based performance-assessment methodology needs to consider regulatory requirements, site-specific parameters, engineering-design parameters, and long-term verification and monitoring requirements. Because many of the contaminants are long-lived, this methodology also considers changes in the environmental setting (e.g., precipitation, temperature) and cover components (e.g., liner integrity) for long time periods (>100 years). Uncertainty and variability in important site-specific parameters are incorporated through stochastic simulations in this method.

Monitoring is an essential component of engineered barrier system design and operation. Preconstruction monitoring is required to develop a conceptual site model for barrier system design and analysis, to establish a baseline for evaluating the effectiveness of the engineered barrier system, and, in the case of a barrier system for preexisting contamination, to establish boundary conditions and geometric constraints for barrier system design. Post-construction (long-term) monitoring is critical to ensure that barrier integrity is sound and that contaminants are not inadvertently released into the environment.

Ultimately, the use of performance assessments (PA) for long-term cover systems provides the following benefits:

- 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;
- Comparison of alternative designs to optimize cost and performance while ensuring that regulatory requirements are met.

However, given the current lack of performance data and deficiencies in monitoring technology and validated and calibrated models, there is a significant potential for misuse of risk-based designs in practice. There is a need for the development of guidance for the practical implementation of performance-based criteria for assessment of containment system performance as an alternative to prescriptive designs.

MODEL DESCRIPTION

Numerical models serve as an important tool in cap design, performance or risk assessment, and post-closure monitoring. PA models are typically probabilistic simulations of multiple (process) submodels which are used to simulate distinct processes, such as infiltration and plant community succession. They should be able to represent lack-of-knowledge (epistemic) uncertainty, as well as natural variability (aleatoric uncertainty), if the uncertainties can influence the conclusions (Ho et al., 2006). Because long-term projections of impacts are the goal of the PA, temporal evolution of the system should be represented. The complexity of the models should be influenced by the amount of information available to support the models and the risks of the problem. The process of performance assessment should be iterative in nature (i.e., results of the initial model are used to improve the model further and indicate where additional data collection is needed).

Over the course of years, evolutionary changes have been observed that had potential bearing on the performance of cell covers. These changes reflect the effects of such phenomena as freeze-thaw, drought, pedogenesis, biointrusion, and the growth of vegetation on covers that is not specifically accounted for in cover designs. It has became clear that these processes could potentially affect the net infiltration of precipitation occurring on the cells, which in turn could affect the leaching of waste materials buried in them. Furthermore, potential changes in soil moisture in cell covers were expected to influence plant growth. Thus, it is important to develop new methods that seek to quantitatively account for the interplay between evolutionary changes in cover properties and net infiltration to underlying wastes.

The degree to which the effects of vegetation are accounted for in most currently used hydrologic models varies. The large majority of hydrologic models that simulate subsurface moisture flow bundle soil water uptake due to plant processes with that due to evaporation from the soil surface, resulting in the estimation of a model flow component referred to as evapotranspiration (ET) (Schwartz et al., 1990). The actual rate of ET, expressed in units of length per time, is typically obtained by scaling potential evapotranspiration (PET) using empirical functions of soil moisture and/or vegetation. It is rare that the Richards equation simulator used contains transpiration algorithms based on processes observed with specific types of vegetation. Therefore, dynamic plant processes are fundamentally ignored by currently utilized models. The need for hydrological models to handle vegetation dynamically has been identified, wherein the bi-directional interactions between vegetation and hydrology are explicitly simulated (Fayer and Gee, 1997). Doing so would facilitate better predictions of transpiration and resulting soil moisture conditions, which in turn would facilitate dynamic simulations of the growth of plant roots, stems, and leaves.

For the purposes of simulation, a generic PA model for analyzing impacts of ecological dynamics on engineered covers utilizes the software platform GoldSim (Kossik, Miller, and Knopf, 2001). The GoldSim software package is a visual model building platform for performing dynamic, probabilistic simulations. GoldSim was ideal for this application because it is graphically-oriented and very flexible. To allow for different features and characteristics of different sites, the platform for building and editing the model has to be inherently flexible. The analyses that will follow are designed to convey some important aspects of assessing the risks from ecological processes on engineered covers over long time periods, but are not necessarily applicable to any specific site. For this problem, the parameters and models determining infiltration/moisture content, plant community succession, and the impact of extreme events, are important. The PA model is composed of numerous GoldSim elements and contains abstracted submodels that represent degradation of the engineered cover and water infiltration as a function of time.

CONCLUSION

In conclusion, effective long-term containment of wastes is difficult and presents a myriad of complex challenges. Effective containment will require insightful comprehensive design that takes ecological processes into account, carefully controlled construction, continual monitoring, and maintenance as required. It is clear that a common view among the research, engineering and regulatory communities exists regarding the measurement of cover performance; few field data sets exist that provide direct measurement of the performance of prescriptive or alternative covers. It is important to note that process-integrated models do exist; however, increased complexity of a model may not be advantageous. These models require greater data input and a higher level of user competence, which combined may result in greater uncertainty in the model predictions. It is for this reason that this study is focused on creating a framework comprised of first order degradation processes. Over the long-term, soil pedogenic processes (e.g., soil structural development), changes in meteorological conditions (e.g., a shift from a rain to a snow-dominated precipitation regime) and altered plant community dynamics (e.g., fire) can significantly alter the initial conditions at a cover site. 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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