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

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To Mama and Papa T for a lifetime of encouragement, support and love

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DISCLAIMER

This dissertation was prepared as an account of work sponsored by an Agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof.

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LIST OF ABBREVATIONS

ACAP	Alternative Cover Assessment Project
ALCD	Alternative Landfill Cover Demonstration
CERCLA	Comprehensive Environmental Response Compensation and Liability Act
CIF	Contaminant Isolation Facility
COC	Contaminants of Concern
CSL	Compacted Soil Layer
CRESP	Consortium for Risk Evaluation with Stakeholder Participation
CFR	Code of Federal Regulations
DOE	Department of Energy
EA	Environmental Assessment
EIS	Environmental Impact Statement
ET	Evapotranspiration
FTA	Fault Tree Analysis
GCL	Geosynthetic Clay Layer
INEEL	Idaho National Engineering and Environmental Laboratory
LLW	Low-Level Waste
LM DOE	Office of Legacy Management
LTSM	Long-Term Surveillance and Maintenance Program
NERP	National Estuarine Reserve Program
NOAA	National Oceanic and Atmospheric Administration
NPL	National Priority List
NRC	National Research Council
RCRA	Resources Conservation and Recovery Act
ROD	Record of Decision
RRM	Residual Radioactive Material
UMT	Uranium Mill Tailings
UMTRCA	Uranium Mill Tailings Radiation Control Act
UMTRA	Uranium Mill Tailings Remedial Action

USACE	U.S. Army Corps of Engineers
USDOD	U.S. Department of Defense
USDOE	U.S. Department of Energy
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USGAO	U.S. Government Accounting Office
USNRC	U.S. Nuclear Regulatory Commission

CHAPTER I

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 (Fig. 1).

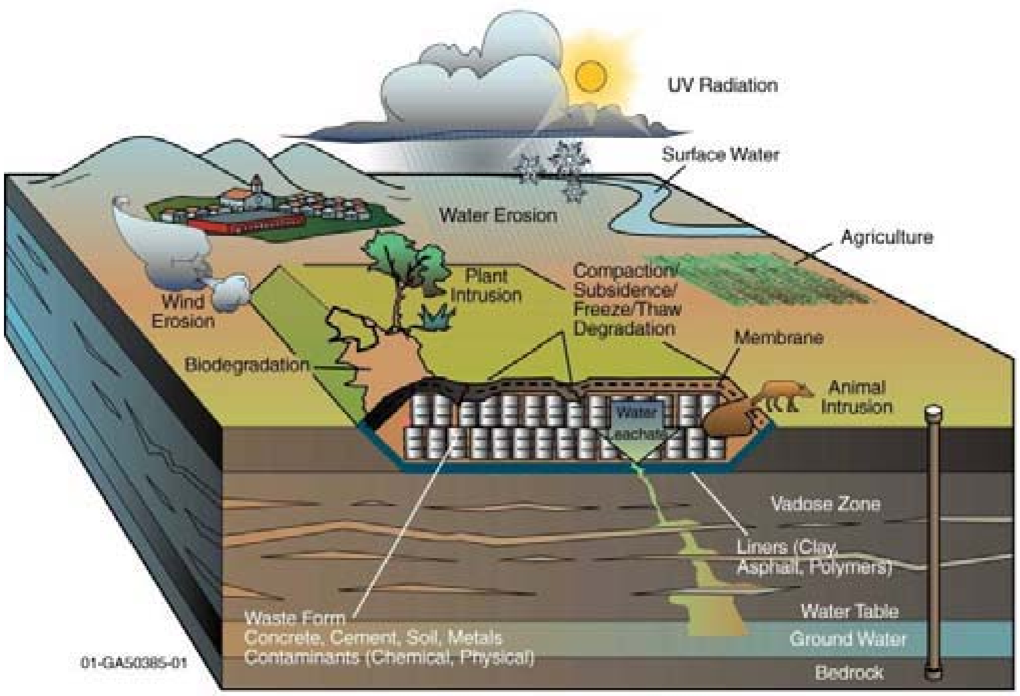

Figure 1. Generic containment isolation facility.

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, regulatory agencies, e.g., the Nuclear Regulatory Commission, specify 100 years of institutional control. Cover design requirements specify 1000 years with minimal monitoring and maintenance (DOE Order 435.1) and the NRC recommends 10,000 years for LLW (NRC, 2000). Furthermore, the hazards and potential risks associated with the waste frequently persist beyond 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 alternative cover systems resulting in a lack of data to inform quantitative modeling of cover performance. 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 identification and 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 long term dynamics 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 and geomembrane) 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 analytical framework to understand the impact of dynamic ecological processes on cover performance over time. An analytical framework will both highlight the most important components for long-term monitoring plans, assist in determining necessary data to collect from existing ET covers, and perhaps most importantly, can guide numerical performance assessment models on a site specific basis.

PROBLEM STATEMENT

The United States is undertaking the monumental task of cleaning up its contaminated and waste disposal sites. This is costing governments and private concerns trillions of dollars. Perhaps the single largest and most expensive portion of this undertaking is closing landfills and underground high level waste tanks at DOE sites across the country. A key element of landfill closure is the design and construction of a final cover intended to isolate the underlying waste material from the surrounding environment. A rigorous method to evaluate long-term performance of covers is needed.

This research includes a review of long term monitoring and performance assessment of engineered covers, an evaluation of key ecological principles in the context of cover performance, the identification of important ecological processes for performance confirmation, and a case study in the use of event tree analysis (ETA) to evaluate risks to performance of ET and conventional covers. Ultimately, the goal of this research is to develop a performance-assessment approach for selection, design, modeling, and monitoring ecological components of covers. The methods presented in chapter V provide a basis for quantitative modeling of dynamic cover degradation with the inclusion of key ecological components.

Cover performance can be affected by complex interaction by ecological processes and drivers. The development of an analytical framework with the inclusion of ecological drivers that are currently absent from conceptual models of cover performance assessments will enhance numerical models that predict future site conditions.

RESEARCH OBJECTIVES

This research is intended to:

- Provide insights into how ecological processes may influence the performance of engineered covers
- Identify important ecological processes influencing performance of covers
- Generate event-tree analyses to guide site-specific scenario and conceptual model development
- Apply event-tree analyses to both an ET and conventional resistive cover to evaluate performance risks
- Develop recommendations for incorporating ecological processes and risks into site-specific performance assessments and ecological monitoring approaches that evaluate performance of engineered containment systems.

PROJECT DEVELOPMENT

When this project began, one of the primary research objectives was to numerically simulate the performance of an evapotranspiration cover with the inclusion of dynamic ecological processes that act on the cover throughout the period of performance. For the purposes of simulating a generic PA model for analyzing impacts of ecological dynamics on engineered covers, the software GoldSim was an ideal platform (Kossik, Miller, and Knopf, 2001). The GoldSim software package is a visual model building platform for performing dynamic, probabilistic simulations.

As used for this project, *simulation* is defined as the process of creating a model (i.e., an abstract representation) of an existing or proposed system (e.g., an engineered cover) in order to identify and understand those factors which control the system and/or to predict (forecast) the future behavior of the system. 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. Simulation is an important tool because it provides a way in which alternative designs of a cover system can be evaluated without having to experiment on a real cover system, which may be prohibitively costly, time-consuming, or simply impractical to do. That is, simulation allows you to ask "What if?" questions about a cover system without having to experiment on the actual system itself (and hence incur the costs and delays associated with field tests, prototypes, etc.).

The model development began by describing the initial conditions of the system (e.g., the geometry, the type of plant community present) and the processes acting on the system (e.g., degradation of the drums containing the waste, migration of contaminants through the environment). The output of this dynamic simulation was set up to represent percolation into the waste as a function of time. In the simulation that was developed for this project, the system changes and evolves with time (in response to both external and internal influences), and the objective in modeling such a system is to understand the way in which it is likely to evolve, predict the future behavior of the system, and determine what can be done to influence that future behavior. In effect, the dynamic simulation can be used to predict the way in which the system will evolve and respond to its surroundings, so any necessary changes can be identified that will help make the system perform the way that is intended. The results can be used to design remediation measures which would minimize the negative environmental impacts at the site.

However, when the development of the generic model was complete, the challenge of adapting it to accurately represent site-specific criteria and processes revealed the absence of a reliable conceptual model development framework. The absence of realistic conceptual models (and methods for developing the conceptual models) would ultimately prohibit the numerical model from accurately simulating the systems. At this point, it was decided that resources would be better spent on devising a method for developing realistic alternative conceptual models that can accommodate the natural range of variability seen across different sites with the inclusion of dynamic ecological processes. While the GoldSim model was not used for the original purposes it was intended to address, the development of the generic model assisted in delineating important relationships between ecological processes and physical characteristics of the system. This knowledge informed the development of event trees that will be presented in Chapter V.

PROJECT RELEVANCE

The results of this research are applicable to a variety of organizations that are responsible for the long-term management of residual waste sites. Sites of interest include both federal facilities and non-federal facilities.

Federal Facilities

Federal facilities are those facilities or lands that are owned or leased by the federal government. The management responsibilities for these properties reside in a specific office within the executive branch of the federal government. The U.S. Government Accounting Office (USGAO) reports that as of fiscal year 2001 the U.S. federal government's environmental liabilities total $307 billion (USGAO, 2003). This is a conservative estimate because it includes only currently known liabilities. Liabilities include excess military bases, closed energy production facilities and legacy waste sites.

Two federal agencies, the U.S. Department of Energy (USDOE) and the U.S. Department of Defense (USDOD), account for 98% of the known environmental liabilities. The USDOE accounts for 78% or $238 billion and the USDOD accounts for 20% or $63 billion (USGAO, 2003). The remaining environmental liabilities are the responsibility of other federal agencies such as the U.S. Nuclear Regulatory Commission (USNRC) and the U.S. Department of Interior (USDOI 2002).

U.S. Department of Energy

The USDOE manages one of the largest environmental remediation efforts in the world. This effort involves the remediation of sites negatively affected by 50 years of nuclear energy research and weapons production. The USDOE has identified 113 known geographic sites located in 30 states and one territory (USDOE, 1997c; USDOE, 1999a). USDOE’s cleanup challenges include the remediation of 40 million cubic meters of contaminated soil and buried waste, 1.7 trillion gallons of contaminated groundwater and the deactivation and decommissioning of more than 4000 excess facilities, as well as the long-term care of uranium mine and mill tailings (USDOE, 2001d; USDOE, 2001e).

In 2001, the Idaho National Engineering and Environmental Laboratory (INEEL), now known as the Idaho National Laboratory (INL), completed a baseline assessment of the USDOE cleanup program (INEEL, 2001). This assessment shows that the USDOE is planning to “close” sites and shift its resources from active remediation (i.e., facility demolition, waste processing, waste containment) to post-closure management (i.e., long-term stewardship). Long-term stewardship, as defined by the USDOE, includes those activities necessary to protect human health and the environment from hazards and wastes remaining at sites (or portions of sites) once active remediation is complete (USDOE, 2001d).

U.S. Department of Defense

The USDOD has responsibility for all active defense sites, major and minor installations slated for realignment (i.e., sites to be reused for other USDOD missions) or closure sites via the Base Realignment and Closure program (BRAC). In addition, USDOD is accountable for more than 9000 Formally Used Defense Sites (FUDS) that had a historic USDOD role. Similar to the USDOE, a significant percentage of these sites have some form of environmental contamination and many are expected to require post-remediation controls.

Questions continue to arise concerning USDOD environmental management practices. For example, the USGAO has questioned whether the USDOD had adequate justification in determining that more than 4000 FUDS have no remaining hazards and, therefore, required no further cleanup study or cleanup action (USGAO, 2002b).

Other Federal Agencies

Other federal agencies face similar challenges with regard to the long-term isolation of residual hazards. Although these agencies were not the focus of this research, they likely would have similar problems and therefore benefit from these results.

Non-Federal Facilities

State and local governments and private industry are also concerned with residual contaminants, Brownfields sites, contaminated landfills, abandoned mine sites and abandoned hazardous waste sites. These sites include publicly held properties of a state or municipality and privately owned sites, as well as abandoned properties.

The environmental remediation of these non-federal sites is accomplished through collaborative efforts of both the federal (i.e., U.S. Environmental Protection Agency) and the individual state regulators. These efforts are conducted consistent with federal regulations established primarily by the U.S. Environmental Protection Agency.

RCRA

RCRA was primarily established to prevent future contamination that could result from solid waste landfills and to take a more prescriptive approach in its legislation. By specifically defining "hazardous" waste and associated contaminants of concern, RCRA's approach serves as an incentive for manufacturers, transporters and users of these products and materials to self regulate themselves and thereby reduce the quantity of these materials. Second, RCRA is technology-specific and defines acceptable treatment technology for various waste stream applications such as RCRA-specific designs for landfill covers.

CERCLA

CERCLA is of primary importance when considering environmental remediation and waste isolation. The U.S. Environmental Protection Agency (USEPA) has managed the Superfund Program for the past 24 years since CERCLA was enacted in 1980. This program has two primary areas of focus: the long-term cleanup of contaminated sites and an emergency response program (USEPA, 2004g).

Superfund is a large, complex program, with approximately $18 billion being expended to date (USEPA, 2004g). The USEPA established the National Priority List (NPL) in 1980 as a way of prioritizing the program's work. The USEPA has placed approximately 1518 sites on the NPL (although 274 have since been deleted) and approximately 30 new sites are added each year. These sites include both federal facilities and non-federal facilities.

Approximately 900 NPL sites have completed remedial construction. Nearly 70% of these sites have some form of post-closure institutional controls as part of their environmental remedy (Bellot, 2003a). Following the completion of remedial construction, the USEPA initiates a five-year review process to verify that the remedies are performing as anticipated. The USEPA completed 134 five-year reviews annually from 1999 to 2003 (USEPA, 2004g). The number of reviews completed by the USEPA annually is increasing, as an increased number of sites are being completed.

The emergency response program within Superfund was originally established to enable rapid response and clean up of sites that presented immediate threats to human health and the environment (USEPA, 1989). The first step of the process involves a preliminary site screening (i.e., scoring of potential hazards). If a site scores sufficiently high, it is listed on the National Priorities List (NPL). NPL sites then proceed through a process known as the Remedial Investigation and Feasibility Study (RI/FS) process. Each step of the RI/FS process improves the definition of the contaminants of concern and identifies the best remediation alternatives. The Remedial Investigation stage defines the extent of the contamination and develops preliminary baseline risk assessments. The Feasibility Study stage focuses on alternative treatments based on the contaminants of concern. The Record of Decision (ROD) formally documents the selected remedy and estimates the magnitude of residual risk remaining (CERCLA 1994).

Although CERCLA baseline risk assessments consider risk in the absence of any institutional controls, it is important to consider the estimated risks associated with residual waste sites with institutional controls in accordance with projected land uses as well as the risk when institutional controls are removed (White et al., 1993).

The USEPA defines institutional controls as non-engineered instruments such as administrative and/or legal controls that minimize the potential for human exposure to contamination by limiting land or resource use (USEPA, 2000). The USEPA specifically excludes access controls, fences and physical barriers in its definition of institutional controls.

CERCLA establishes several key requirements with regard to the implementation of institutional controls for managing residual contaminants. First, CERCLA stresses the importance of permanent remedies and treatment technologies in cleaning up hazardous waste sites rather than the containment or removal of contaminants. However, when containment is chosen as the ideal remedy, this research could be useful in evaluated the best type of cover to construct and will help evaluate potential performance risks over the lifetime of the cover.

Site Managers

Site managers are the individuals who are in charge of overseeing daily operations of a cover at each site. The event trees developed in this paper will be a useful tool for managers to prioritize long term monitoring funds and activities, and can assist managers in the decision making process on how best to allocate maintenance funds throughout the period of performance.

DISSERTATION STRUCTURE

The structure of this dissertation is as follows. Chapter I introduces the problem of long term monitoring of engineered containment systems and presents the objectives of the research project. Chapter II provides a description of current management systems, including both conventional engineered barriers and alternative covers (e.g., evapotranspiration covers). Chapter

III reviews the relevant long term monitoring literature with a focus on the monitoring ecological components. Chapter IV identifies important ecological processes that should be included in performance assessments. Chapter V contains an application of event tree analysis to ecological systems to aid in development of site-specific conceptual models. Chapter VI presents research conclusions and recommendations.

CHAPTER II

REVIEW OF LONG TERM MONITORING AND PERFORMANCE ASSESSMENT OF ENGINEERED CONTAINMENT SYSTEMS

History of Disposal Methods

Disposal and isolation methods of radioactive wastes have evolved with time. Before 1970, disposal of high level wastes (HLW) on the ocean floor was common. HLW, defined as spent nuclear fuel from civilian and government sources and wastes from the reprocessing of spent fuel, is now being stored in pools and dry casks storage (spent fuel) and tanks and as vitrified glass logs (reprocessing wastes) at reactor sites and DOE facilities while awaiting disposal in a geological repository (Blackman 2001; U.S. Department of Energy 1997). Transuranic (TRU) waste was buried in shallow trenches prior to 1970. Currently, TRU waste is being stored in drums and boxes while awaiting disposal at the Waste Isolation Pilot Plant (WIPP) (Blackman 2001; U.S. Department of Energy 1997).

While wastes with more activity and longer lives await a more permanent disposal, near surface burial is still a common disposal method for low level wastes (LLW) a, uranium mill tailings (UMT), and chemical wastes. Many of the UMT burial sites are close to residential areas, and so an effective isolation system is imperative. The burial sites are essentially landfills which make use of a cover to isolate and protect the buried radioactive wastes (Blackman 2001). The landfill covers may be compromised by poor maintenance, weathering, or intrusion of humans, animals and vegetation. Evidences of all these compromises have been seen at DOE

UMT disposal sites within ten years, and in some cases only a year after site closure (U.S. DOE 1990a; U.S. DOE 1990b; U.S. DOE 1992; U.S. DOE 1993).

The U.S. Department of Energy Office of Legacy Management (DOE−LM) is responsible for long-term stewardship of disposal sites for uranium mill tailings and other facilities that have completed closure requirements. Final remedies at most sites include engineered covers. Cover design and performance evaluation guidelines have historically been narrow and frequently fail to consider consequences of inevitable changes in ecological settings. It is becoming apparent that in order for long term monitoring of engineered barriers to be successful, it must combine monitoring, modeling, and natural analog studies to evaluate long-term performance of covers.

Near Surface Waste Disposal

Disposal refers to the emplacement of solid radioactive waste into a facility with no intention of retrieving the waste. A disposal facility is designed to contain the waste and to isolate it from the accessible environment to the extent demanded by the hazard of the waste. Although the radiological hazard presented by radioactive waste will reduce with time because of radioactive decay, the timescales over which the hazard remains significant can extend over many generations, depending on the radionuclides involved. The emphasis in radioactive waste disposal is therefore on the provision of long term safety through passive controls (i.e. not relying on mechanical movement, the supply of power, or human intervention) built into the engineered design of the disposal facility, and their compatibility with the environment in which the facility is located.

Concentrating and containing radioactive waste, and isolating it from the biosphere, is the accepted management strategy for the majority of radioactive waste. Containment and isolation can be provided through a series of complementary barriers (e.g. the waste form itself, waste containers, other engineered features associated with the facility design, and the local environment), each of which serves in some way to prevent the release of radionuclides from the waste form and/or to ensure that contaminants are not transported from the facility to the accessible environment.

Near surface disposal refers to the emplacement of solid, or solidified, radioactive waste in a disposal facility located at or near the land surface. The depth chosen for disposal, and the type of facility that is developed, will depend on a number of factors including, but not limited to, the nature of the waste and local environmental conditions at the site where development occurs. A distinctive feature of near surface disposal is the possible need to maintain institutional control over the site for a period of time following closure, owing to the need to protect the facility and its contents from potential disturbance by human activities. A key component of the institutional control period is a long term monitoring program for the waste site.

Contaminant Isolation Systems

Waste containment systems are designed to isolate the waste until it has decayed or biodegraded. Figure 1 shows the components of a typical contaminant isolation system and possible interactions with the surrounding environment. Radioactive waste may be in various forms: cemented or concreted, stored in drums or boxes, soils, or loose contaminated debris. A low permeable liner of clay, asphalt, or a geosynthetic polymer may be placed below the waste layer. The liner prevents leachate from seeping through to the groundwater. A leachate recovery system may be above the bottom liner as an additional precaution against groundwater contamination. The waste is isolated from the surface by a cover system comprised of earth and sometimes of geosynthetic materials. The contaminant isolation system is placed in the natural environment, and it is subject to physical, chemical, and biological interactions.

Physical factors include climatic influences such as temperature changes, precipitation, and wind patterns. Chemical interactions can occur by UV radiation exposure or other chemical reactions either in the waste layer or in the containment system. Biological effects on the containment system include the proximity of human, animal, or plant life.

Cover Systems

Landfill covers over buried waste are designed to protect against physical, chemical and biological factors. Specifically, the landfill cover should prevent contaminant from entering the environment, protect humans from exposure to the contaminants, and minimize water infiltration to the waste. Landfill cover designs typically include multiple layers, each with a specific function. The layers needed in a design are dependent on the type of waste and the climate region of the landfill site. The uppermost layer can be a vegetated soil layer or a layer composed of riprap. A vegetated soil layer usually is uncompacted, native topsoil. The vegetation on a landfill cover reduces the soil water by evapotranspiration and helps prevent erosion of the landfill cover. A riprap layer, composed of rocks, cobbles or gravel, is an alternative to vegetation on the top of the landfill cover. The riprap aids in preventing erosion, although it allows infiltration of water (Suter et al. 1993).

The biointrusion layer (biota barrier) lies below the topsoil layer. The rock or gravel layer is meant to discourage burrowing animals from reaching the waste layer. The biointrusion layer may also be designed to inhibit deep-rooting plants. A landfill cover may be designed with the biointrusion layer on the surface instead of subsurface (Smith et al. 1997; Suter et al. 1993).
The drainage layer is designed with a large hydraulic conductivity (Ks ≥ 10-2 cm/sec) (U.S. Environmental Protection Agency 1983b) to encourage water transport off and away from the barrier layer. A coarse material such as sand or cobbles can be used to achieve the large hydraulic conductivity. The drainage layer also serves to protect the physical integrity of the barrier layer below (Caldwell and Reith 1993).

The barrier layer, also called the infiltration layer, is intended to retard and reduce the flow of water to the waste layer below. The barrier layer may be a compacted clay or a geosynthetic material. The compacted clay layer or compacted soil layer (CSL) has a designed maximum infiltration rate of 10-7 cm/sec (U.S. Environmental Protection Agency 1983b). The compacted clay layer is simple to construct and easy to implement (Caldwell and Reith 1993). The geosynthetic clay is composed of bentonite clay. The bentonite clay is less susceptible to cracking than clay because it has high capacity for swelling and shrinking and is able to 'heal' itself after a freeze-thaw cycle or after drying. A study by Shan and Daniel revealed that no change in hydraulic conductivity of geosynthetic clay was evident after three freeze-thaw cycles

(Daniel 1994). The geosynthetic clay can have a design hydraulic conductivity of 5x10-9 cm/sec (Dwyer et al. 2000a).

As additional barrier, a geomembrane layer may be used. The geomembrane is a low permeability layer placed below the compacted barrier layer. The geomembrane may be made of high density polyethylene (HPDE), polyvinyl chloride (PVC) or other type of polymer (Qian et al. 2002).

RCRA Cover Designs

Specifications regarding landfill covers are regulated by the Resource Conservation and Recovery Act (RCRA) in Title 40 of the Code of Federal Regulations, as mandated by the Environmental Protection Agency (EPA). These cover designs include one or more of the component layers discussed previously. The RCRA subtitle C landfill cover is designed for hazardous waste, and is often used for low level radioactive waste. Figure 3 shows a schematic of the RCRA Subtitle C cover design. The top layer of the cover is 60 cm of native soil for vegetation growth. Below this layer is a 30 cm drainage layer of sand or synthetic material with a minimum hydraulic conductivity of 10-2 cm/sec. A geomembrane layer is below the drainage layer. At the bottom of the cover is the barrier layer comprised of 60 cm of native soil compacted to a maximum hydraulic conductivity of 10-7 cm/sec (U.S. Environmental Protection Agency 1983b).

The RCRA Subtitle D landfill cover is designed for municipal solid wastes. Figure 4 shows a sketch of a RCRA Subtitle D cover design. The upper fifteen centimeters is the erosion layer with plant growth for erosion prevention. The lower 45 cm of the cover is a compacted barrier layer of native soil, designed with a maximum 10-5 cm/sec hydraulic conductivity. The total depth above the waste layer is sixty centimeters (U.S. Environmental Protection Agency).

Alternative Covers

Alternative cover designs are being explored in landfill cover performance studies (Albright et al. 2002; Dwyer et al. 2000a). Alternative covers may be complex designs with geosynthetic materials, or simple designs such as the Evapotranspiration Cover. An Evapotranspiration Cover generally consists of a thick monolith layer of native soil. The fifteen-centimeter erosion layer shown in Figure 5 is the layer designed for vegetation. Plant growth is expected and encouraged to aid evapotranspiration (Dwyer et al. 2000a). With no clear distinction in the erosion layer and the underlying evapotranspiration layer, plants may root much deeper than fifteen cm. The design depth of the evapotranspiration layer should be great enough to hold infiltrated water until removed by plant roots and evaporation (Albright et al. 2002). The Evapotranspiration cover may be compacted, but has no specific designed maximum hydraulic conductivity.

Long-Term Monitoring

Monitoring refers to continuous or periodic observations and measurements of engineering, environmental and radiological parameters important to safety of a site. Long-term monitoring programs are developed prior to the construction of the disposal facility. The monitoring program provides input to safety assessments, the continuing assurance of performance of the facility, and the subsequent confirmation that actual conditions are consistent with the assumptions made for post-closure safety. A baseline survey of the site, including characteristics of the host environment, is typically conducted before commencing construction of the site. The monitoring program should be revised periodically to reflect new information gained during construction, operation, and closure of the site. The monitoring program should define monitoring methods (e.g., sampling of soil, vegetation, water), measurement techniques, requirements, limits and tolerances, monitoring and measuring frequencies and reporting requirements, including the retention and use of monitoring and measurement results.

History of Ecological Monitoring by Federal Agencies

Monitoring the long-term performance of systems of interest is a challenge not only to the Department of Energy but to other institutions and federal agencies. National Environmental Research Parks (NERP), National Estuarine Research Reserves (NERR), and Long Term Ecological Research (LTER) areas operated by the US government agencies are designed with the specific goal of intensely monitoring and conducting research over long time scales and within diverse geographical settings. New ecological monitoring paradigms are necessary due to the importance of organizing and utilizing the massive inventory data sets that originate from many federal research facilities.

The Atomic Energy Commission recognized the ecological importance of Department of Energy (DOE) lands by designating the Savannah River Site as the first NERP in 1972. This ultimately led to the designation of seven NERP sites: Fermilab, Hanford, Idaho National Engineering and Environmental Laboratory, Los Alamos, Nevada, Oak Ridge, and Savannah River Site. Due to the presence of DOE's hazardous waste sites within almost every major biome represented within the contiguous United States, additional value emanates from the geographical diversity of NERP sites (figure 1). The NERPs were established to develop methods for assessing the environmental consequences of human actions related to energy and weapons use, to explore methods to eliminate or minimize the adverse effects of energy and weapons, and to train people in environmental science. The NERPs are of great national significance because they are, on average, five times larger than the long-term ecological research sites established by the National Science Foundation in 1979, indicating their potential for the preservation and study of large landscapes representing complex ecosystems.

Site	Year Designated	Acres	EcoRegion
Savannah River	1972	198,000	Southeastern Mixed Forest
Idaho	1975	568,000	Shrub-steppe
Los Alamos	1976	28,400	Juniper-Pinyon and Grassland
Hanford	1976	366,000	Shrub-steppe
Oak Ridge	1980	21,500	Eastern Deciduous Forest
Fermi Lab	1989	6,800	Tallgrass Prairie
Nevada	1992	865,000	Desert Shrub

Figure 1. The United States Department of Energy's National Environmental Research Parks

Most of the NERPs have long-term data sets for many ecologic variables (e.g., water quality, soil carbon, precipitation), biodiversity, and a wide range of species (microorganisms to vertebrates) that can be used to assess not only the effects of waste management activities on undisturbed, functioning ecosystems, but broader global changes on physical and biological environments. These are some of the longest running environmental monitoring data sets and their potential value is enormous. Information on data sets resides with the individual NERP offices, which are established on each of the DOE sites that are so designated. While some of NERP datasets have been discontinued, they do still provide the baseline for additional monitoring that could be conducted in the future, and for monitoring protocols and paradigms.

Understanding long-term ecological interactions at multiple spatial and temporal scales is difficult or, in some cases, impossible without a foundation of long-term observations. Observations have been made on NERP sites for almost thirty years. These long-term observations and experiments are important to long-term management goals isolated contaminants for several reasons. First, observations over long time periods can define the range of natural variability of ecological systems and provide baseline information from which to determine if a system is changing due to human interactions. Additionally, long term data sets allow for the assessment of relationships among physical, chemical, and biological components of ecological systems, and also allow us to determine the effects of unforeseen changes (e.g., climate change, fires or other catastrophes). Experiments that are maintained over long time scales enable detection of cause and effect relationships among slowly changing variables and could provide a tool that could be used to predict the performance of engineered barriers within these complex ecological systems.

Environmental management goals of NERPs include the following: managing legacy wastes; remediating inactive waste sites and groundwater units; controlling, minimizing, and monitoring radionuclide releases e.g., tritium; and characterizing, evaluating, and sustaining the health, productivity, and diversity of natural resources (DOE, 2000). Natural resource management is designed to be consistent with the DOE missions. Biological and physical conditions associated with physiographic regions, climate, and land use history also constrain resource management.

Each NERP has a Natural Resource Management Plan (NRMP) that led to the creation of several program areas. These areas are delineated to implement the goals and objectives of the NRMP. Ultimately, forecasting ecological change requires understanding interactions of spatial and temporal dynamics of ecological systems. To gain this understanding, it is important to study long-term ecological dynamics at multiple spatial scales.

Similar to NERPs, NERR and LTER research areas are specifically designed to undertake research that delineates complex ecological interactions over large temporal and geographical areas. One of the fundamental strengths of these three networks is that long-term dynamics are studied at spatial scales ranging from individual locations to cross-biome comparisons. The inventory data can potentially be constructive in examining potential signals and indicators of the performance of engineered barriers. After all, in ecology, historical change is often key to understanding the present and anticipating the future.

Monitoring Engineered Covers

A systematic monitoring program is critical for evaluating the long-term performance of a contaminant isolation facility (USEPA, 1998). Monitoring involves the active investigation and observation of processes, operations, structures and controls applied at a specific site. Visual inspection of the contaminant isolation facility and all of its physical features continues to be the primary qualitative monitoring technique. These inspections are useful in identifying deficiencies in both the engineered and institutional control subsystems. Natural events, which can affect the engineered structures and could include erosion, bio-intrusion, subsidence, material degradation, infiltration and seepage, can be observed through visual inspections. Likewise, anthropogenic events, such as deliberate human intrusion, vandalism and property restriction violations inconsistent with the land use restrictions, can also be detected through visual inspections.

The second form of monitoring applied at a contaminant isolation facility is quantitative. This method consists of analyzing samples from the area surrounding the contaminant isolation facility, including the vadose zone, the saturated zone and the leachate recovery system. These quantitative methods serve to indirectly detect evidence of performance deficiencies such as increased saturated conductivity or material performance deficiencies. Although the intent of this approach is to provide an early warning of future problems, this approach, in many instances, serves as confirmation of a system failure. Failure, for the purposes of this research, is defined as a "departure from design performance objectives." Monitoring measures need to be performed in accordance with a schedule best defined after considering site-specific conditions. Sampling strategies generally are conducted on a monthly, quarterly or annual basis. Site-wide visual inspections are often performed annually or every five years (e.g., CERCLA five-year reviews).

Purpose of Performance Assessment

The design life of a containment isolation system is based on the type of waste to be isolated. A design life of 200 to 1000 years is considered “long-term (Caldwell and Reith 1993).” Factors compromising landfill covers have been documented after only a few years (U.S. DOE 1990a; U.S. DOE 1990b; U.S. DOE 1992; U.S. DOE 1993; Waugh 1999), suggesting that design regulations should be reconsidered. In addition to the RCRA design requirements which include a minimum thickness and a maximum hydraulic conductivity for the cover, Ho et al (Ho et al. 2004) indicated that site-specific information such as climate, soil, and vegetation should also be considered.

Many disposal sites have closed only recently and so long-term evaluations are not available. Continued monitoring is imperative at disposal sites (Kumthekar et al. 2002; Waugh 1999) as a preventive measure and to evaluate future improvements to landfill cover design. Computational evaluations of long-term landfill performances have been developed (Ho et al. 2004; Leoni et al. 2004). Results from such models revealed that potential failures occur in the clay layer by wet-dry cycles and water percolation through the cover, resulting in elevated concentration of contaminants in groundwater.

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).

Landfills and Water Balance

In a landfill, water content comes from the waste itself, from the landfill soil cover, and by precipitation (Bengtsson et al. 1994). The water content in contact with the waste should be minimal to prevent hazardous contaminants from leaching. The resulting leachate could eventually flow into the groundwater, thereby contaminating it (Bengtsson et al. 1994; Johnson et al. 1998). The water balance in the landfill cover is also a very important issue. Part of the landfill cover design is to limit the water reaching the waste and thus protecting against leaching and groundwater contamination (Khire et al. 1997). However, a compacted clay barrier layer would crack if the residual moisture content were not maintained (Suter et al. 1993). The ideal balance allows the barrier layer to retain effective moisture content while limiting the flux through to the buried waste.

A study on a municipal solid waste incinerator (MSWI) bottom ash landfill showed that discharge through the landfill and landfill cover after a precipitation event was rapid and in large proportion to the precipitation volume (Johnson et al. 1998). A single precipitation event in the winter resulted in more than 90% of the water volume discharging through the bottom of the landfill within days (50% transported in less than 4 days), while precipitation events in the summer months resulted in less discharge (between 9 and 40%). This was attributed to increased evaporation during the summer (due to the warmer temperature) and increased transpiration from plant growth. Preferential flow paths through the landfill can also account for some volume of water not discharged through the bottom of the landfill (Johnson et al. 1998; Ludwig et al. 2000). However, even with preferential flow, evaporation, and transpiration in periods with little precipitation, Johnson et al (Johnson et al. 1998) observed that the discharge through the landfill was never zero. According to Johnson et al (Johnson et al. 1998), the landfill acted as a reservoir for water that was held within the landfill by perched water tables with a residence time of approximately three years.

Groundwater contamination from leaching is expected more in humid areas than in arid areas, but an arid site study found that “considerable quantities of leachate” were present (Al-Yaqout and Hamoda 2003). This was attributed to rising groundwater levels and to the liquid wastes disposed at the site. Current near-surface barrier models and regulations assume that barriers can be designed, built, and perform at nearly a constant rate over a fixed time. After the design life of the barrier has been expended, its performance is assumed inconsequential. Monitoring of such barriers generally takes place by detecting barrier failure rather than barrier degradation. (In some places, caps are visually inspected for signs of erosion or subsidence, which could lead to barrier failure.)

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)," 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 percolation through the cover and 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, 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 Often Not Included in Performance Assessment

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-informed performance-assessment methods are available to assist DOE site managers in the selection, design, and monitoring of long-term containment isolation systems, but are not always 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-informed 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.

Performance Assessment Models

Numerical models serve as an important tool in cap design, performance or risk assessment, and post-closure monitoring. Performance Assessment (PA) models generally attempt to simulate the total performance of the system and are typically comprised 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 is usually 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 those 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, dyanamic 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.

In ET cover systems, the controlling parameters, processes and events may be uncertain and/or poorly understood. In a deterministic simulation, these parameters are represented using single values (which typically are described either as "the best guess" or "worst case" values). Probabilistic simulation is the process of explicitly representing this uncertainty by specifying inputs as probability distributions and specifying any random events that could affect the system. If the inputs describing a system are uncertain, the prediction of future performance is necessarily uncertain. That is, the result of any analysis based on inputs represented by probability distributions is itself a probability distribution.

The steps necessary to carry out a dynamic simulation are briefly summarized below:

1. **Define objectives and measures of performance.** Before attempting to simulate a system, it is important to clearly identify what types of questions should be answered with the model. The objectives of the model define the performance measures for the system. A performance measure is a model output by which performance of the system can be understood (e.g., percolation into the waste).

2. **Select scenarios for evaluation and develop the conceptual model.** The most important step in simulating any system is developing a conceptual model of the system.

A conceptual model is a representation of the significant features, events and processes controlling the behavior of the system. It is essentially a body of ideas, based on available information, that summarizes the current understanding of the system.

3. **Create the mathematical model.** Once a conceptual model of the system is developed, it is necessary to represent it quantitatively within a mathematical model. A mathematical model consists of a set of input assumptions, equations and algorithms describing the system.

4. **Quantify the input parameters.** The mathematical model identifies specific inputs (e.g., infiltration rate of water into cover, growth rate of plant community) which are required in order to simulate the system. These must be quantified by specifying their values or probability distributions.

5. **Implement and solve the mathematical model using a computational tool.** After developing the mathematical model and quantifying all of the input parameters, the model must be implemented within a computational tool capable of solving the equations representing the system. This implementation of the mathematical model within a computational tool is referred to as the simulation model.

6. **Evaluate, explain and present the results.** The final step in the simulation process is to produce results, and evaluate and draw conclusions from these results.

Models which are constructed by conceptual models that can be continuously updated in a refined manner can provide a systematic framework for organizing and evaluating the available information related to a complex system, and can act as management tools to aid in ongoing decision-making regarding ET cover design and performance assessment.

Modeling Ecological Systems

Predicting behavior of ecological and biological systems is inherently complex and uncertain since they involve systems made up of many component parts that are interrelated, the components interact in complex ways with numerous feedback mechanisms, and in many cases, the systems are poorly characterized. In addition, such systems are often controlled by stochastic variables (i.e., precipitation, temperature) and involve uncertain processes, parameters, and events.

The challenge when evaluating such systems is to find an approach that can incorporate all the knowledge available to planners and scientists into a quantitative framework that can be used to predict the outcome of alternative management approaches, policies and plans. To be effective, the framework needs to be both flexible (so that it can accurately represent the systems) and transparent (so the models can be easily explained to decision-makers and stakeholders).

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CHAPTER III

ASSESSING THE IMPORTANCE OF ECOLOGICAL PROCESSES THROUGH BIOMONITORING AND ECOLOGICAL FORECASTING AT NUCLEAR MATERIALS AND WASTE SITES

BACKGROUND

Knowledge of important ecological processes can provide critical information needed for decision making at nuclear materials and waste sites. Biomonitoring and ecological forecasting are especially valuable when considering the potential long term effects of radiation on ecological resources. They are powerful tools that can aid in decision-making concerning environmental management strategies to prevent the release and migration of radioactive materials to the environment and remediate sites where contamination has occurred through past practices that were not protective of the environment. As a result of past waste management practices, that were not protective of the environment, environmental remediation is needed at 100s of sites contaminated with hazardous chemicals and radionuclides. Due to technical and economic limitations, many, if not most, of these remediation efforts will necessarily have to rely on the implementation of engineered barriers and other controls, both technical and institutional, to isolate these materials from humans and the environment. Consequently, there is a need to develop and rely on the use of conceptual and mathematical models to assess future performance and aid in the development of monitoring approaches. Waste containment systems are designed to isolate the waste until it has decayed or biodegraded to a point where it no longer poses a risk to human health and ecology. In the past, performance assessment models have excluded ecological inputs. The aim of this chapter is to elucidate fundamental ecological principles that should be considered when designing, modeling, and monitoring engineered covers for radioactive waste sites. Specifically, the following eight ecological processes will be evaluated within the context of cover design and long term monitoring planning: (1.) Habitat Functions, (2.) Habitat Patches, (3.) Natural Disturbance Regime, (4.) Structural Complexity, (5.) Hydrologic Patterns, (6.) Nutrient Cycling, (7.) Biotic Interactions, and (8.) Species Diversity. Additionally, recent work by the authors on identifying and incorporating the important ecological processes into the models and the development of site-specific ecological monitoring strategies and risk analyses will be discussed.

Introduction

Any activity that produces or uses radioactive materials generates radioactive waste. Mining, nuclear power generation, and various processes in industry, defense, medicine, and scientific research produce byproducts that include radioactive waste. Radioactive waste can be in gas, liquid or solid form, and its level of radioactivity can vary. In comparison to other wastes, radioactive waste is unusual in that the very property that makes the waste hazardous, its radioactivity, will disappear with time. Because it can be so hazardous and can remain radioactive for so long, finding suitable disposal methods for radioactive waste is difficult. Proper disposal and subsequent long term monitoring is essential to ensure protection of the health and safety of the public and quality of the environment including air, soil, and water supplies. Radioactive waste disposal is just one of a growing number of environmental challenges that face our nation and the world. If we cannot learn from our past failures in confronting this disposal challenge, we will be doomed to fail with the alternative approaches that are now emerging.

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. The primary objective of a final cover is the isolation of the waste materials from human and ecological receptors by reducing the amount of water that contacts the material, thereby minimizing the generation of leachate and subsequent transport of contaminants to ground and surface water. Although the hazards and potential risks associated with radioactive waste frequently persist well beyond 100 years, cover design and performance evaluation guidelines frequently fail to consider consequences of inevitable changes in ecological processes. Furthermore, a rigorous methodology 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.

In this chapter, we discuss lessons learned from experience gained through monitoring existing covers, designing alternative covers that accommodate ecological change, and using natural analog studies in combination with monitoring and modeling to project the long-term performance of covers. This investigation into the role of ecological monitoring of contaminant isolation systems includes ways to identify parameters and processes for performance confirmation and monitoring. 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, it is essential to develop a risk-informed performance-based approach for selection, design, modeling, and monitoring ecological components of covers.

Conventional "Resistive" Cover Designs

Engineered covers assist on-site isolation of subsurface contaminants in landfills and other near-surface disposal sites. The primary objective of a final cover is the isolation of waste from human and ecological receptors by preventing direct contact and by reducing the amount of water that contacts the material thereby minimizing the generation of leachate and subsequent transport of contaminants to ground and surface water (Clarke et al., 2004, Kostelnik and Clarke, 2008).

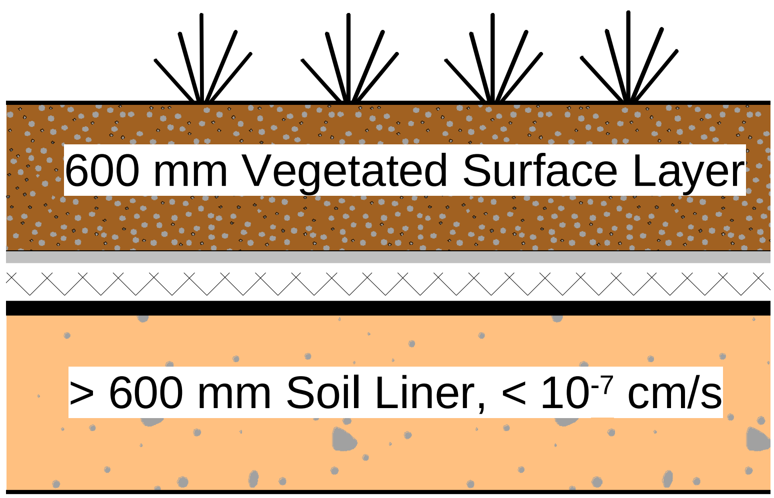

Figure 1. Conceptual diagram of a conventional resistive cover

Often federal regulations and guidance for limiting infiltration through landfill covers require use of low-permeability compacted clay materials either alone or in combination with geomembranes (Kodikara 2000). Figure 1 shows an example of such a "resistive" cover design as embodied in the Resource Conservation and Recovery Act (RCRA) regulations. This design is often employed to provide final covers for solid and hazardous waste landfills and in remediation activities that seek to isolate contaminants at contaminated sites.

While the concept is sound, there is a growing concern that such “resistive” cover approaches will not perform effectively over the very long times that are required without substantial monitoring and intervention. For example, clays have the potential to desiccate and fracture, permitting infiltrating precipitation to enter the waste materials (Benson 1996). Desiccation as well as the freeze/thaw cycle, and intrusion by plant roots, or burrowing animals, can create openings in the barriers resulting in the development of flow paths in resistive barriers, thus compromising long term performance. There is a growing concern that conventional resistive covers will be unable to resist effects from ecological processes over intended performance time scales (Sharma and Reddy 2004).

Alternative Cover Designs – The Evapotranspiration Cover

Conceptually, the simplest type of alternative cover consists of a soil layer overlain by vegatation. An evapotranspiration (ET) cover (also called a water balance cover or a store and release cover) is a specific type of alternative cover, 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 purpose of which would be to resist the infiltration of water into the material being isolated.

The ET cover uses two natural processes to control infiltration into the waste: the soil provides water storage, and natural evaporation from the soil plus plant transpiration removes water from this soil reservoir (Waugh 1994). An ET cover is a relatively inexpensive, practical, and easily maintained biological system that can perform effectively over extended periods of time, perhaps centuries, at relatively low cost (see Figure 2).

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. 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 design procedure.

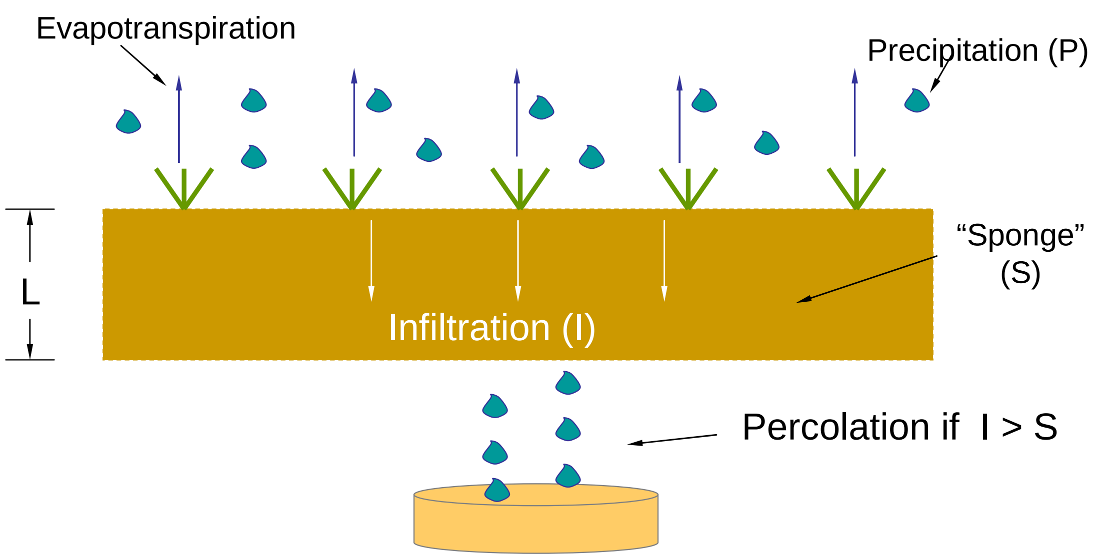

Fig 2. Evapotranspiration (ET) Cover

A Capillary Barrier is a specific type of ET cover that typically consist of two layers of granular materials designed so that the contrast in hydrologic properties and sloping interface between the layers keeps infiltrating water in the upper layer (Fig. 3).

Evapotranspiration (ET) covers are an alternative design that may reduce the long term performance risk of conventional restrictive covers. However, information on ET cover performance is limited to relatively short times, generally less than 10 years, and is incremental at best. Additionally, interactions between engineered barrier degradation and ecological dynamics are complex, and typically omitted from long-term performance models and monitoring plans. This chapter presents a review of important ecological principles that will guide cover performance over the period of performance, suggests an approach to performance assessment for engineered covers and identifies the ecological parameters and processes believed to be most important.

Capillary Barrier

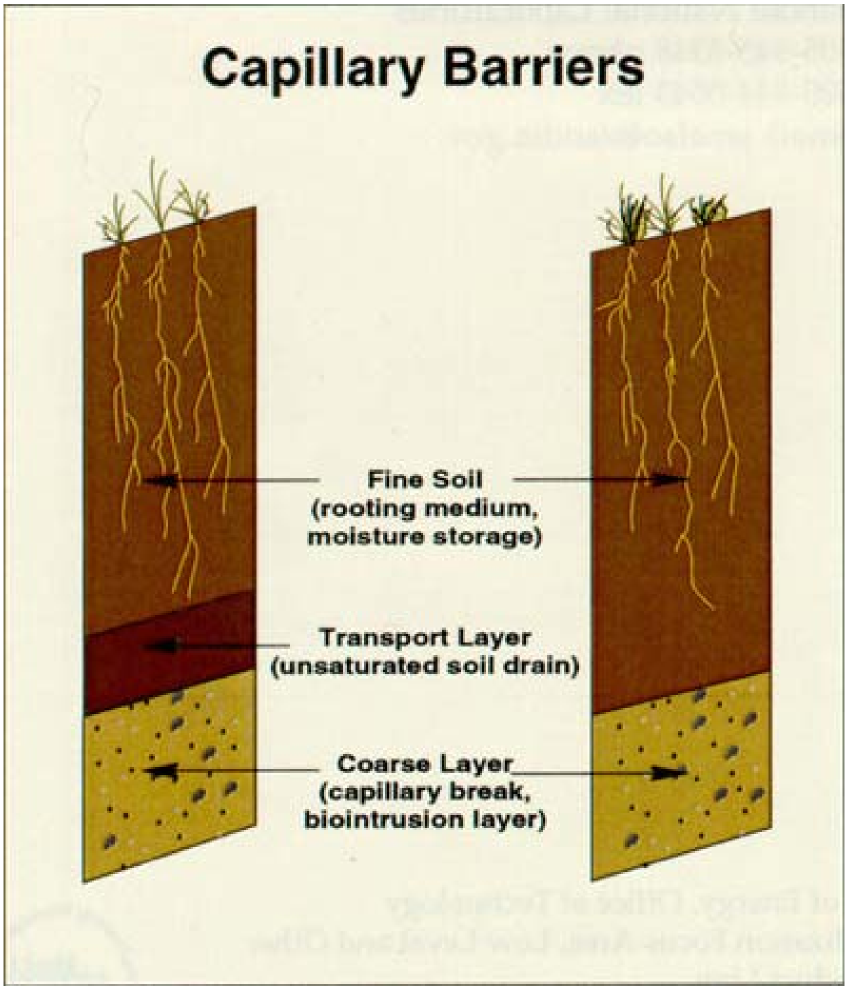

Figure 3. Cross section of a generic capillary barrier.

Ecosystem Integrity

In the past, engineered covers have been applied deliberately with the intention of thwarting the natural progression of ecological processes. Ecological processes have been viewed as a threat to the integrity of the engineered system. This goal becomes impossible to ensure without human intervention often within the first ten years of the construction of the containment systems. Ecological integrity is the long-term health and sustainability of the interactions among the physical, chemical, and biological elements of an ecosystem (e.g. Holling

1973; ed. Waltner-Toews et. al. 2008). Integrity is diminished when the quality of habitat is degraded, the distribution and abundance of species is altered, or natural ecological processes are degraded (Costanza et. al. 1997). The most severe habitat destruction can occur when a natural ecosystem is converted to an artificial system, such as an engineered containment system. While we have learned to appreciate that the engineered system will eventually return to its more natural state, it is less well known how the ecological processes inherent to these ecosystems have been altered or degraded, and more importantly, how they will respond to the multitude of ecological processes acting on them over time.

While the consequences of waste emplacement and subsequent cover installation on ecosystems will vary between cover projects and the environmental setting, it is useful to evaluate long term sustainability by investigating discrete ecological processes. This section will describe eight ecological processes that effectively capture the function of a cover ecosystem, and should be evaluated within the context of cover design and long term monitoring planning:

1. Habitat Functions
2. Habitat Patches
3. Natural Disturbance Regime
4. Structural Complexity
5 Hydrologic Patterns
6. Nutrient Cycling
7. Biotic Interactions
8. Species Diversity

Habitat Functions

Ecosystems are degraded when habitats remain but their composition, structure, or function is substantially altered, as is the case when a cover is engineered into an existing landscape. At the level of a landscape, certain natural habitat types are especially important for the ecological functioning or species diversity of the ecosystem (Andrewatha and Birth 1954). Unusual climatic or edaphic (soil based) conditions may create local biodiversity hotspots or disproportionally support ecological processes such as hydrologic patterns, nutrient cycling, and structural complexity. For these reasons, preservation of native habitats should have priority.

Natural analogs are especially useful as a tool in understanding the dynamic of the native habitat on a site specific basis. Historically, environmental impact assessments (EIS) have identified the potential impacts of project activities on habitats of concern (NEPA 1969). An EIS is an important step in understanding how the function of the engineered cover will impact the existing ecology. Certain habitats disproportionately contribute to ecosystem functioning. In general, these are areas that integrate the flow of water, nutrients, energy, and biota through the ecosystem. The concept is analogous to that of keystone species that have a disproportionate effect on community structure (Paine 1969). The best understood examples of habitats critical to ecosystem functioning are wetlands. However, arid environments are less studied from the perspective of habitat function, yet are disproportionately represented in hosting engineered covers. Therefore, it is imperative to better understand the ecosystem functions where these covers are installed and to recognizing that certain habitats, or types of habitats, are of special value for ecosystem functioning because of unique attributes that may provide.

Habitat Patches

At the landscape level, natural ecosystems have a characteristic pattern and connectivity of habitat patches (Forman 1995). The amount and juxtaposition of these patches supports the movement of species and the transfer of materials (energy and nutrients) among habitats. Prior to human intrusion, natural landscapes were characterized by large expanses of contiguous habitat. The fragmentation of these areas into disconnected engineered systems and isolated patches can significantly disrupt ecological integrity of the whole system. The installation of an engineered cover system represents a major disruption to the natural landscape, and effectively becomes a habitat patch. All natural systems have characteristic patterns of habitat patches; in addition, the larger landscape can be viewed as a mosaic of adjacent ecosystems. To understand a landscape's patterns, such as the mosaic of wetlands and forest in a humid environment, its elements and its processes require a holistic analysis to understand the function of the whole (Barrett and Bohlen 1991). Ecological patchiness generally involves natural gradations which can be severely disrupted through the construction of an engineered cover. Insights from ecology support the notion that an engineered cover should be viewed as a component of the larger landscape in which it has been embedded.

Ecological and evolutionary processes produce the pattern and connectivity of landscapes. For example, Levin (1976, 1978) showed that biotic predator-prey interactions, combined with spatial movement, can result in patchy spatial patterns of populations. Paine and Levin (1981) demonstrated that natural regimes of disturbance and recovery also produce spatial pattern. In turn, landscape patterns influence the ways organisms move on the landscape (Wiens and Milne 1989) and the ways they utilize resources (O'Neill et al. 1988b). Dispersal processes and spatial pattern interact to separate competitors and make coexistence possible (Comins and Noble 1985).

Landscape connectivity involves the linkages of habitats, species, communities, and ecological processes at multiple spatial and temporal scales (Noss 1991). In a natural landscape, connectivity among like habitats is usually high. In isolated habitats, such as those that are created on engineered covers, populations are much more susceptible to environmental catastrophes and invasion by exotic species (Harris 1984). Arid systems in particular tend to experience regular patterns of episodic events that seriously alter the landscape. This is especially a concern considering the highest density of covered waste systems in this U.S. have been built in environments vulnerable to catastrophic events.

Natural Disturbance Regime

Ecosystems do not exist in a steady-state; they are dynamic, each possessing a characteristic composition, structure, and function that varies within limits over a course of tens to hundreds of years (Cowles 1911). Natural disturbance events, such as fires, floods, and wind, result in a significant change in ecosystem structure or composition. The natural disturbance regime of an ecosystem is the type, magnitude, and frequency of disturbances that would occur within the landscape in the absence of human intervention. At the landscape level, natural disturbances destroy patches of vegetation and restart plant succession (Connell and Slatyer 1977). Examples of natural disturbances include fires, floods, droughts, wind storms, insect outbreaks, herbivory, beaver activity, and soil disruption by burrowing and trampling. These disturbances affect plant structure and community composition and may shape the dominant land forms in the landscape. An ever changing pattern of vegetation types and stages may determine the productive capacity of the ecosystem by changing the spatial and temporal patterns of nutrient availability (Pickett and White 1985), adding or removing biomass (McNaughton et al. 1988), and changing the ratio of live to dead material (Pastor et al. 1988).

Ecosystems and species have adapted to habitat and disturbance conditions over long periods of time. Any deviation from these patterns or regimes can result in species losses or other undesirable ecological consequences. Unintended ecological consequences have been seen on many engineered covers and provide valuable lessons learned. For example, disturbances have created microhabitats that provide the ideal conditions for invasive plants and burrowing animals to thrive (Probst and Weinrich 1993). Natural fires are another serious threat to covers where plants are integral to performance. Yet, fire plays an important ecological role at both a species level and to the function of entire ecosystems (Ewel 1996). For example, fire greatly influences the cycling of nutrients, often increasing nutrient availability to immediate post-fire pioneer species. In regions where climate or nutrient availability limits the decay of debris, fire is a major agent of organic decomposition. The patchiness created by these disturbances results in vertical and horizontal heterogeneity and diversity in habitat types, adding to the productivity of the ecosystem. Each landscape possesses a characteristic natural disturbance regime that differs from other ecosystems in type, intensity, and timing (Forman, 1995). It is critical in assessing environmental impacts to determine how the area affected by the proposed engineered cover fits into the natural disturbance regimes of the landscape in order to understand how the cover will affect and be affected by the natural disturbance regime.

Structural Complexity

At the local scale, ecosystems possess a natural complexity of physical features that provides for a greater variety of niches and more intricate interactions among species (Whitaker 1975). Local structural complexity increases with more shrubs in an arid environment. At other scales, spatial heterogeneity is equally important, affecting a wide range of ecological processes from predator-prey interactions to energy transfer among ecosystems. All ecosystems have physical features that increase the structural complexity of the environment. This structural complexity is a key factor determining its species diversity; ecosystems with more three-dimensional structure have more species (MacArthur and MacArthur 1961). For this reason, high structural complexity is most remarkable in biologically diverse ecosystems such as tropical forests and coral reefs. Both of these ecosystems possess vertical layers of structure in addition to intricate spaces in and around the living infrastructure (trees and corals). Where vertical stratification in less complex, such as those that exist in the arid west, structural complexities usually involve stratification of light and temperature, as well as shelter and food sources.

Considerable ecological evidence supports the concept that physical structure may prevent generalist foragers from fully exploiting resources and thus promote the coexistence of more species (e.g., Werner 1984). Simply put, complex habitats accommodate more species because they create more ways for species to survive (Norse 1990). Additionally, research also suggests that natural disturbance maintains structural complexity and that this complexity promotes plant and animal diversity (Hansen et al. 1991). Therefore, as ecological processes interact with the engineered cover over time, the system with evolve towards greater complexity, and greater sustainability so long as other foundational ecological principles have not be negated.

The benefits of structural complexity can easily be noted in a complex, productive ecosystem like a rainforest. However, it is also important in more homogenous environments such as deserts and other arid ecosystems where a large number of covers have been built. Even small amounts of physical structure can dramatically increase species diversity and ecological interactions. On the desert floor, "cryptogamic crusts" of nonvascular photosynthetic plants such as algae, lichens, and mosses support a microecosystem of bacteria, fungi, actinomycetes (as well as protozoans, nematodes, and mites). Biological soil crusts are formed by living organisms and their by-products, creating a surface crust of soil particles bound together by organic materials (Alexander 1969). These crusts perform the critical functions of protecting soil from erosion, aiding in water infiltration, augmenting sites for seed germination, and increasing the soil's supply of nutrients (Klopatek 1992). Microtopographic features such as depressions or pits in the soil create environments for the collection of water and other resources that support shrubs or savanna vegetation. Both live and dead organisms, generally plants, constitute the majority of structural diversity, although edaphic characteristics to landforms contribute to physical structure. Leaf area index, branch density, and vertical layer analysis are common measurements used to capture structural diversity of a cover system.

Hydrologic Patterns

Hydrology is a central concept to alternative engineered covers that accommodate ecological changes (e.g., evaopotranspiration covers) and will be discussed in greater depth and detail within the context of performance assessment. Most broadly, ecosystems possess natural hydrologic patterns that provide water for organisms and physical structure for habitats. This cycle of water is also the vehicle for the transfer of abiotic and biotic materials through the ecosystem (Richter et.al. 1996). The natural hydrologic patterns of an ecosystem include the magnitude, frequency, duration, timing, and rate of change (flashiness) of water flow.

Nutrient Cycling

Nutrient cycles are the processes by which elements such as nitrogen, phosphorus, and carbon move through an ecosystem. Ecosystems have evolved efficient mechanisms for cycling nutrients, which combined with sunlight and water determine the overall productivity of the system. The natural flow of organisms, energy, and nutrients is essential for maintaining the trophic structure and resiliency of a cover ecosystem (Daily et. al. 1997). Reduction or augmentation of nutrient inputs to a cover ecosystem can drastically alter trophic interactions and ultimately the long term sustainability of the system. The input and assimilation of nitrogen is perhaps the most common measure of nutrient cycling, but the dynamics of other essential compounds are also important.

Historically, ecosystem studies have focused on the transfer of nutrients and energy among the various components of the biotic and abiotic environment (Odum 1971). Many aspects of organismal ecology are also based on the importance of nutrients for species growth and survival because nutrients often set the limits of primary or secondary productivity of populations and communities. As with all ecological processes, when the natural level or flow within the ecosystem is changed (either increased or decreased), ecological integrity is degraded.

Ecosystems that develop on engineered covers are not isolated from one another; nutrients come into and out of these ecosystems via meteorological, geological, and biological transport mechanisms (Krebs 1978). Meteorological inputs include dissolved matter in rain and snow, atmospheric gases, and dust blown by the wind; geological inputs include elements transported by surface and subsurface drainage; and biological inputs include movement of animals between ecosystems. Trophic interactions within ecosystems (e.g., the food chain of plant-herbivore-carnivore) are the most visible part of the cycling of energy and nutrient within ecosystems. Changes in the input or export of nutrients within cover ecosystems can affect trophic interactions and can have ramifications for biotic interactions as well as ecosystem functioning (Wright 2002). Less obviously, decomposers (such as invertebrates and microorganisms) serve the critical role of recycling dead material at each stage of the nutrient cycle and ultimately supply the soil nutrients that feed the plants that capture the sun's energy.

Soils are a key factor regulating element and nutrient cycles. The amount of carbon and nitrogen in soils is much greater than that in vegetation, 2 to 20 times respectively (Daily et al. 1997). Soil consumes wastes and the remains of dead organisms and recycles their constituent materials into forms usable by plants. In the process, soil organisms regulate the fluxes of carbon dioxide, methane, and nitrogen oxides in the atmosphere.

Plants require 21 essential elements that, along with water, determine growth (Vogt et al. 1997). Plants acquire nutrients from soil exchange sites, soil weathering, above- and below-ground litter that is decomposed by soil fauna and flora, and internal movement within the plant tissues. The importance of the vegetation community will once again be discussed in a later section on alternative covers. But, it is important to recognize the integrated nutrient processes that drive the health of the cover plant community.

A valuable lesson from existing covers underscores the importance of plant-mycorrhizal associations in the soil after designed plant communities failed to develop in soils that lacked the necessary mycorrhizal populations. Therefore, it is important to recognize that the total nutrient content of the soil may not accurately reflect availability for uptake by plants, and that plant-mycorrhizal associations often play an important role in influencing the rate of plant succession (Vitousek 1990). Ultimately, nutrients are excellent parameters to monitor when assessing the impact of a management activity (e.g., cover design and construction) on ecosystem resistance and resilience, because nitrogen integrates ecosystem function across many different levels (e.g., nitrogen deficiencies create a positive feedback between decreased productivity and slowed decomposition rates). Using indices related to nutrient use and cycling may be especially important at sites where nutrients limit plant growth and influence carbon allocation. (Vogt et al. 1997).

Biotic Interactions

Interactions between organisms are a major determinant of the distribution and abundance of species. They include intraspecific and interspecific competition for resources, predation, parasitism, and mutualism. Although the natural function of ecosystems comprises all biotic interactions, the relative importance of these interactions varies: relatively few have a disproportionate role on the structure of the community. It has been argued that unexpected changes in community dynamics are a result of pervasive indirect effects throughout the ecosystem (Pimm 1991).

The far-reaching effects of a disturbance depend on the nature and strength of the target species' connections to other species in the ecosystem. These indirect effects may include feedback loops that propagate or dampen the effect of the original disturbance. The magnitude of the interaction between species is termed the "interaction strength," and species whose effect on their communities is disproportionately large (relative to their abundance) have a high "community importance" and are commonly known as "keystone" species (Power et al. 1996). While the identification of a keynote species is an important ecological research area, keynote species of covers may not yet be known and may only be revealed through the demise of a cover ecosystem. Ecosystem traits that may be affected by keystone interactions include productivity, nutrient cycling, species richness, or the abundance of one or more functional groups of species. Once again, nitrogen-fixing mycorrhizae serve as a valuable example of biotic interactions; the absence of specific mycorrhizae has been observed to hasten succession.

All species are not created equal in terms of ecosystem structure and function. For instance, most abundant species play a major role in controlling the rates and directions of ecological processes. The dominant species typically provide the major energy and nutrient cycling and the physical structure that supports other organisms (Menge et al. 1994). However, also of importance is the phenomena of keystone species which are less abundant species that have much larger effects on their ecosystems than would be predicted from their abundance. Such an organism plays a role in its ecosystem that is analogous to the role of a keystone in an arch. While the keystone is under the least pressure of any of the stones in an arch, the arch still collapses without it. Similarly, an ecosystem may experience a dramatic shift if a keystone species is removed, even though that species was a small part of the ecosystem by measures of biomass or productivity (Mills et. al. 1993). This has become a very popular concept in conservation biology. A lesson from ecology is that it is important to consider all biotic interactions of a cover ecosystem early on in order to identify the potential sources of changes to ecosystem-specific biotic conditions in the future.

One example of biotic interactions that could severely affect cover performance is the potential for invasion by exotic species. Because exotic species come from different environmental settings, they are not generally as well adapted as native species (although in engineered ecosystems, such as a cover, they may be better adapted). When conditions are favorable, however, they can be very successful (lacking the constraints of co-evolved predators and competitors) and dramatically change the biotic interactions in the ecosystem (Paine, 1969). Our lack of complete understanding of biotic interactions, including the affects of exotic species, highlights the importance of applying an adaptive management approach to engineered covers. The understanding and management of potential keystone species is often limited, and the full ramifications can only be determined by adjusting project implementation according to monitoring results.

Species Diversity and Composition of Plant Community

Diversity at the genetic level underlies the more visible diversity of life that we see expressed in individuals, species, and populations. Over evolutionary time, the genetic diversity of individuals within and among populations of species contributes to the complex interplay of biological and nonbiological components of ecosystems. The preservation of genetic diversity is critical to maintaining a reservoir of evolutionary potential for adaptation to future stresses that will affect cover performance (Paine, 1966).

The genetic variants found in nature are integrated not only into the physiological and biochemical functions of the organism, but also into the ecological framework of the species. Perhaps the most important influence of species diversity on ET cover sustainability is that the genetic diversity of a species is a valuable resource to long term ecosystem sustainability (Naiman 1988). For example, if a disease were to compromise a dominant plant species on the cover, the ability of the vegetation to persist will be highly dependent on the underlying genetic diversity of the plant community (Paine, 1966). Ecological processes are the product of evolution, and genetic diversity is the basis of the evolutionary process. Genetic diversity enables a population to respond to natural selection, helping it adapt to changes in selective regimes (MacArthur 1972). Evidence from plant and animal breeding indicates that genetic diversity promotes disease resistance (Strong et al. 1993). Through its effects on interspecific interactions, genetic diversity could even affect ecosystem dynamics and stability.

The design of an ET cover must include careful consideration of the types of plants that are best adapted to the site, and the types of plants that will transpire to the greatest extent possible. This can clearly be seen in the design malfunction of a test ET cover in Sacremento, CA. The construction and monitoring of the test cover was performed under the U.S. Environmental Protection Agency (EPA) funded through the Alternative Cover Assessment

Program (ACAP). Detailed hydrologic performance monitoring of the covers from 1999 through 2005 provided a significant amount of information in support of a final design for the site. Important lessons learned from this work were: 1) Failure to establish the target perennial vegetation contributed to inadequate hydraulic performance; and 2) With improved attention to soil/vegetation interactions and requirements for successful establishment of perennial vegetation, target hydraulic performance can be achieved. In this specific case, an annual plant community established and was more competitive than a perennial community that was intended for the site. Therefore, species composition of ET cover vegetation can shape long term cover performance and must be considered early on in the cover design phase.

Regulatory Guidance

From a regulatory perspective, statutory requirements for monitoring systems are determined in accordance with the regulatory classification of the waste. Thus, monitoring requirements depend on whether the waste contained by the barrier system is regulated under the Resource Conservation and Recovery Act (RCRA; Subtitles C and D); the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA); the Uranium Mill Tailings Remedial Action (UMTRA); the Low Level Waste Policy Act; and land disposal requirements for low level waste (10CFR61). Two common elements among almost all statutory monitoring programs are post-closure monitoring and the ability for regulatory programs to be delegated to state governments and tribal authorities with regulatory programs that conform to the minimum federal requirements.

Integrating Ecology Principles into Cover Performance Assessment and Long Term Monitoring Plans

Waste containment systems are designed to isolate the waste until it has decayed or biodegraded to a point where it no longer poses a risk to human health and ecology. A performance assessment (PA) is an analysis of a cover 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 (Helton 1996). Current cover design guidelines, such as those prescribed by RCRA, are not risk-based nor are they 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 ecological features, events, and processes at the site that may contribute to the long-term risk of groundwater contamination and human exposure. Performance assessment for radioactive waste disposal is a powerful tool in understanding how the disposal site will evolve and involves many scientific disciplines. At its core, PA attempts to answer three questions about potential disposal sites: (1) What could occur at the site in the future?, (2) How likely are different occurrences at the site?, and (3) What are the consequences of different occurrences at the site?

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.

Ecological monitoring is a complementary component of the overall environmental waste management and monitoring program. Ecological monitoring is the systematic observation and measurement of ecosystems (or their components) to establish their characteristics and/ or changes over time (Spellerberg 1991)). Landscape is a geographical unit characterized by a specific pattern of ecosystem types, formed by the interaction of geographical, ecological and human-induced forces (Forman 1995). Post-construction (long-term) monitoring of engineered containment systems is critical to ensure that barrier integrity is sound and that contaminants are not inadvertently released into the environment. Monitoring systems may observe both the physical conditions of the barrier and the environment surrounding the barriers. The length of time is fundamental to the design and purpose of all environmental monitoring programs (Ewel 1996). Two fundamental reasons for monitoring the natural environment are (1), to establish baselines representing the current status of ecosystem components and (2), to identify changes over time, particularly, any changes that are above the natural variation in these baselines. Closely associated with these reasons is the desire to determine the causes of observed changes. Information from monitoring of existing waste containment systems provides valuable information on the long-term performance of engineered barriers.

While surface processes are fairly well understood for some settings, such as a controlled laboratory, they are complex and not well understood in most natural, especially semi-arid, environments and the uncertainties in feedbacks between physical and biological components can introduce large errors in estimated water balance estimates for the cover (Green et al 1996).

Figure 4 lists some of the important physical and biological processes that need to be considered in developing a long term monitoring plan.

Physical Processes	**Biological Processes**
Erosion	Root penetration
Slope instability	Burrowing animals
Wet/dry cycles	Bioturbation
Freeze/thaw cycle	Human intervention
Settlement	Bacterial clogging
Extreme/Catastrophic events	Vegetation establishment

Figure 4. Summary of physical and biological processes that could influence cover performance.

The proper examination of water balance requires investigation into plant dynamics. Plants are “largely responsible for the water removal from the landfill cover” (Albright et al., 2002), and therefore have a major influence on the landfill water balance. While plant root water uptake is a design consideration of landfill covers, unintended plant growth may be detrimental rather than beneficial (e.g. Burger 2007, Traynham et.al. manuscript submitted to Risk Analysis).

The very nature of ecological monitoring, to detect changes in ecosystems over time, demonstrates the importance of having long-term data records. The ecological responses to a changing environment occur over long time periods and therefore, require observations and research that integrate short term changes to long term trends. Environmental and ecological management cannot operate effectively without reliable information on changes in the environment and on the causes of those changes (Burger 2004). Ecological monitoring can represent an important source of information. Our ability to conduct long term ecological monitoring has increased significantly since the development of environmental monitoring technologies and techniques. Ecological monitoring needs have also been increasing in complexity; it is now accepted that many of the issues interact causing synergistic or cumulative changes (Wilson and King 1995). Thus the need has shifted from understanding not only single-cause, single-effect issues, but also multiple-cause, multiple-effect issues. This is certainly true with respect to ecological monitoring of engineered disposal covers.

DISCUSSION

The problem for engineers is thus how to design covers that work with the environment, rather than against it by incorporating elements of the ecosystem (as discussed above). Since covers should be designed to have longevity, incorporating ecosystem processes into their design is critical, and being able to monitor their effectiveness is paramount. These aspects will be discussed below.

Challenges of Incorporating Ecological Monitoring into Long Term Performance Assessment

Environmental risk assessments are used to predict the impact that a loss of control from failure of a cover system might have on human health and the environment. A major challenge with integrating ecological monitoring techniques into existing long term monitoring paradigms emerges from the disparate goals of ecological risk assessments (ERA) and environmental monitoring. While ERA and environmental monitoring would seem to be potentially complimentary activities, they have long been incongruent in practice (Lerche 2006). This is because of fundamental discrepancy in goals and end products. Environmental monitoring determines status and trends in indicators to determine whether the environment is improving. ERA estimates effects of stressors on endpoint attributes to reinforce decision making. Indicators are, by definition, indicative of some unmeasured condition. Assessment endpoints are those variables of interest (e.g., health or overall fitness of a species, reproductive success), while the measurement endpoints are measure parameters that tell something about overall fitness or health (Glasson 2005). Assessment endpoints are valued properties of the environment that are susceptible to stressors of concern. Assessment endpoints are justified by their potential susceptibility and by environmental policies and public values. Indicators are often expressed in terms of indices or scores that obscure the actual condition of the environment. Because assessment endpoints must be clear to decision makers and the public, they require real units of actual environmental properties.

Current monitoring programs are only peripherally concerned about causal relationships, while risk assessment is aimed almost entirely at illuminating causal relationships. As a result, risk assessments may use the results of monitoring studies, but only after disaggregating the indicators to their components and choosing those that are appropriate. Long term monitoring programs on DOE lands could be more useful if they used a risk informed approach to address important problems rather than simply tracking indicators. Even more importantly, selected indicators should be integrated much more appropriately into these monitoring programs in order to be used more effectively as early warning signals associated with failure of engineered barrier performance (Burger 2007).

Because of the many challenges that face long-term monitoring programs at hazardous waste sites, there is no simple solution or role for ecological monitoring of these sites. It is expected that there will be complex ecological responses to the changes that occur due to the presence of hazardous waste. Measuring the biological effects and determining the interactions with hazardous waste stresses will be very difficult and will require integrated monitoring. Any cause and effect relationships used to support hazardous waste and resource management programs will have to stand up to rigorous examination. This represents a major challenge for DOE monitoring programs, and particularly for the integrated monitoring sites that can provide the long term perspective supported by process research and experimental evidence that will be needed for the scientific defense of proposed management plans.

The challenges involved with the ecological component involved range from basic ecology (e.g., identifying useful bioindicators) to engineering (attaining superior reliability in data reporting in remote networks) to regulatory affairs. However, many operational monitoring programs are not very effective and are not very useful for decision-making (Niemi and McDonald 2004). What seems to be lacking is a general concept for the design of ecological monitoring systems. Given the enormity of the DOE obligations, it is imperative to develop much more efficient monitoring paradigms.

Cover Performance Numerical Models

The advantage of numerical modeling is that it allows for coalescing and evaluating a set of complex conditions, processes, designs, and decisions into a comprehensive effort. The purpose for numerical modeling in general is threefold. First, modeling can be conducted to interpret a mechanism or process (e.g. to prove a hypothesis or to "train" our thinking), or to assist with interpretation of field data (Freudenthal 1951). Second, modeling can be used to evaluate the relative performance of alternate conditions. And finally, modeling can be used for predicting a final behavior or impact. In general, the latter two aspects tend to be the focus of numerical modeling, when in fact the first rationale should be the foremost use of a numerical model (Churman 1968). For example, numerical modeling is often dismissed as being "useless" due to a lack of predictive accuracy. However, the key advantage to numerical modeling is the ability to enhance judgment, not the ability to enhance predictive capabilities. In short, numerical modeling should focus on improving our ability to understand key ecological processes and characteristics, as opposed to enhancing predictive capability. Generally, there are four potential sources of failures in an ecological process model, each associated with a different phase of the modeling activity (Churchman 1968):

- 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).

Natural Analogs

Natural analog studies are investigations of natural, anthropogenic, or archaeological systems which have some definable similarity with an engineered cover system and its surrounding environment. Experience with existing covers has determined that covers have already changed in ways that could not have been predicted with numerical models. Therefore, natural analogs are a useful tool to assist in making long term performance prediction. No natural system is exactly like a cover in all aspects and, thus, there is no complete analog. There are, nonetheless, many natural systems which have close similarities to certain components of a cover or to processes that control cover evolution. This is especially true for natural processes that will act on the cover performance through the intended years of performance.

By careful study of appropriate analog systems, important lessons can be learnt which may be used to improve our conceptual understanding of short and long-term repository behavior and our safety assessment modeling capability. Moreover, analog information can increase our conceptual understanding of long-term cover behavior in support of long term performance assessment (PA), provide quantitative data for PA models and provide ways of communicating safety information to non-specialist audiences. More specifically, 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; therefore, analogs may be important components of a robust cover screening tool.

Natural and archeological analogs exist for ecological change, pedogenesis (soil development), and climate change (Waugh et al. 1994). Effects of ecological change are inferred by measuring water balance parameters in plant communities representing chronosequences of responses to climate shifts and secondary disturbances (e.g., fire). Pedogenic effects are inferred from measurements of key physical and hydraulic soil properties in natural and archaeological soil profiles that are considered analogous to future states of engineered soils. Analogs of local responses to future global climate change exist as proxy ecological records of similar paleoclimates. To date, these functions of analog studies have received very little attention in the context of performance assessment.

CONCLUSIONS

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, allowing transport of radionuclides and other contaminants into the environment, and may need to be renovated to incorporate ecological processes. Important ecological principles and processes need to 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. Central questions include how soon and to what magnitude do ecological processes occur, and what other confounding effects can be expected.

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CHAPTER IV

IDENTIFICATION OF IMPORTANT ECOLOGICAL PROCESSES FOR LONG-TERM PERFORMANCE EVALUATION OF LANDFILL COVERS

Background

The application of engineered covers over contaminated soil and landfills used for disposal of radioactive, hazardous chemical, and municipal solid waste (contamination isolation and containment) is an approach that is often taken to minimize human and ecological risks. However, while the hazards and potential risks associated with the waste frequently persist well beyond 100 years, 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 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 methodologies that include those processes that will affect performance are needed to evaluate long-term performance of covers with quantification of risk and uncertainty.

In this paper, we present lessons learned from experience gained through numerical modeling, monitoring existing covers and designing alternative covers that accommodate ecological change. Our goal is the identification of the important ecological processes that could affect cover performance adversely. This investigation into the role of ecological monitoring of contaminant isolation systems also addresses ways to identify parameters and processes for performance confirmation and monitoring. While there are a myriad of potential ecological influences, our focus is on large scale, first order processes that predominantly govern most ecological interactions.

Regulatory Concerns

There are three main areas of regulatory concern regarding landfilled waste, and the same broad concerns apply to working, closed,or abandoned sites. These are most evident in the case of abandoned landfills. The main environmental hazard is the threat to groundwater. Precipitation either as rain or snow can infiltrate the surface of a waste mass, percolate through the mass, and pick up dissolved or suspended contaminants, and carry those contaminants to groundwater. This contaminated groundwater, or leachate, can travel to drinking water wells or emerge as surface water, sometimes carrying the pollutants for long distances.

The second regulatory concern is the generation of gases through biological activity in a landfill. Organic waste such as food, yard waste, and paper can be consumed by microbes in the presence of water and in the absence of oxygen to produce methane and carbon dioxide, two primary greenhouse gases. Methane from landfills has also been known to cause explosions and fires when unintentionally concentrated and accidentally ignited.

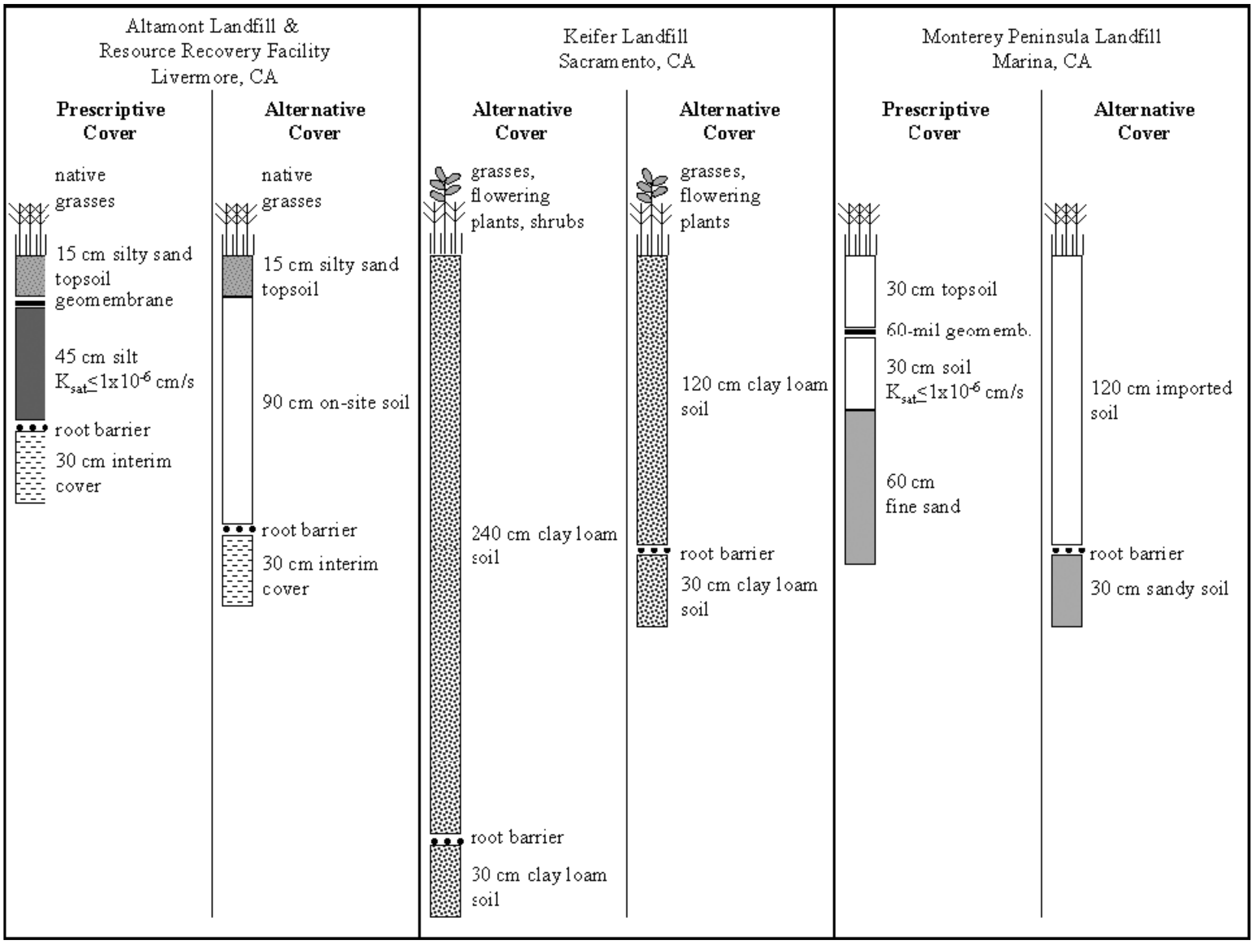
The third regulatory concern is physical contact with the waste, either through direct exposure to humans, by means of rodents and other disease vectors, or through litter scattered by wind. As the US Environmental Protection Agency (EPA) is charged with protecting human health and the environment, regulatory strategies have been to prevent or mitigate these three concerns.

Alternative Cover Paradigm

In contrast to a conventional cover, The ET cover system does not aim for total exclusion of water from the site, in contrast to a conventional cover. The system, which is sometimes called a 'sponge and pump' in contrast to the conventional cover 'raincoat' cover, allows a certain amount of water to be stored in the soil-root layer or rhizosphere, where it is held until the plants can use and transpire it. The water balance for an ET cover is somewhat more complicated than that of the conventional cover: the input of water equals the interception by plants, plus run-off, plus storage followed by evapotranspiration. Evapotranspiration is the combination of evaporation that would occur in a particular spot in the absence of plants, and the transpiration that occurs as plants process water for nutrient transport, cooling, and structure.

The rate of ET depends on plants species and placement, as well as the climatological characteristics of temperature, wind speed, humidity, and growing season. Evapotranspiration can be estimated using the Pennman-Monteith equations [13]. Because ET covers will work differently in different areas, all installations need site specific designs. The best candidate sites are those where the evapotranspiration from the native climax vegetation exceeds precipitation. Generally speaking, those parts of the country region that receive between 10 and 20 inches of precipitation each year are considered semi-arid with a native climax ecosystem of prairie grassland. Areas with more than 20 inches per year are classified as humid, with a native climax of woodlands or forest. Less than 10 inches per year is possibly too arid to sustain vegetative cover, although evaporation in very arid areas tends to exceed precipitation by far.

In an effort to gather data for eventual guidance on alternative covers, in 1997, the US EPA Office of Research and Development (ORD) in conjunction with the Remediation Technology Development Forum (RTDF) launched the Alternative Cover Assessment Program (ACAP). Phase One of this multi-year study involved a survey of existing field testing systems sites in conjunction with an analytical and a comparison and analysis of existing computer models for predicting and evaluating the performance of various landfill cover systems. This survey discovered that despite 28 projects that measured alternative cover performance, none of the results were nationally applicable, and few had any direct comparison to conventional covers. Similarly, while there were many computer models that have been used for alternative covers, none were consistently accurate for the unique situation of the ET cover [(7)]. Each site involved in the ACAP has a site specific design, usually paired with an site appropriate conventional cover for the site. Since the climatic range of the different test sites is broad, there is an equally great variety in ET cover configurations. Figure 1 shows some cover designs that ACAP is currently evaluating.


Altamont Landfill &
Resource Recovery Facility
Livermore, CA
Prescriptive Cover
native grasses
15 cm silty sand topsoil
geomembrane
45 cm silt $K_{sat} \leq 1x10^{-6}$ cm/s
root barrier
30 cm interim cover
Alternative Cover
native grasses
15 cm silty sand topsoil
90 cm on-site soil
root barrier
30 cm interim cover
Keifer Landfill
Sacramento, CA
Alternative Cover
grasses, flowering plants, shrubs
240 cm clay loam soil
root barrier
30 cm clay loam soil
Alternative Cover
grasses, flowering plants
120 cm clay loam soil
root barrier
30 cm clay loam soil
Monterey Peninsula Landfill
Marina, CA
Prescriptive Cover
30 cm topsoil
60-mil geomemb.
30 cm soil $K_{sat} \leq 1x10^{-6}$ cm/s
60 cm fine sand
Alternative Cover
120 cm imported soil
root barrier
30 cm sandy soil

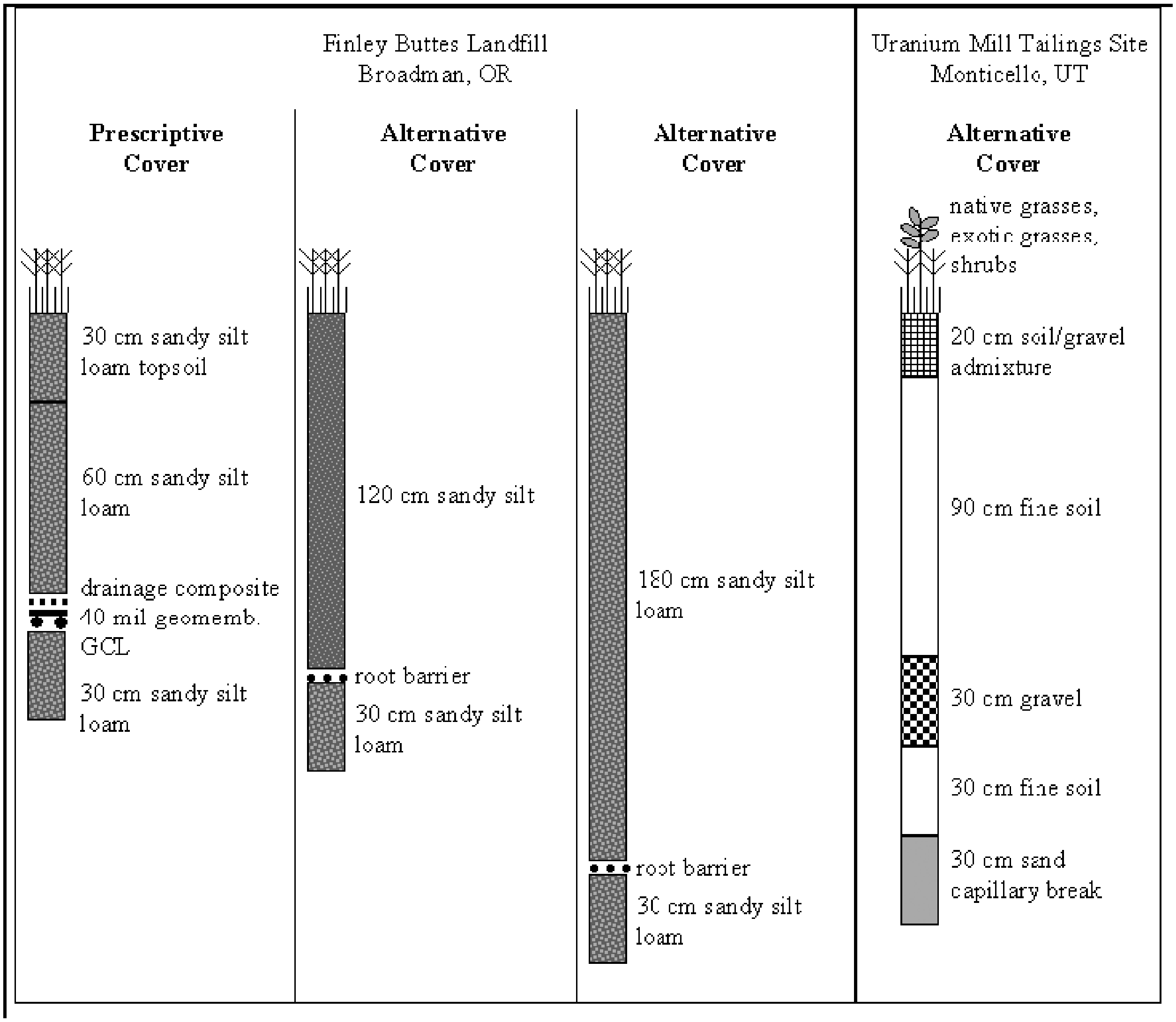


Figure 1. Example ET cover profiles from ACAP program [5].

Cover Performance, Natural Analogues and Conceptual Models

Use of Models for Cover 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[13-14]. However, such models can never be validated due to the limited observation of system dynamics[15]. They can, however, be used to investigate deficiencies in the relationships they define between ecological theory, model structure, and assessment data.

Two principal types of water transport modeling software exist: those that solve the Richards' equation and those that solve the water balance[7]. Water balance models, or storage-routing models, calculate the water retention curve parameters based on user input. Generally, the required input points are field capacity, wilting point, and saturated water content, and the calculated values are drainable porosity (saturated water content minus field capacity) and water-holding capacity (field capacity minus wilting point) [6]. Water transport software have been included in various studies comparing the appropriateness of water transport models [13-14] and include the following:

EPIC

The EPIC (Erosion-Productivity Impact Calculator) modeling software was developed in the early 1980s as an agricultural tool and solves for water retention by the water balance. It contains extensive plant and other agricultural considerations and accepts precipitation input. Albright et al (Albright et al. 2002) found that the EPIC software under-predicted drainage, and that the HELP was superior to EPIC for landfill cover simulations.

HELP

The Hydrologic Evaluation of Landfill Performance, or HELP, was developed by the U.S. Army Engineers Waterways Experiment Station. The HELP model solves the water balance by the storage routing method. Input information required by HELP includes daily weather information, and HELP considers plant growth and water uptake. HELP is the only model specifically designed for landfill cover evaluation, but it is limited by its solving method. Model comparisons generally find that HELP, as a water balance model, is not as accurate as models based on Richards' equation [9]. Albright found that HELP, like EPIC, under predicted drainage from the landfill cap.

TOUGH-2

Transport Of Unsaturated Groundwater and Heat, or TOUGH-2, is a finite-difference model solving Richards' equation for multi-dimensional transport. TOUGH-2 was designed for use in nuclear waste isolation studies and variably saturated water transport [10]. TOUGH-2 does not have any plant growth considerations, although it allows ET input data. TOUGH-2 was used in the evaluation of Yucca Mountain and has been used in alternative landfill cover evaluations.

MACRO

MACRO is based on Richards' equation and includes an additional term to account for preferential flow though macro pore and micro pore water movement. MACRO may be used to model saturated or unsaturated media. MACRO can account for plant water uptake and calculates solute transport as well as water transport. Johnson compared MACRO with HYDRUS, and found that preferential flow was significant and should be included in a model.

UNSAT-H

UNSAT-H, developed at Pacific Northwest Laboratory (PNL), solves Richards' equation for one-dimensional flow in unsaturated media by the finite difference method (2005). UNSATH accounts for plant transpiration, and allows user input about the soil media properties. A study by Khire[11] found that UNSAT-H was more accurate than the water balance solver HELP. Albright et al found that UNSAT-H under-predicted drainage, but that the model was physically realistic. UNSAT-H is comparable to HYDRUS, and so if a two-dimensional model is required, Albright et al suggest HYDRUS-2D.

HYDRUS-1D

HYDRUS-1D is a finite element solution to Richards' equation for one-dimensional flow in variably saturated media. The HYDRUS-1D software includes plant growth and plant root water uptake options. In addition to the modeling of water flux, HYDRUS can simulate contaminant transport through the media and contaminant root uptake. A soil catalogue is contained within the software, but user input data of soil hydraulic properties is also allowed[12].

HYDRUS-2D

HYDRUS-2D includes all the function of HYDRUS-1D and includes the modeling software SWMS_2D for two-dimensional water movement. The two-dimensional solution is useful when lateral flow modeling is required. Albright 2002 found that the predictions of HYDRUS-2D were physically realistic, but that drainage was under-predicted.

LEACHM

The Leaching Estimation And Chemistry Model, LEACHM, is a one-dimensional transport model solving Richards' equation with a finite difference approach (2005). The code was created for use in agricultural applications and solves only for unsaturated media. Although it was developed for agricultural use, it is limited by its lack of plant considerations and does not account for water runoff. LEACHM does account for chemical transport in addition to water flow. A 2002 survey of users did not find any use of LEACHM in landfill cover modeling.

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[(16)]:

- 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).

Identification of Important Ecological Processes

Large Scale Processes Affecting Performance

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, evapotranspiration, vegetation and climatic factors (10). These processes are comprised of highly coupled parameters that must be characterized in order to develop an appropriate screening tool (19). 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. For the purposes of organizing this paper, each process will be described separately; however, the interconnect nature of climatic factors, soil water storage, evapotranspiration, and the vegetative community makes it impossible to describe one without the other.

Climatic factors

Climate is one factor that cannot be controlled or engineered by the designers of alternative landfill covers. The most important factors influencing evapotranspiration are precipitation and the atmospheric parameters (i.e., dew point, atmospheric pressure) [(20)]. Other factors (i.e., temperature, humidity, etc) influence the rate of transpiration, but the amount and timing of precipitation, such as period of heavy rain, is most important to proper design of an ET cover. 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. 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.

The striking effect of climatic variability can easily be seen in a quick comparison between an arid and humid site. Studies that have examined water variability in humid environments have found that more frequent watering increased plant growth or survival [21]. In contrast, studies and simulations related to arid environments show that longer intervals between water pulses can have positive effects when rain pattern and the water holding capacity of the soil interact to produce a longer-lasting soil water reservoir [22].

Of particular interest to ET covers is the relative timing of precipitation and transpiration. Both average and extreme event precipitation data is to performance assessment [23]. 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 (non-transpiring) season while the other experiences predominately summer precipitation. The effect of rainfall on plant communities varies along a gradient of mean annual precipitation (MAP) and daily mean rain (DMR) [24]. Rainfall drives soil moisture storage which must be explicitly considered on a site-specific basis. Increasing MAP generally increases water availability, establishment, and peak shoot biomass. Increasing DMR increases the time that water is continuously available to plants in the upper 15 to 30 cm of the soil (longest wet period, LWP)[25]. The effect of DMR diminishes with increasing humidity of the climate. An interaction between water availability and density-dependent germination increases the establishment of seedlings arid regions, but in more humid regions the establishment of seedlings decreases with increasing DMR [26]. As plants mature, competition among individuals and their productivity increases, but the size of these effects decrease with the humidity of the regions. Therefore, peak shoot biomass generally increases with increasing DMR but the effect size diminishes from the semiarid to more humid environments.

Soil water storage

Design of an ET cover in any climate depends on the water holding capacity of the soil. Water must be stored in that layer of soil that is in the range of the influence of the plants, either in direct contact with the roots or within range of the capillary suction that plants can exert. Plant root influence also depends on the soil characteristics. For example, a sandy soil will allow easier penetration by roots, while a more silty soil will hold more water but restrict root penetration.

Climate determines the types of plants available, while soil type determines the water holding capacity and hence, the depth of the soil cap needed to store the water. Therefore, the depth of the soil layer influences the type of plants chosen by dictating the necessary root architecture. 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). 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(27). 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 [28], 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 [29]. Therefore, soil edaphic properties will interact with plants differently in arid versus humid environments.

Evapotranspiration

Evapotranspiration is arguably the best indicator of ET cover performance and is driven by climatic influences, health and composition of the vegetation, and soil properties. 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, performance will be heavily influence by the cover plant community. Several variables must be considered when designing a cover vegetative community:

- the plants must be capable of rooting through the entire depth of the soil column that makes up the cover;
- the plants should be capable of transpiring throughout the growing (warm) season;
- native species may be best suited to the environmental factors at the site; and
- plant community should exhibit 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 [30]. 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. In cold climates where transpiration is essentially nonexistent for several months each year, the soil holding capacity will almost entirely determine performance of the cover. 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.

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.[31] A mix of plant species may be appropriate to maximize the number of days of effective evapotranspiration, as well as the total amount of transpiration by plants.

In arid and semi-arid prairie grasslands, there can be a tremendous variety of plants present. Some thrive during the cool and wet spring months but then yield to hot weather species during the summer. Some spread quickly into disturbed areas while others wait for the shade provided by the early species. Some have wide shallow root systems and some extend long roots that give them the capacity to withstand droughts. These plant characteristics help determine which species or combination of species will do the job of tapping into and using the water that will be stored in the cover system. Prairie species, like most plants, have most of their roots in the top three feet of soil, although some grasses send roots 30 feet or deeper. In semi-arid areas, most ET covers are designed with a three to four foot water holding layer, and that is vegetated with a variety of plant species. In wetter climates, a thicker soil layer is needed to capture the greater precipitation. Since trees have a greater root structure than grasses to support their larger biomass, designers of ET covers can use more depth for water holding. It is possible to design a water storage layer of up to eight feet thick that may be within the root zone of some trees.

A variety of plant species should comprise a vegetative community, 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, is established [32]. ET is effective soon after plants initiate growth and development, but the rate of ET will change as a more mature plant community establishes. A mature plant community can take 3–5 years or more to develop.

The most common trees proposed for use on ET covers are hybrid poplars or hybrid willows [17]. These trees are members of the Salicaceae family. They are hydrophilic and phreatophyitic which means that they tend to thrive in water rich areas, are undamaged by overwatering or inundation, and they withstand drought with a deep and extensive root architecture. Despite popular misconceptions, tree roots do not seek water, nor do they have a way of sensing water behind barriers. Trees can and will follow water such that when a slug of precipitation is descending through a soil column, roots will follow and extend as deep as necessary to obtain sufficient moisture. Some groundwater fluctuates annually or seasonally. Therefore, a rising water table may inundate tree roots. Many tree species will shed or slough off roots that are under water and deprived of oxygen. Furthermore, some non-Salicaceae trees may even be killed under these circumstances [20]. Phyreatophytes maintain their roots even when saturated and are still in place when the water table descends. Therefore, they are immediately ready to draw water from the deeper seasonal water level. No trees, not even phyreatophytes, will extend their root systems farther than necessary to obtain water. Similarly, trees will not penetrate into a saturated zone if their water needs can be met in the vadose zone.

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 [33]. 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.

A common way to monitor vegetation is through percent ground cover. Ground cover can be composed of live plant material, mosses, lichen, standing dead plant material, litter, rock, and even miscellaneous debris [34]. Total percentage of ground cover summed with percentage of bare ground should equal 100%.

A growing plant community consists of different components: stem, leaves, roots, and rhizomes or seeds. Individuals plants extract the resources needed for further growth and regeneration according to the area of light-exposed leaves and the soil volume penetrated by its roots. Annual plants invest all carbon available at seeding time, in seeds, while perennials invest only one-third of their available carbon in seeds. Perennials are able to reproduce vegetatively through underground stems. Daughter individuals are formed at a distance preventing shading between mother and daughter individuals. Plant growth is limited by a maximum growth rate or by lack of assimilate which is consumed by respiration. The resources available to an individual plant depend on the area of light-exposed leaves and the volume and nutrient status of the soil penetrated by the roots [(35)].

Scale of Processes

The drivers of ET cover performance (e.g. the vegetative community) are linked to several scales of ecological processes [(36)]. It is necessary to identify the different scales of important ecological processes to predict the key processes that will ultimately determine cover performance. An example of the variability of scales can be shown in the temporal and spatial variability of rainfall. Patterns of wet and dry periods that occur at longer temporal scales interact with finer scale "pulse" dynamics to influence water availability to plants [(37)]. For instance, frequent small pulses may have different effects on water availability than one large pulse, depending upon time scale these pulses occur (e.g., during a decadal drought or during a wet period).

Semi-arid and arid areas exhibit great temporal variability both in water availability and vegetation dynamics. In some of these regions, rainfall is delivered in discrete pulses followed by intervening dry periods of variable length. Although many systems are characterized by wet and dry periods, the distinction is that these pulse periods differ so dramatically in soil moisture that the biotic and abiotic function of the cover associated with these periods also differs substantially, especially during the summer growing season [37]. Fine-scale pulses of precipitation interact with longer scale variation in climate and weather to generate temporal variation in plant community composition [38]. This is especially true in arid regions. Figure 2 illustrates the different scales of temporal variation in water availability and the interactions between precipitation and vegetation that collectively drive the performance of an ET cover.

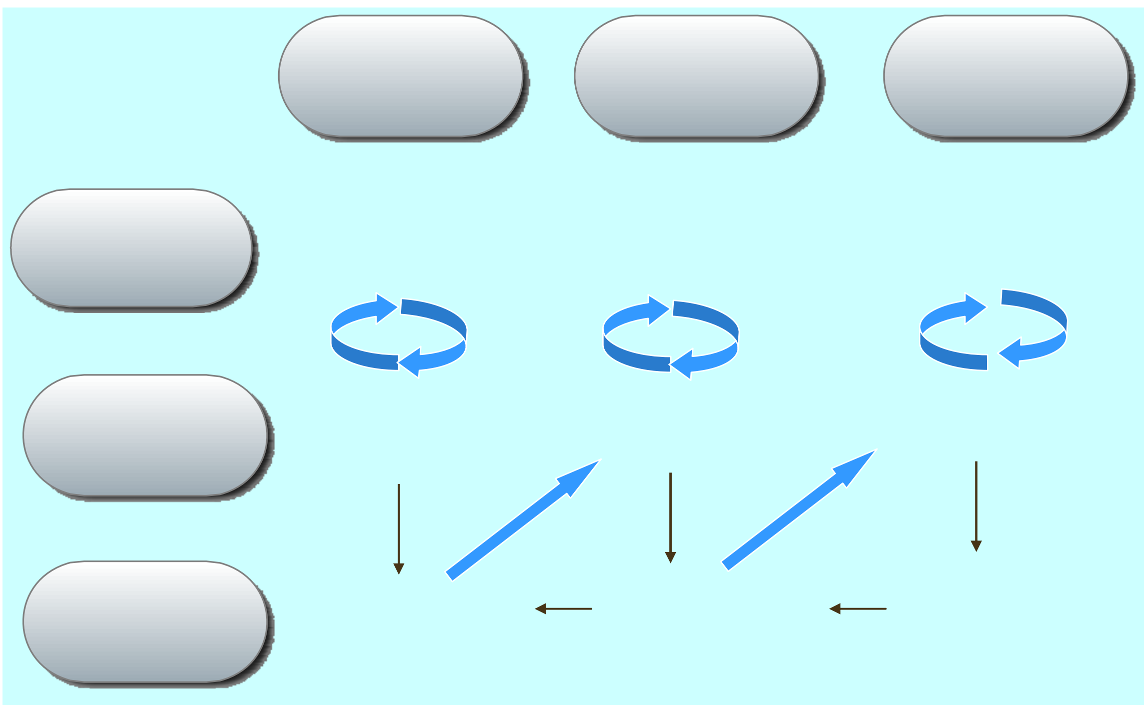


Figure 2. Conceptual diagram illustrating different scales of temporal variation in water availability and the interactions between precipitation, vegetation, and the physical characteristics of the site that collectively drive the performance of an ET cover.

Centuries

It is clear that in order to understand performance drivers, it is important to account for the variability in a range in scales of ecological processes.

Climatic
Characteristics

Magnitude
and timing

CONCLUSIONS

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. The design of alternative cover systems must also take into account the seasonal nature of planted systems. 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 explicating the major processes that need to be considered when designing a cover and subsequent monitoring program, and the extent to which the natural range of variability of these processes can change predicted degradation rates of the cover.

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CHAPTER V

AN APPLICATION OF EVENT TREE ANALYSIS TO ECOLOGICAL SYSTEMS: UNDERSTANDING THE LONG TERM PERFORMANCE OF ENGINEERED COVERS

BACKGROUND

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. Although the hazards and potential risks associated with radioactive waste frequently persist well beyond 100 years, cover design and performance evaluation guidelines frequently fail to consider consequences of inevitable changes in ecological processes. Due to past failures associated with conventional resistive covers, alternative cover designs are being developed that are designed to work with natural processes as opposed to thwarting them. An evapotranspiration (ET) cover is a specific type of alternative cover that will be examined in this paper. A rigorous methodology 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. Ecological risk assessment is a common environmental management tool that is routinely used to understand risks to an ecological system. Developing realistic conceptual models and identifying hazards correctly is critical to any risk assessment. In many ecological examples, however, this stage of the analysis is poorly developed. This paper applies a risk-analysis tool that is commonly used in complex engineering systems – fault-tree analysis – to an ecological system, evapotranspiration (ET) covers. These fault-tree analyses highlight the complexity of the ecological processes acting on ET covers over long time periods. The top event in the fault-tree is an ecological "trigger". The fault-tree identifies the parallel and sequential possible events leading down to a range of possible scenarios, determined by the origin conditions and possible effects of the ecological trigger. In the past, fault-trees have had a limited application to ecological systems because of the difficulty of estimating the probability of the basic or undeveloped events in the tree. As this paper demonstrates, however, fault-tree analysis can have considerable heuristic potential when applied to ecological systems.

Introduction

It is clear that in order to understand performance drivers, it is important to account for the variability in a range in scales of ecological processes. In the following, cover "failure" is meant to indicate a departure from the expected performance of the cover system due to a departure from design requirements irrespective of the consequences of the departure. Potential failures of engineered covers that accommodate ecological processes require site managers and regulators to consider the following performance questions:

- How does the cover system failure occur?
- What aspect or aspects of the cover actually fail?
- Are there precursors to failure?
- Is cover failure imminent? If so, is it detectible?
- What are the consequences resulting from failure of cover components (i.e., plant community)?
- Is the loss of one control key to cover failure or is there an accumulation of minor failures that form a critical mass?

Ecological Risk Assessment

Ecological risk assessment is becoming an increasingly popular management tool for environmental problems. It is commonly used to assess chemical stressors with an eco-toxicological emphasis. This perspective does not, however, reflect the much wider application of risk-assessment techniques. Biological stressors, such as introduced species or genetically modified organisms, are not governed by the same decay and dispersion rules that typically characterize chemical stressors (see e.g. Schobben and Scholten 1993). Ecological risk assessments for biological stressors are consequently much more difficult to conduct than their chemical counterparts. Good hazard identification is a critical component in this process – hazards that are not identified in the early stages of a risk assessment are not carried through the assessment, and may seriously undermine its efficacy.

Fault Tree Analysis

Fault-tree analysis (FTA) was conceived in 1961 by the Bell Telephone Laboratories to study the launch control systems of the Minuteman missiles (Haimes 1998). It was quickly adopted by the nuclear power industry for analyzing the safety and reliability of nuclear reactors, and the petro-chemical industry for analyzing events that lead to hazards in complex engineering systems (Hope et al. 1982; Kletz 1986). Fault trees are routinely used by the USNRC for reliability engineering (Vesely et al., 1981; Gertman and Blackman, 1994). Recently, master logic diagrams have been used to evaluate active chemical storage plants (Papazoglou and Aneziris, 2003).

Fault-trees are a “top-down” hazard-analysis tool in which the analyst specifies a failure event (the ‘top-event’) and then, using two logical functions OR and AND, identifies all of the events that cause the specified failure. The causative events are laid out in a tree with the branches connected by ‘gates’ comprising either of these logical functions. A fault-tree is, therefore, a graphical model of all the parallel and sequential combinations of events that lead to the top event. The OR gate represents the union of events attached to the gate. An OR gate can have any number of inputs (branches) running into it. The event above the gate is realized if any one or more of the inputs occur. The AND gate represents the intersection of events attached to the gate. An AND gate can also have any number of inputs running into it, but the event above the gate is only realized if all the inputs occur.

In industrial systems, the faults are likely to be associated with such events as hardware failure or human error, however, the fault-tree should only include events that are necessary and sufficient to cause the top event. External events that may influence the probability of failure, but which are not indispensable logical links in the failure mechanism, are not typically included (Pate-Cornell, 1984); earthquakes, floods and lightning strikes, for example, are normally excluded.

The FTA process is initiated by first defining an undesired state of the system. An analysis of the details of the system is then performed to determine logical ways in which the undesired event could occur (Vesely et al., 1981). In this manner, FTA is a useful tool in clarifying how undesired events can occur and, likewise, how mitigation efforts can reduce system failure. Fault trees are cause-and-effect diagrams useful for evaluating the root causes of failure modes. These trees provide a graphical means of displaying qualitative information known about ET covers, including site-specific information.

Developing Event Tree Analyses (ETA) for Ecological Processes

Event trees are fault trees without the assignment of probabilities to the events. As described in chapters II-IV, there exists a range of ecological influences on cover performance that isolate residual contaminants. 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.

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 and likely hazards in an appendix of event trees most relevant to that area.

Barnthouse et al. (1986) note that there is an appealing analogy between complex engineering systems and complex ecological systems, and therefore suggest that ecological fault-trees can serve important heuristic functions. To date, this appears to be one of the only published examples of fault-tree analysis applied to ecological systems. Its heuristic potential with respect to ET covers is clear. Simple conceptual diagrams of the important processes influencing an ET cover (Figure 1) belie the true complexity of this system. By contrast, the fault-tree analysis highlights the roles of vegetation succession, soil development processes, meteorological influences, and episodic events in multiple performance scenarios. Furthermore, event trees provide a broad range of alternative conceptual models that are useful for variable site-specific conditions. It has also identified a number of avenues of research as more ET covers are established and cover designs evolve.

Event tree analysis is versatile and systematic. It forces the analyst to carefully examine the system, focus on the events that relate to the top event and describe (using logical functions) the event sequences that lead to this event. The logical structure of the event series is one of the principal advantages of fault tree analysis over conventional risk identification techniques (such as simple brainstorming), because:

1. It helps emphasize that cover performance risks are a function of the properties of the cover and the site-specific conditions
2. It captures the necessary and sufficient conditions necessary for a range of possible scenarios, and
3. Provides a qualitatively coherent conceptual model of the system that forms an excellent basis for a quantitative model.

Failure modes and effects analysis

Failure modes and effects analysis (FMEA) was developed in the mid-1960s by the aerospace industry to improve safety (McDermott 1996). It is now widely practiced in the petro-chemical industry (Hope et al. 1982). FMEA examines the components and operating modes of a system. It identifies the failure modes of each component and the effects of failure on other components and the overall functioning of the system (Ozog and Bendixen 1987). FMEA is a 'bottom-up' hazard-analysis tool – it starts with the individual components and assesses the consequences of their failure. In industrial systems, FMEA is formalized in a six-step procedure (Figure 1): Identify and list all components; identify all failure modes, considering all possible operating modes; list the potential effects of each failure mode and score their severity; list the potential causes of each failure mode and score their likelihood; list the current controls to prevent the failure mode and score the likelihood of detection; and, calculate the risk priority number (RPN). The severity, likelihood and detection ratings are usually scored from 1 (lowest rating) to 10 (highest). The RPN is the product of the scores assigned to these three ratings, thereby ranking the failure modes from highest priority to lowest.

It is important to note that the in industrial systems, the RPN is typically assigned by an experienced systems manager. The case study in this paper utilizes historical data as opposed to someone's knowledge of the cover system. However, it is reasonable to assume that future application of these methods can be completed by site managers or operators. This is addressed further in the final section of this paper in "future work".

Infection modes and effects analysis

FMEA forms the basis of the hazard analysis that has potential for assessing cover performance. Its close resemblance is reflected in its name: infection modes and effects analysis (IMEA). The main difference is that the analyst is seeking to identify ecological hazards, i.e. how ecological processes 'infect' or negatively influence cover performance, and likewise, how episodic events ‘infect’ ecological components of the cover. The procedure is formalized in the following steps:

1. Identify and list all the ecological components and subcomponents of the cover that could be ‘infected’.
2. Identify all ‘infection modes’, i.e. how vegetation death occurs.
3. Describe the environmental conditions associated with the components and score their suitability for site-specific conditions.
4. List the causes of each infection mode and score their likelihood.
5. List the current controls to prevent the infection mode and score the likelihood of detection.

This approach allows the IMEA to highlight differences in the way certain ecological components of a cover may fail under a range of conditions. The importance of each sub-component of the cover can therefore vary depending on region, the development stage of the component (i.e., early or late stage vegetative community), and stresses to the component. The IMEA accordingly allows scaling of each sub-component (1-10 most typical) to reflect this type of uncertainty.

Information gathered from ETA and IMEA can be used to inform numerical performance assessment models. Management activities should, in the first instance, be directed to the high priority subcomponents, and where practicable, the medium level sub-components. Palady (1995) suggests the following hazard management strategy:

1. eliminate the occurrence;

2. reduce the severity;

3. improve the detection.

In the IMEA context, eliminating the occurrence is equivalent to eliminating the occurrence of cover performance failure events. For all practical purposes, however, this is not possible. Reducing the severity is equivalent to ensuring that the ecological sub-components of a cover are kept healthy and sustainable. For example, making sure newly planted vegetation is well suited to the site specific conditions of the area. The results of the IMEA indicate where on a cover failure is most likely to occur based on local knowledge of site specific conditions. Finally, detection of cover failures can be improved by informing site operators on the areas in which they operate.

ETA and IMEA have rarely, if ever, been applied outside of its original (industrial) context yet share many advantages of their industrial counterpart:

- it has the potential to identify all the potential hazards associated with engineered cover performance – in this instance, the ecological sub-components of the cover that are most likely to fail;
- it quickly prioritizes the hazards – the ecological subcomponents and their ‘infection’ modes can be ranked into high, medium and low priority based on historical data or knowledge of site specific conditions by someone who has extensive experience in the area;
- the process is rigorous, systematic and transparent.

For ETA and IMEA to be useful, they must be informed by either direct historical monitoring data, or in the cases of a new site, by site managers who are familiar with local conditions and can reasonably assign numerical rankings to potential hazards. To be successful, ecological risk assessment must be systematic and rigorous. This is particularly important during the early hazard identification stage of the assessment – hazards that are not identified in the early stages of the analysis are not carried through to the risk assessment leading ultimately to underestimates of ecological risks in the total cover performance.

Cover Components and Failure Modes

FTA is first used to compare the performance risks of conventional and ET cover. Figure 1 summarizes key cover components and failure modes for a generic ET cover, and provides and example of a performance process that could ultimately lead to percolation into the waste. Note that some designs will not necessarily include all of these components (e.g., geomembranes).

ET Cover Component	**ET Component Failure Mode**	**Examples**
Vegetation	Death of vegetation	Fire kills vegetation
Compacted soil layer (CSL)	Integrity compromised	Development of preferential pathways
Soil fertility	Non-supportive of vegetation	New soil lacks necessary microbial associations, pH, nutrients
Geomembrane	Integrity compromised	Root penetration
Seed bank	Non-supportive of revegetation	Lack of seed bank in initial month after cover construction

Figure 1. Summary table of key ET cover components, performance processes that influence each component, and an example of each process.

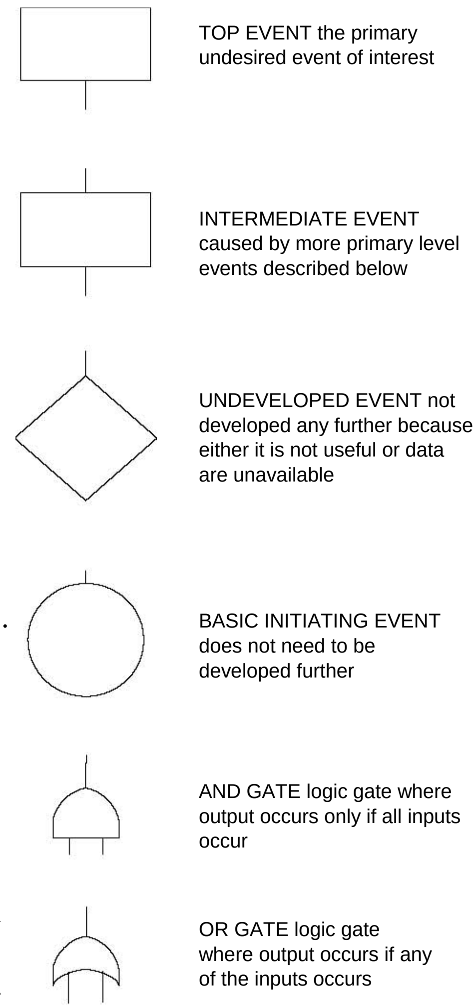
Figure 2 summarizes key cover components and failure modes for a generic conventional cover, and provides and example of a performance process that could ultimately lead to percolation into the waste.

Cover Component	**Component Failure Mode**	**Examples**
Compacted soil layer (CSL)	Integrity compromised	Development of preferential pathways
Geomembrane	Integrity compromised	Root penetration
Liner	Integrity compromised	Incorrect installation

Figure 2. Summary table of key conventional engineered cover components, performance processes that influence each component, and an example of each process. The liner is typically not considered a cover component; however, it will ultimately influence the transport of hazardous waste out of the site, so it will be included for the purposes of this research.

FTA Symbology

This FTA in this paper uses a simplified set of standard symbols to represent fault events and logic gates as shown in Figure **BLANK**. Functional descriptions of what occurred or did not occur are described in each symbol. The top event, represented by an rectangle, describes the system fault. This is the undesired state of the system. Basic faults are intermediate events representing observable problems. These basic fault events are also illustrated as rectangles. Circles are used to represent initiating events. Initiating events represent the lowest point of examination for this research and require no further development. Diamonds represent undeveloped events either because of complex interdependencies or because of inadequate information. A triangle is a transfer symbol, which indicates that this branch of the tree is further developed in another portion of the tree.



Two types of logic gates are used to connect events as input and output. The And-Gate is used to represent the situation in which the output event occurs only when all of the input events occur. The Or-Gate represents the situation in which the output occurs if at least one of the inputs occurs. In terms of strengthening controls and thus reducing the likelihood of failure, the And-Gate is viewed as the more robust condition because multiple input events are required for the output to occur. Conversely, the conditions illustrated with an Or-Gate are less robust because these gates indicate that a single point failure could lead to the undesired output state.

Development of Conceptual Model for ET and Conventional Cover Performance Risks

Using the cover components and failure modes (i.e. ways in which the component performance can be compromised) and following the fault tree analysis technique, the ET and conventional cover performance risk conceptual models were formulated (Fig 3 and 4).

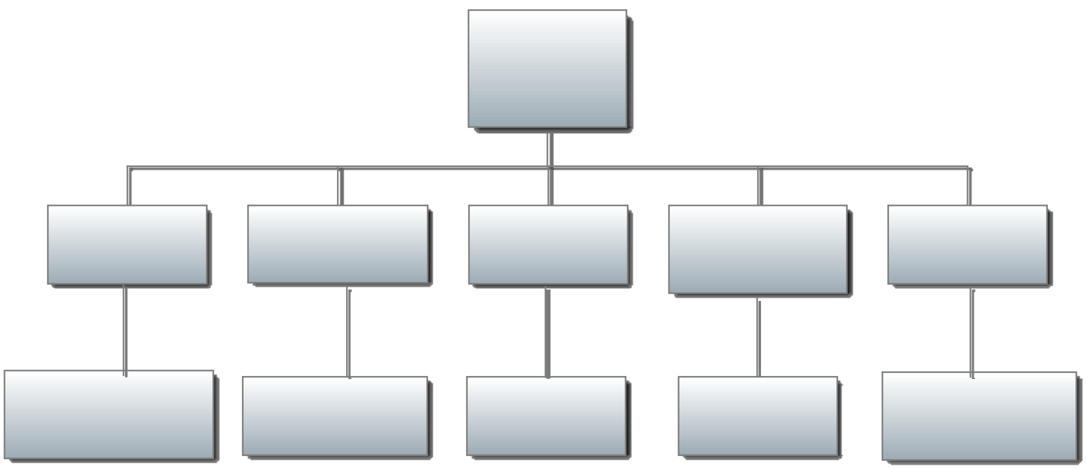


Figure 3. Generic event tree for ET cover X illustrating possible events and failure modes that could lead to the performance metric "percolation" due to events influencing five key cover components (3.1-7.1).

Cover X

Perc
into

3.1 4.1 5.1

Seed bank Geomembrane Veg

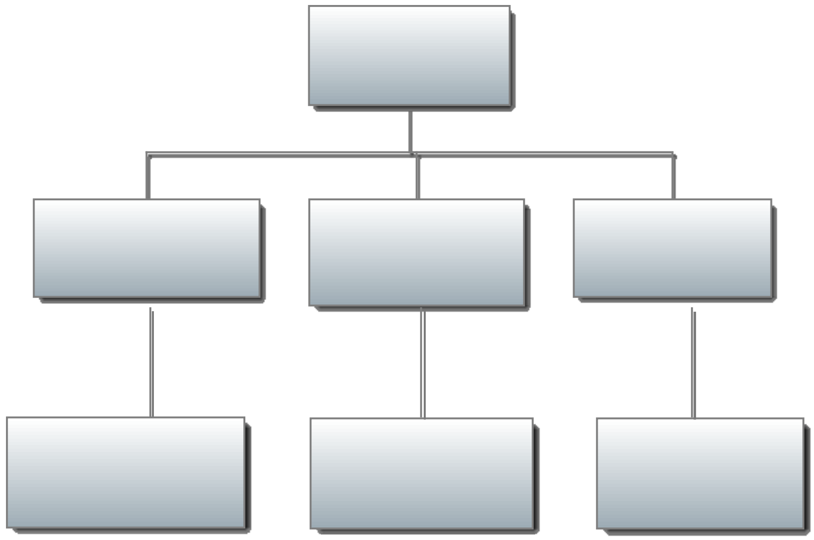


Figure 4. Generic event tree for conventional cover Y illustrating possible events and failure modes that could lead to the performance metric "percolation" due to events influencing three key cover components (8.1-10.1).

Five cover components (i.e. vegetation, compacted soil layer, soil fertility, geomembrane, and seed bank) and four failure modes were considered (i.e. death, physical integrity compromised, non-supportive of vegetation, and non-supportive of revegetation) for ET covers, and three components and one failure mode were considered for conventional covers.

The failure mode "death of vegetation" refers to the death of greater than fifty percent of the vegetative community resulting in a loss of transpiration capabilities. This failure mode may require the compounding effects of several events. "Integrity compromised" on the other hand, refers to the possible failure of two engineered components of the cover that only require one event (i.e., physical penetration) to fail. The failure modes, "non-supportive of vegetation" and “non-supportive of revegetation” refer to the failure of the soil to support productive vegetation establishment and growth.

The events that could lead to percolation of water into the waste were identified as possible pathways of the fault trees. These initial conceptual models serve as the primary models for all major possible fault trees that could lead to percolation into the waste. The events incorporated into the models were based on data collected from existing covers, personal observations, and conversations with experts.

Generic ET Cover Conceptual Models

The following more detailed conceptual models developed through ETA’s represent percolation into the waste due to a series of necessary and sufficient events to key ET cover components. The models consider the five cover components and four failure modes summarized in figure 1. All events in the figures have been numbered based on their citation in the text. This means that an event is referenced by the number of the figure and the number of the event in that figure. For example, “Percolation into the waste (3.1)” means that this is the event number 1 in Fig. 5. From Fig. 5, it is evident that in order for “Percolation into waste” (3.*1*), which is the top event of the analysis, all of the following events must occur: the vegetation must disappear and revegetation must be inhibited due to a lack of seed bank present in the soil.

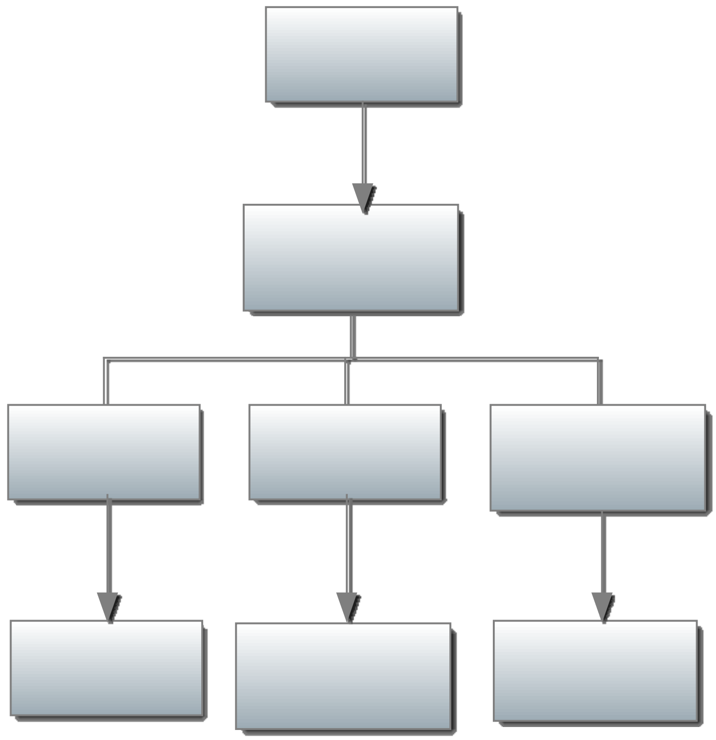


Figure 5. The necessary and sufficient events related to the seed bank in the cover soil that can lead to percolation into waste; time is represented horizontally from year 0 to year 4+.

As any of the five components of *Cover X* could fail, each component (i.e., 3.1-7.1) is analyzed as a potential contributor to percolation into the waste. Event trees for each of these components, and rationale for their inclusion, are detailed below. The models must be based on the environmental characteristics of the area, the length of time since construction of cover, and the engineered components of the cover. Furthermore, if it was assumed that one of more components of the cover fail, whether or not percolation into the waste occurs would depend on a number of factors affecting such timing of extreme events and the health of other cover components, and may involve a considerable element of. As noted earlier, the model in this paper is focused on the performance metric of percolation of water into the waste container.

Fault Trees for Failure of Cover Components

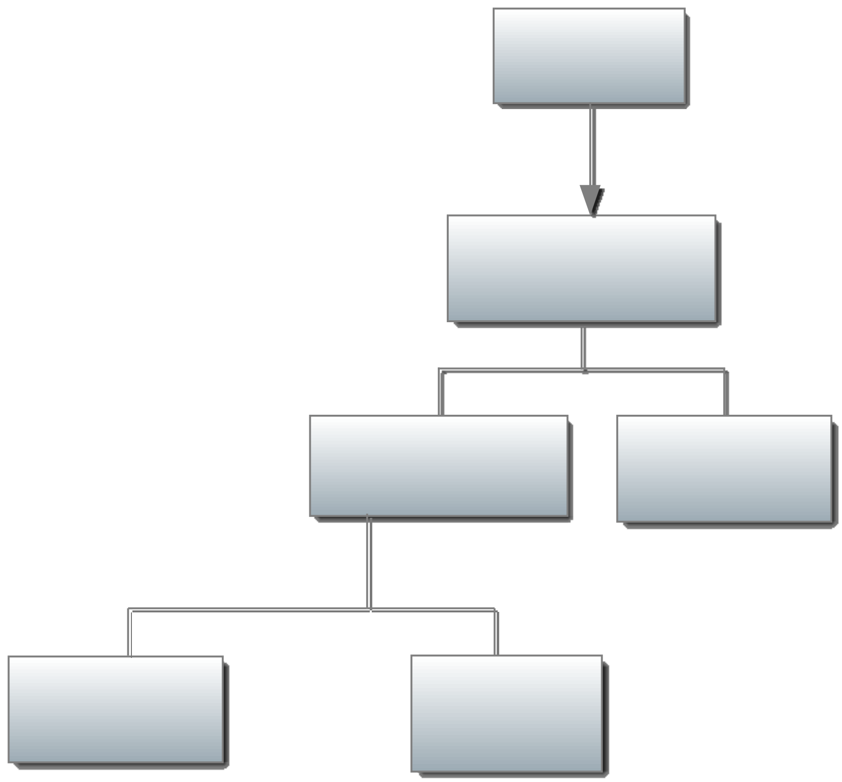


Figure 6. The necessary and sufficient events related to failure of the geomembrane that can lead to percolation into waste.

Event Tree Application to Case Studies

In order to demonstrate the applicability of this technique, specific sites are considered using the realized or potential failure of two existing covers: the Monticello ET cover located in Southeastern Utah, and Burrell, PA a conventional cover located in the humid east. These examples are used to demonstrate the utility of ETA in defining cover failure scenarios under very different site conditions and cover construction types.

ET Cover Site Description

The Monticello Mill Tailings Site is located in southeastern Utah, south of the town of Monticello (Fig 7).

Figure 7. Map of Monticello, Utah with location of Uranium Mill Tailings site.

The present climate at Monticello is “sub-humid,” with an average annual precipitation of ~38 cm (15 inches) and an average annual temperature of 7.8 ºC (46 ºF). In 1941, the Monticello mill was constructed and used to process nearly a billion kilograms of ore. By 1960, when operations were terminated, approximately 2 million cubic meters of radioactive uranium mill tailings had been left behind from the operations (DOE 2002). To contain the mill tailings, DOE began construction of a repository south of the original mill site in 1995, and in 1996 the construction of a composite double- liner system at the base of the repository was completed.

The cover was designed to mitigate the release of radon gas to the surface and to minimize water infiltration to the mill tailings. It consists of a thick topsoil layer with vegetation that can store precipitation and allow evaporation and transpiration via vegetation (Fig 8).

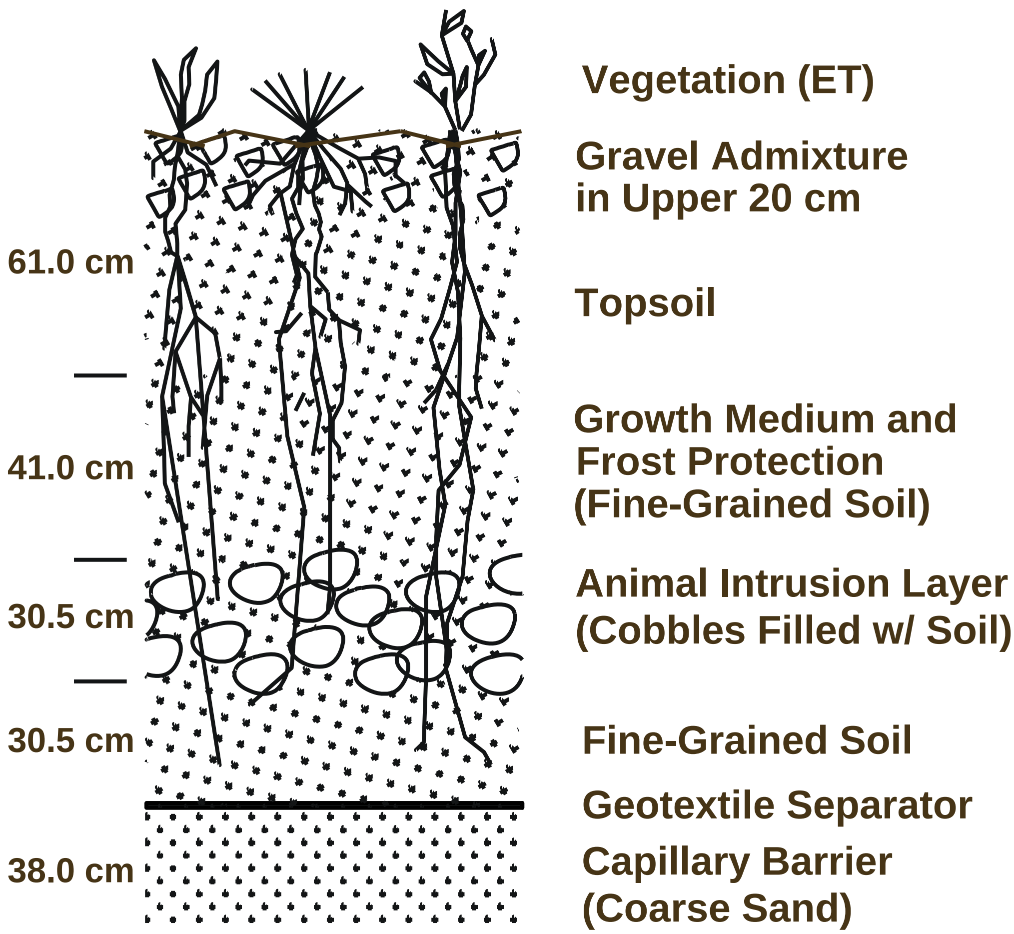


Figure 8. Cross-section view of Monticello ET cover located in Southeastern Utah.

This top layer overlies a coarse sand layer that acts as a capillary barrier and is intended to drain any infiltrating water laterally above a high-density polyethylene geomembrane. Beneath the geomembrane is a compacted clay layer that serves as a barrier to radon gas transport and water infiltration. The clay layer rests directly on top of the mill tailings. At the base of the repository beneath the mill tailings is a double composite-liner system composed of sand, two geomembrane liners, two geosynthetic clay-liners, and a transmissive leachate collection system. The entire repository is surrounded by Quaternary deposits consisting of sandy loam, clay, and pediment gravels (DOE 2002).

Beneath the repository, two aquifers exist--a perched alluvial aquifer, as close as several meters below the bottom of the repository and the regional Burro Canyon aquifer beneath the alluvial aquifer. The perched aquifer was contaminated by mill tailings prior to construction of the repository. The contaminants of concern include uranium, as well as its radioactive decay products (thorium-230, radium-226, radon-222), and heavy metals such as vanadium, lead-210, and arsenic. The Burro Canyon aquifer and has not been contaminated. Between the alluvial aquifer and the Burro Canyon aquifer are unsaturated layers of shale and sandstone. The water from the upper alluvial aquifer is used for irrigation purposes, but all drinking-water wells are located in the lower Burro Canyon aquifer.

Monticello site data has been collected since January 2000 and includes comprehensive data sets of the following information:

Meteorology (1999-2009, hourly and daily)
Precipitation (tipping buck)
Wind speed
Wind direction
Relative humidity
Solar radiation
Temperature (hourly, daily max/min)

Soil Hydrology (1999-2009, hourly and daily)
Percolation flux (lysimetry, dosing siphons)
Soil water content (water content reflectometers, gravimetric)
Soil water potential (heat dissipation units)
Runoff (lysimetry, dosing siphons)
Evapotransiration (mass balance)

Soil Hydraulic and Physical Properties
Hydraulic conductivity
Soil water characteristic curves
Soil bulk density
Soil particle size distribution (ASTM, USDA)

Soil Edaphic Properties (2007)
pH; Salinity
Sodicity
N, P, K; Organic Matter

Soil Morphology (2007)
Soil profile taxonomy
Soil structure and horizonation
Observed shrub root depths
Root density distribution

Vegetation
Revegetation
- Seed sources and variety
- Revegetation methods

Species Composition
Shrub Density
Nearest Neighbor Method
Point-Centered Quarter
Shrub Mortality
Seed Bank
Canopy Cover
Leaf Area Index
- LiCor LAI-2000
- Harvest and electronic planimeter

Ground Radiometric (2002 and 2008)
- Hand-held ASD spectroradiometer

Hyperspectral Imagery (HyVista)

Results for Monticello ET Cover

The top event in this instance is successful percolation of water into the waste. This event is considered the risk-assessment endpoint. Successful percolation, and therefore failure of ET cover performance, occurs if the following events take place:

- water storage capacity of the soil exceeds storage capacity, AND,
- all barriers beneath the soil layer fail to perform as intended (i.e., geomembrane and compacted soil layer).

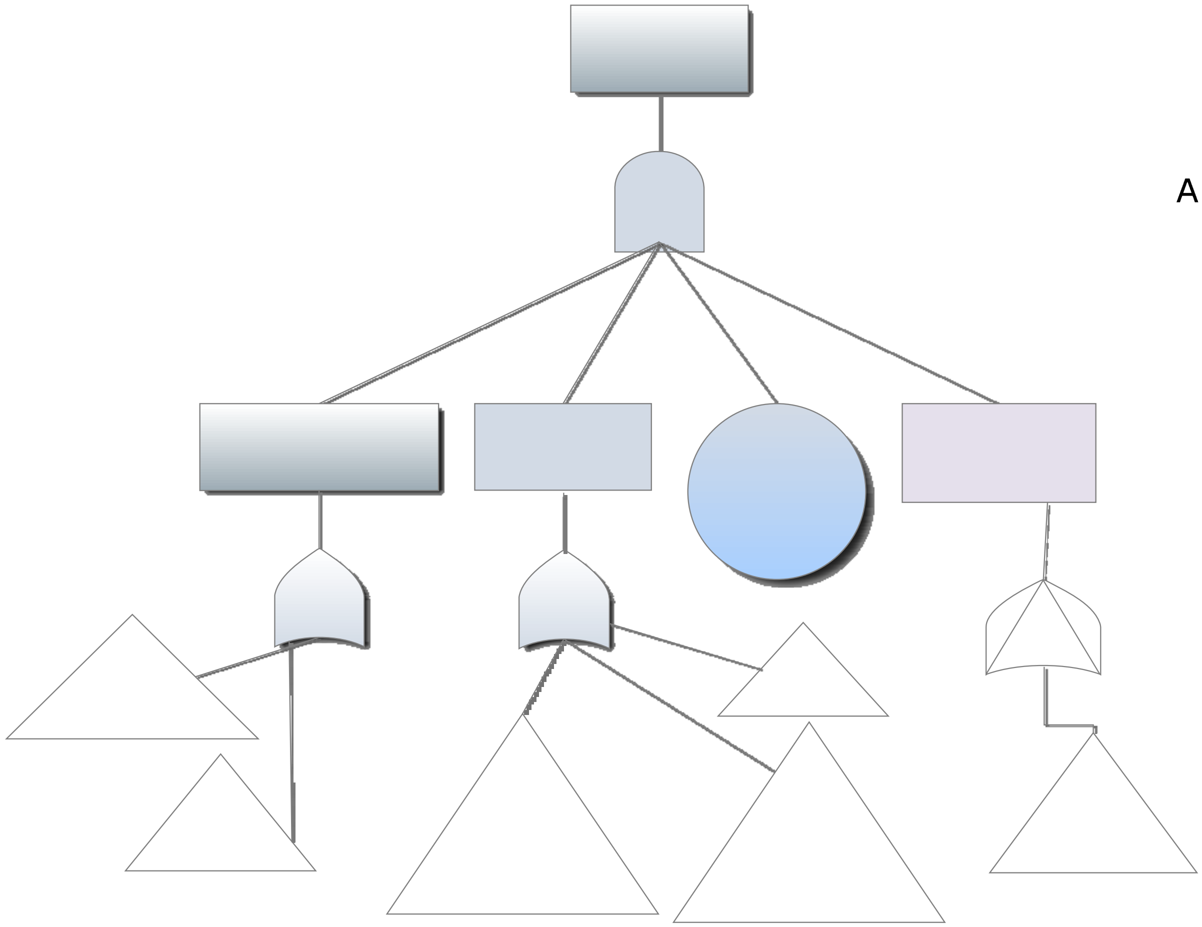


Figure 9. Top-level FTA for Monticello ET cover (A1).

According to figure 9, the necessary events for percolation to occur includes all of the following events: soil storage capacity exceeds ET potential, capillary barrier failure, geomembrane failure to perform as intended, and the permeability of the compacted soil layer (CSL) exceeds design standards. The failure of the geomembrane represents a basic event in this analysis. The reason for this is that it is a physical barrier in which the integrity is either compromised or not during installation. Beyond this, the dynamics of the geomembrane degradation processes are assumed to be known by the site managers and do not include ecological processes. Additionally, the FTA dynamics of the CSL will be deferred to the FTA for Burrel's conventional cover where the CSL is the primary barrier to percolation. The other two events, on the other hand, do involve ecological processes, are unique to ET covers, and are explored through more detailed FTAs in this section.

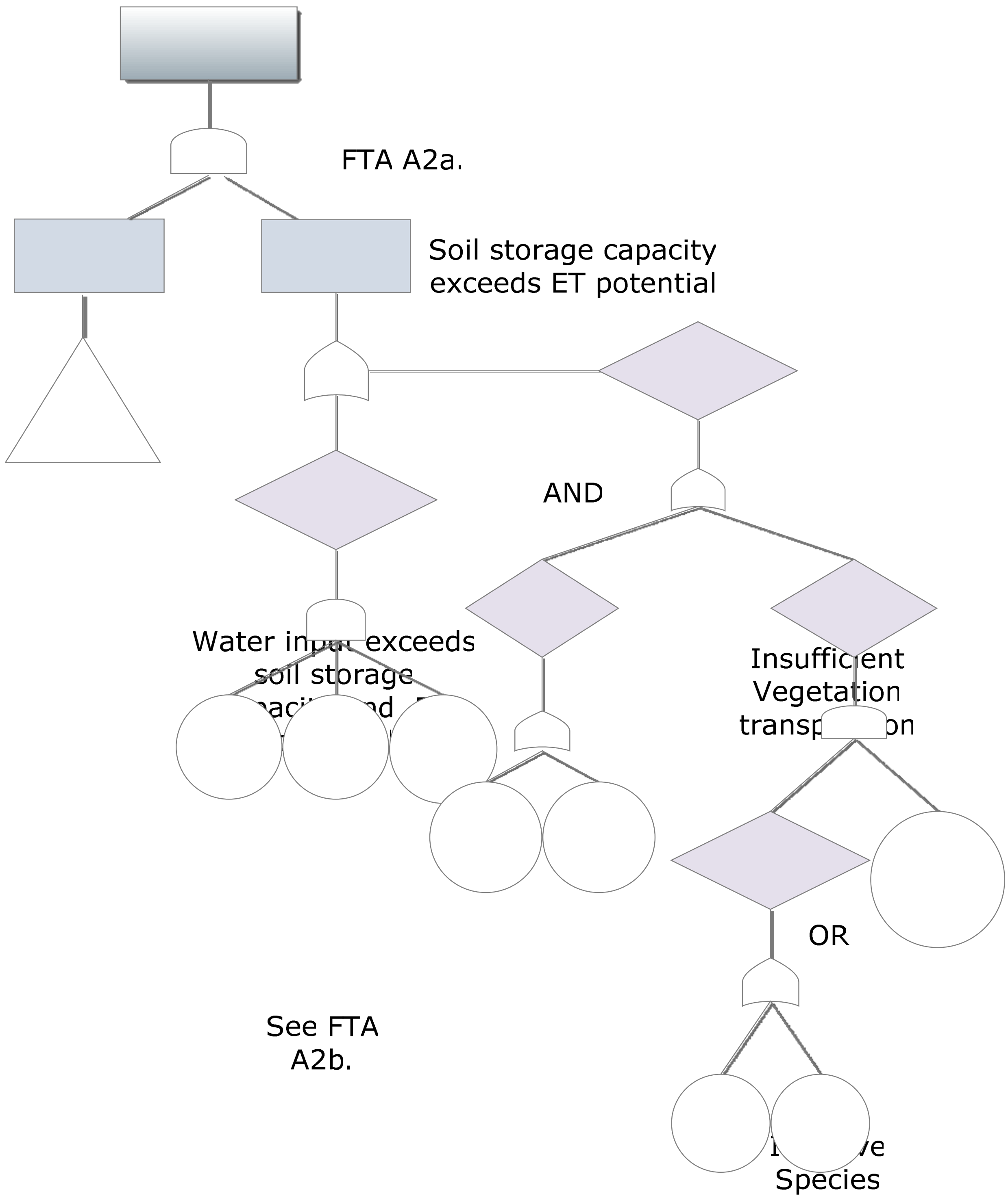


Figure 10. FTA (A2a) delineates the possible necessary and sufficient pathways that lead to the amount of water entering the cover to exceed both the soil water storage capacity and the ET; this ETA highlights pathways emanating from insufficient vegetation transpiration.

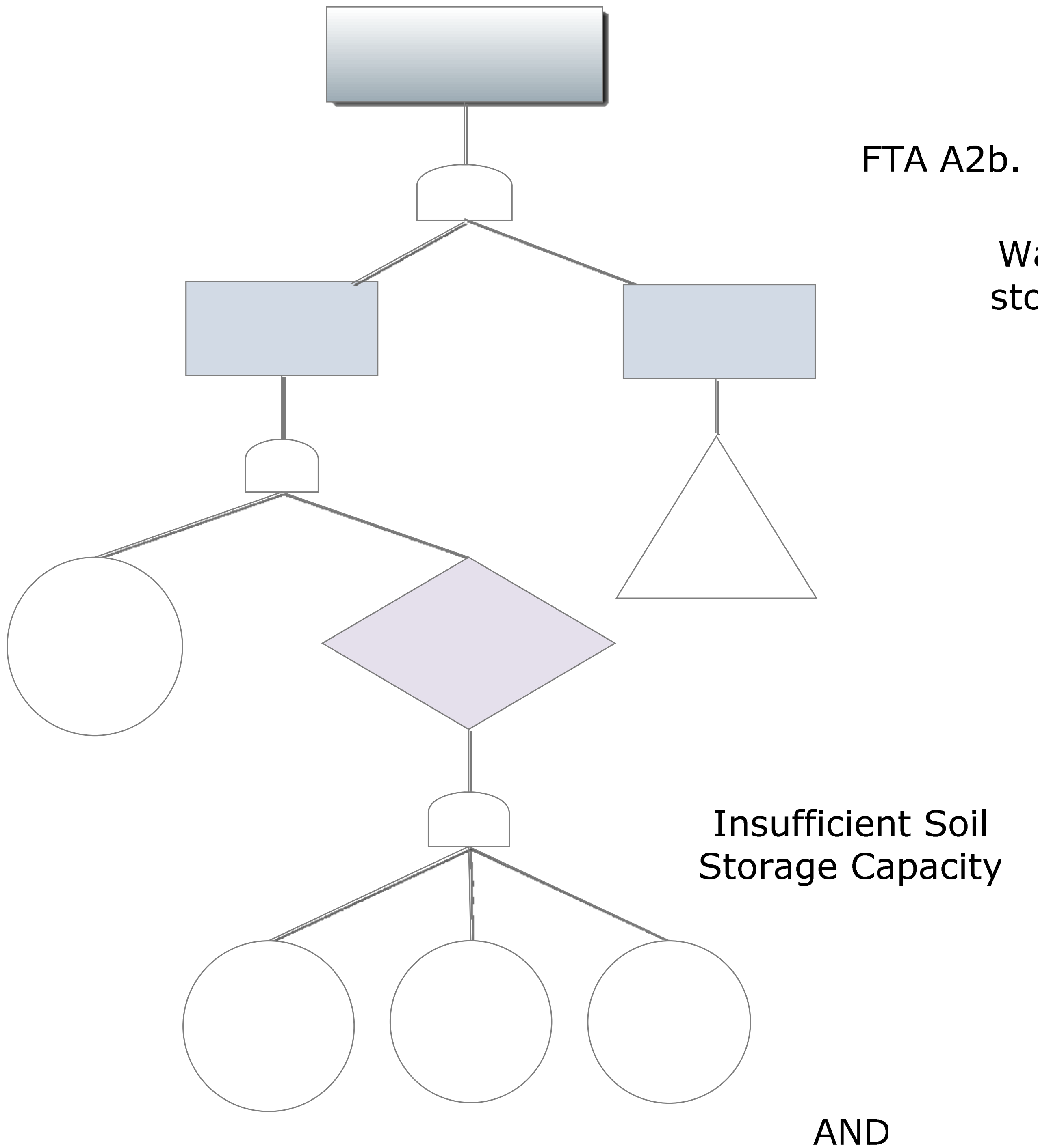


Figure 11. FTA (A2b) delineates the possible necessary and sufficient pathways that lead to the amount of water entering the cover to exceed both the soil water storage capacity and the ET; this ETA highlights pathways emanating from insufficient soil water storage capacity.

Insufficient
depth of soil
layer

The capillary barrier of the Monticello cover acts as a redundant barrier. The performance of the capillary barrier depends on maintaining a sharp gradient at the interface. Several phenomena may degrade capillary barrier performance as conceptually illustrated in Figure 12.

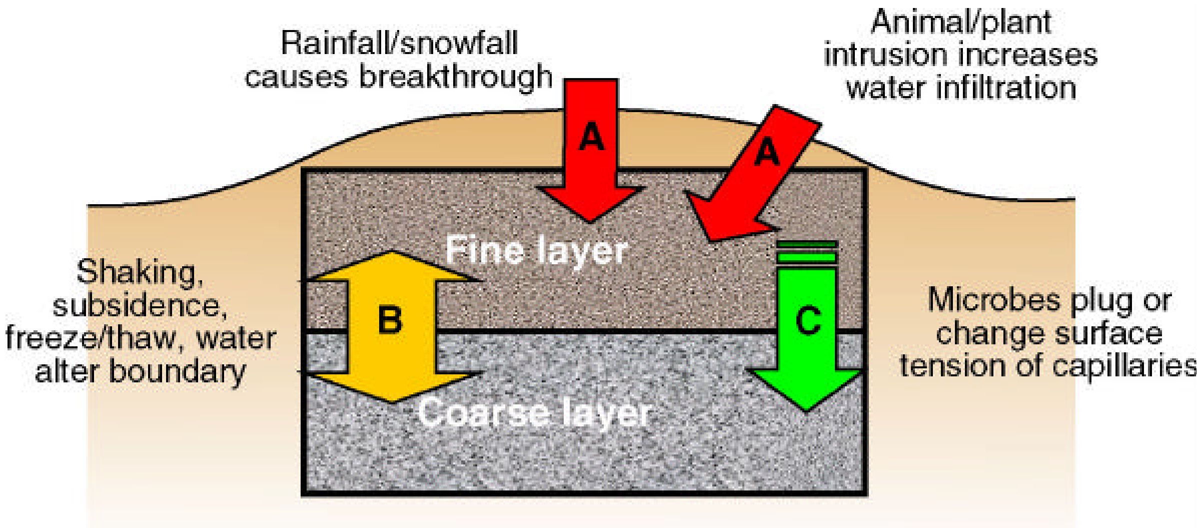


Figure 12. Major risks to capillary barrier component performance of Monticello cover: (A) represents physical perturbation into the upper fine layer of the barrier either through animal or plant intrusion or meteorological inputs; (B) represents a physical disturbance to the lower course layer of the barrier through such mechanisms as shaking, subsidence, freeze/thaw; (C) represents the influences of microbes that may change the surface tension at this boundary through plugging or other alterations.

The following ETA illustrates the potential failure pathways for the capillary barrier component of the cover (Fig. 13):

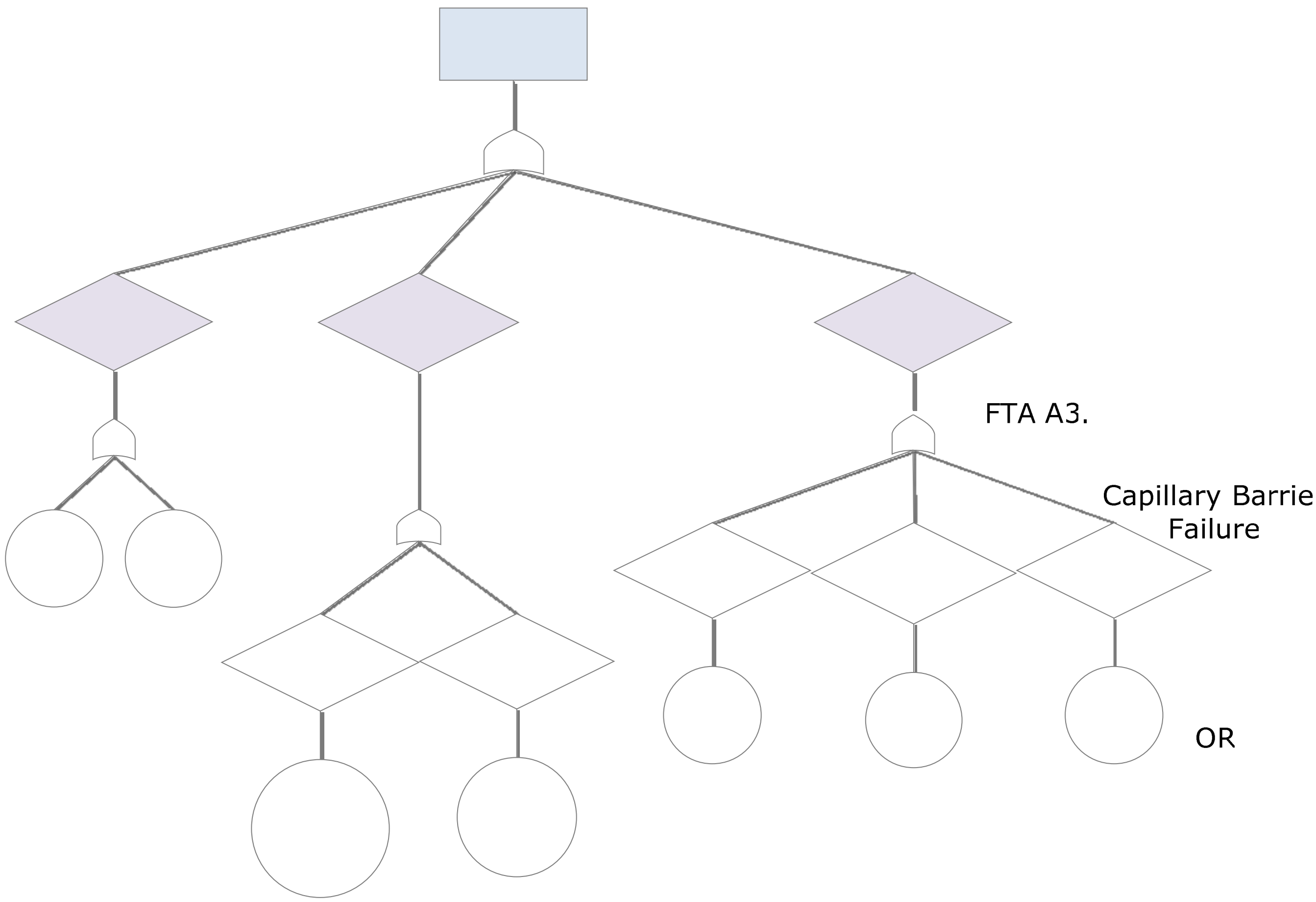
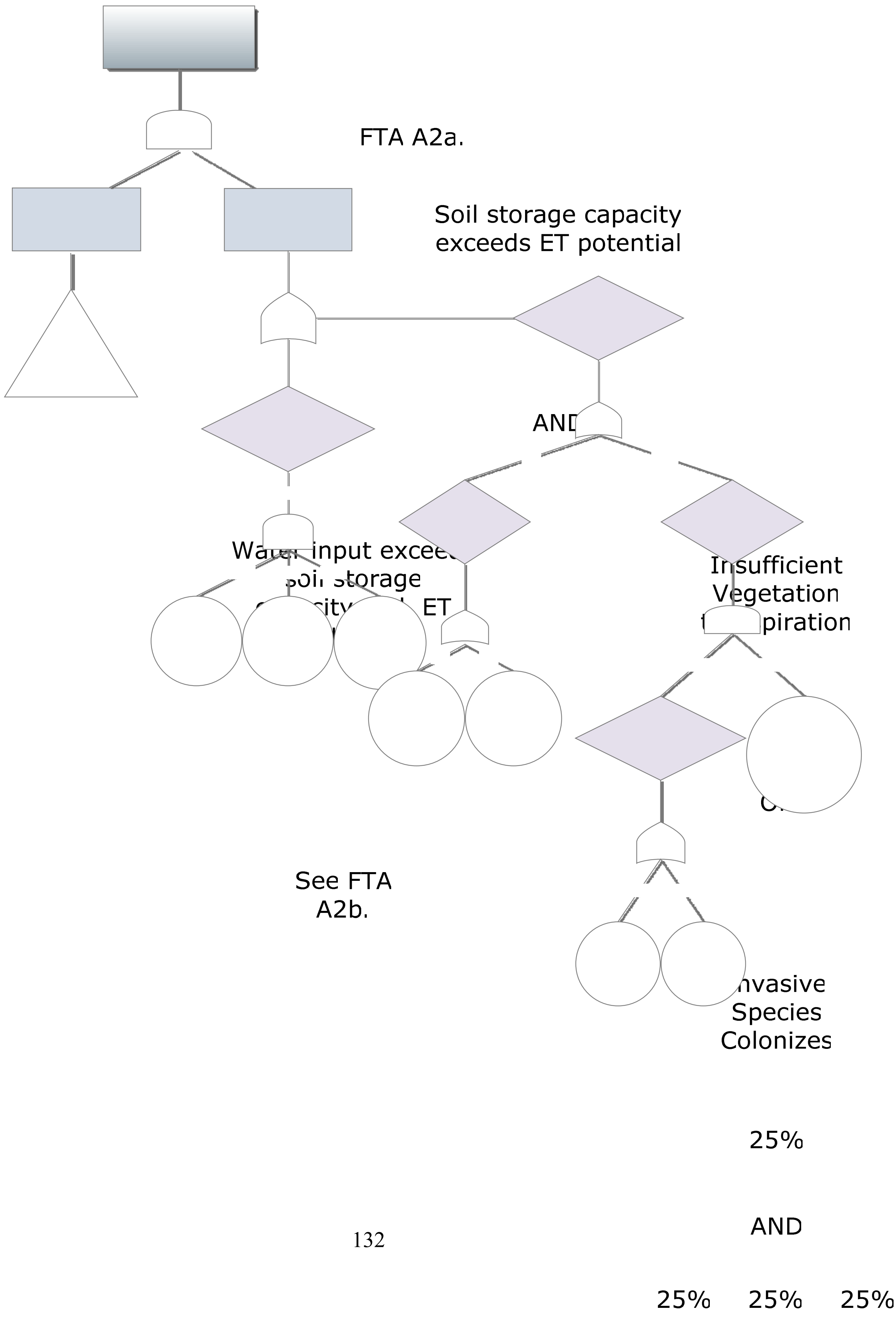


Figure 13. FTA (A3) delineates the possible necessary and sufficient pathways that lead to failure of the capillary barrier.

Assigning Probabilities

The probability that the amount of water entering the cover will exceed the storage capacity is an undeveloped event. This can be calculated by comparing, for example, meteorological characteristics of the region (i.e., the amount and type of participation) with characteristics of the soil storage layer (i.e., grain size and dimensions) and water removal mechanisms (i.e., surface area for evaporation and vegetation for transpiration). There are a variety of statistical techniques for doing this (i.e., Hayes and Hewitt, 2000). The ETA in figure 7 delineates the top order events and possible pathways than can lead to percolation. Using site data, meteorological conditions, and possible future scenarios, it is possible to determine whether an event leading to percolation will definitely occur (100%), likely occur (75%), may occur (50%), probably will not occur (25%), and will not occur (0%). Since the purpose of the FTA is to highlight performance risks to specific components or through specific processes, probabilities need only to be applied to the basis events and their connecting undeveloped events. It is not necessary to assign probabilities up to the initiating event level. Additionally, it is not possible at the current time to assign probabilities to the capillary barrier layer of Monticello due to a lack of performance data. The following FTA's are examples of how the addition of probabilities can be used to guide attention to the risks and events that are most likely to occur over the lifetime of the cover, and have the greatest potential consequence:


FTA A2a.
Soil storage capacity exceeds ET potential
AND
Insufficient
Vegetation
See FTA
A2b.
Species
Colonizes
25%
AND
25%
25%
25%

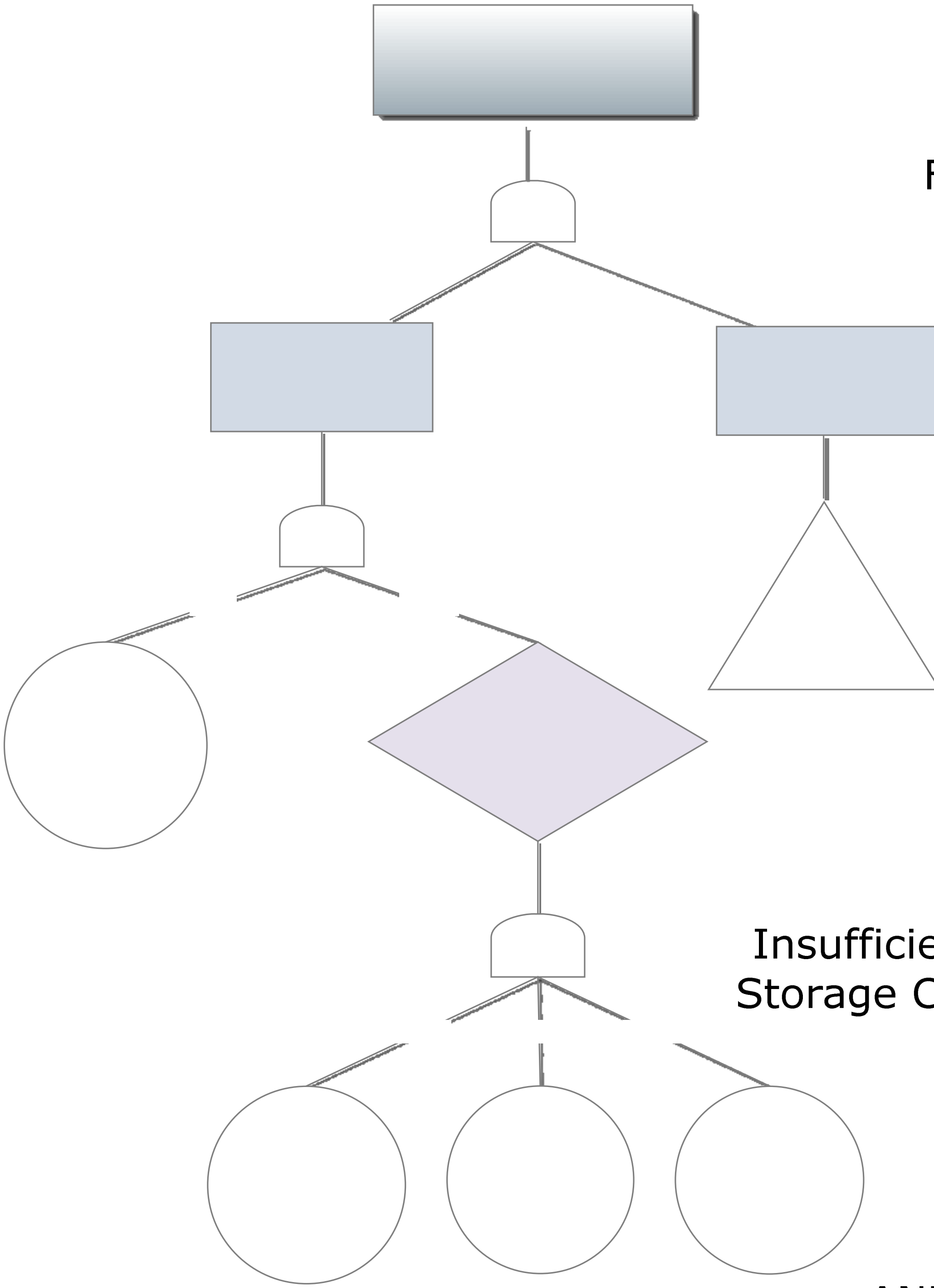


Figure 14. FTA examples of how the addition of probabilities can be used to guide attention to the risks and events that are most likely to occur over the lifetime of the cover, and have the greatest potential consequence.

Conventional Cover Site Description - Burrell

The Burrell UMTRCA Disposal Site is located in a rural setting approximately 1 mile from the Borough of Blairsville in Indiana County, PA and approximately 40 miles east of Pittsburgh, PA, as shown in Figure 15. The Conemaugh River directly borders the site on the south. A railroad track of the Norfolk Southern Rail Corporation directly borders the site on the north (USDOE, 2001a).

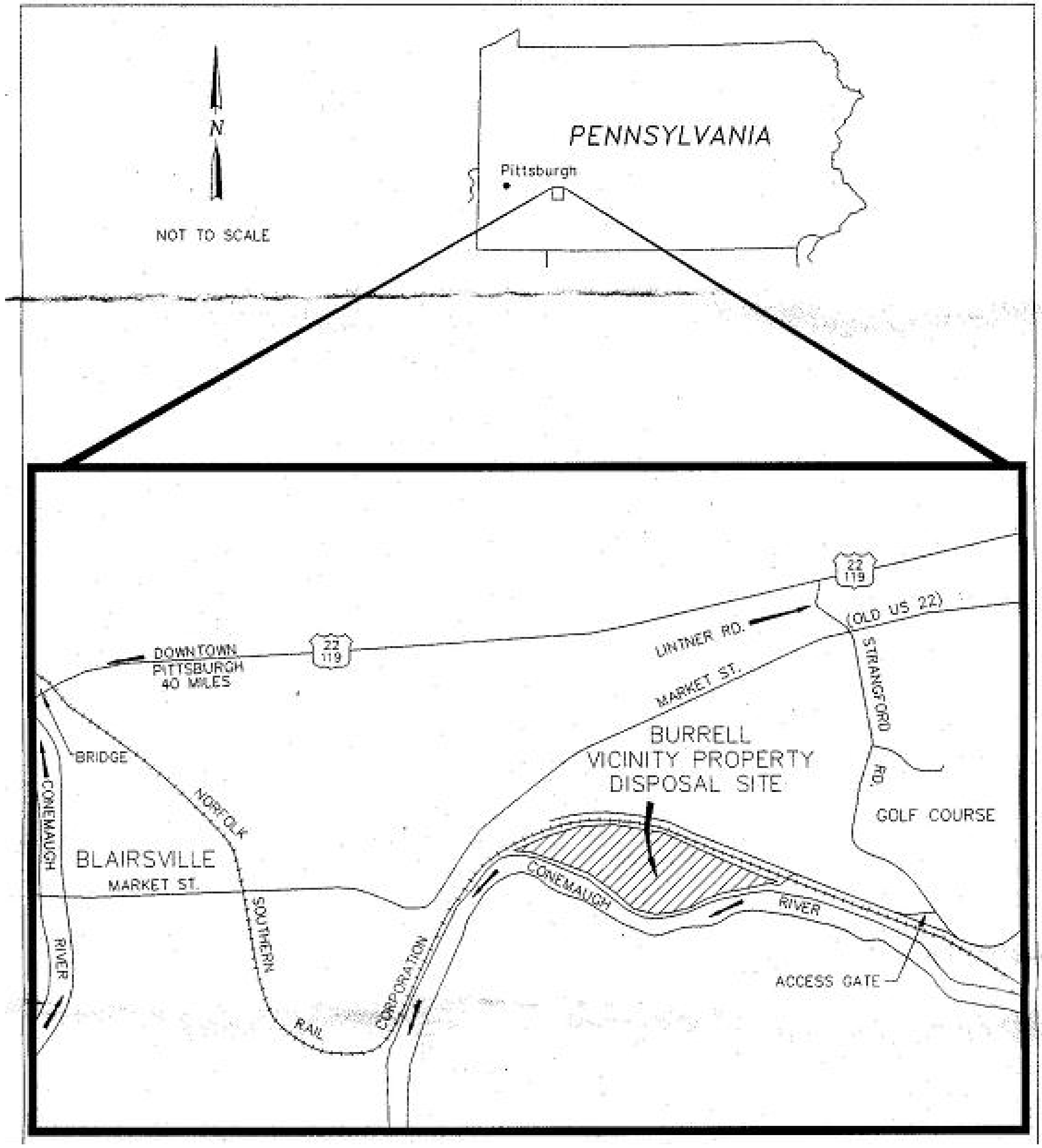


Figure 15. Map showing location of Burrell UMTRCA Disposal Cell (USDOE, 2000b).

The property has been associated with rail service since 1882 when the Western Pennsylvania Railroad Company acquired the property (USDOE, 2002b). During the 1940s the Pennsylvania Railroad Company used the area as a landfill and a considerable amount of fill material was placed on the property to level its grade. This fill material consisted of gravelly loam, cinders, gravel, sandstone, construction debris, etc. As a result of these activities, the site is in essence, a small man-made plateau consisting of fill material measuring 50 to 60 feet in depth. Beneath this fill, claystone and shales of the Pennsylvanian Casselman Formation underlie the entire site (USDOE, 2000b). The Burrell site encompasses approximately 72 acres. RRM has been consolidated into a five-acre on-site disposal cell. The cell contains 86,000 tons of RRM with the total cell radioactivity calculated to be 4 Ci ^{226}Ra (USDOE, 2001a). The Burrell disposal cell was capped and closed in 1987. The disposal cell is intended to properly function for 1000 years but at a minimum it is required to last at least 200 years (USDOE, 2001a).

The Burrell Disposal Cell cap consists of three layers. A 3-foot-thick low-permeability radon barrier, consisting of a compacted soil layer, was installed directly above the RRM. The purpose of this primary layer is to prevent the escape of radon gas and prevent the infiltration of precipitation. Above the radon barrier a 1-foot-thick soil-bedding layer was installed. The purpose of this second drainage layer was to promote precipitation runoff. The third, and outer-most layer, consists of a 1-foot-thick riprap layer. This cover layer was designed to prevent surface erosion (USDOE, 2001a).

Soon after the cell was constructed, the USDOE began to report observations of plant growth on the cell's riprap cover. These observations were reported in 1988. Within three years of the cell's construction, a diverse plant community was reported to be present on the cell cap. Within ten years of construction, the two top layers of the cap, the riprap cover layer and the compacted soil drainage layer, were believed to have been penetrated by the vegetative community (USDOE, 1999b; Waugh, 2004). The vegetative growth was evident during the site visit by Kevin Kostelnik in 2004 and is shown in Figure 16.

Figure 16. Photograph of Burrell, PA conventional cover demonstrating vegetation growth.

The site stewards attempted to minimize the growth of these plants through periodic spraying of herbicides. This practice has since been halted. Site stewards have estimated that the hydraulic conductivity through the barrier has increased by two orders of magnitude as the result of the plant growth. A revised risk analysis, however, showed that this plant growth did not increase the risk potential to unacceptable levels (USDOE, 2004a).

Results for Burrell Conventional Cover

The top event in this ETA is once again successful percolation of water into the waste and is again considered the risk-assessment endpoint. Successful percolation, and therefore failure of cover performance, occurs if the following event takes place:

• all barriers beneath the soil layer fail to perform as intended (i.e., geomembrane and compacted soil layer)

The probability that the CSL will develop preferential pathways is one of the primary undeveloped events. The following ETA depicts the conditions necessary for water to percolate into the waste buried in Burrell (Fig. 17):

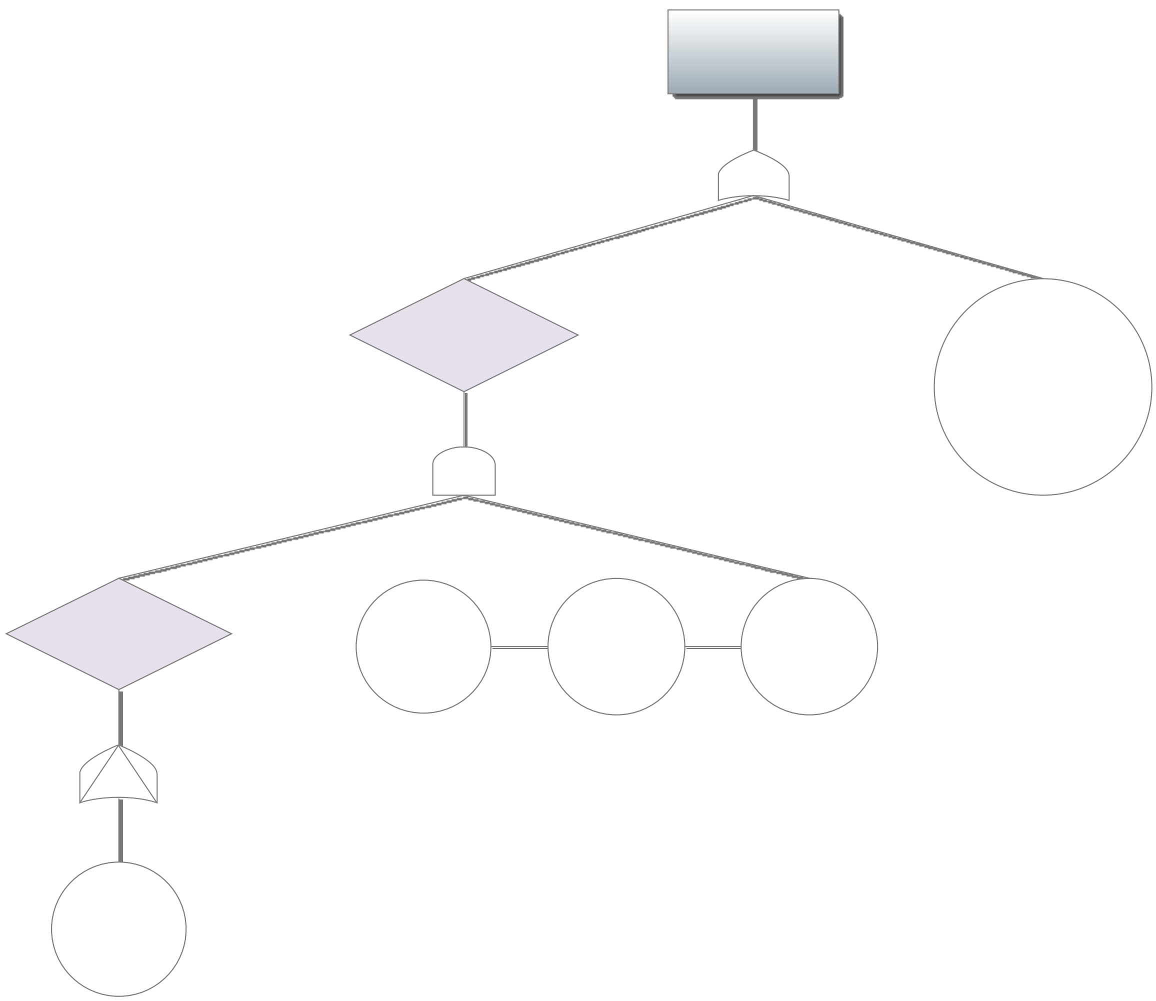


Figure 17. (B1) delineates the possible necessary and sufficient pathways that lead to percolation within Burrell's conventional cover.

Probabilities

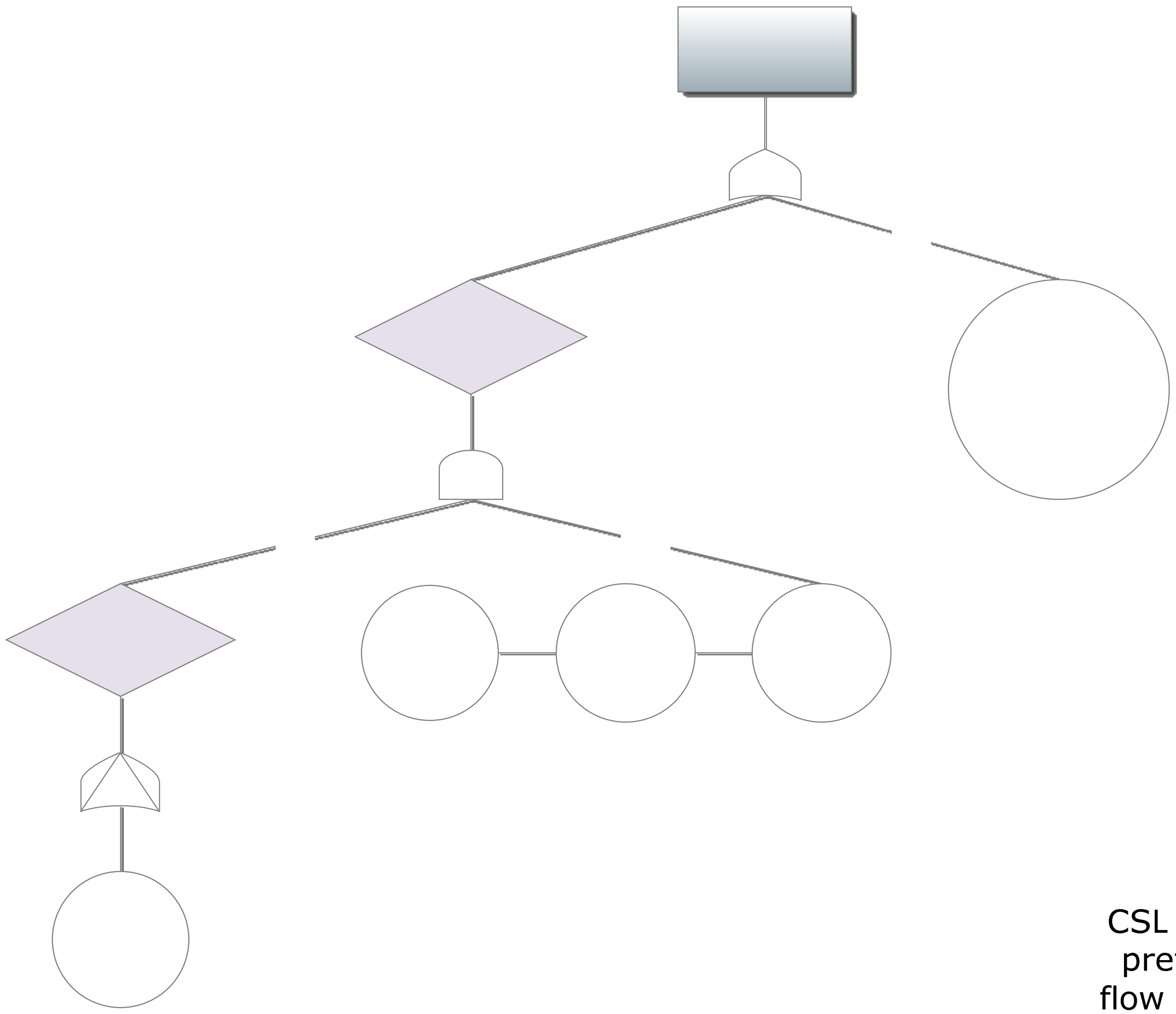


Figure 18. (B1) delineates the possible necessary and sufficient pathways that lead to percolation within Burrell's conventional cover with the inclusion of probabilities.

The FTA for Burrell is much more simple and than the FTA for Monticello because there exists only one primary barrier to percolation, the CSL. The other two layers of the cover, the soil drainage layer and the rock rip-rap were designed to combat other aspects of performance, runoff and erosion respectively. It is also important to note that Burrell has an additional performance risk in the form of deep rooted plants. The cover depth was not designed with roots as criteria; therefore the depth of the cell may not be sufficient to prevent developing roots from eventually intruding the waste directly.

As previously mentioned, based on site experience since construction of the cover, it is evident that deep rooted plants are well established on the Burrell cover. Therefore, one of the two necessary events to the development of preferential pathways in the CSL has a 100% of occurring. The second necessary event, a significant increase in the hydraulic conductivity, has also been measured at the site. However, currently, the amount of water infiltrating the cover has not exceeded the ET established by the unintended growth of deep rooted plants. But, there is indeed a chance that this may occur over the lifetime of the cover.

Discussion

The effective performance of an engineered cover is contingent on the identification and effective management of all high risk failure modes of cover components. Whereas engineered components have been recognized as a potential high risk pathway for cover failure, the focus of this research has been on the ecological components and risks. The conceptual model presented here provides a framework for assessing ecological risks of ET cover performance in a systematic and comprehensive manner, and makes evident the variety of mechanisms in addition to engineered components of the cover that potentially contribute to the cover performing in a way other than initially intended. Evaluation of model application using Monticello as a case study highlighted examples where different ecological components could influence cover performance. Both the conceptual model and cases study also highlighted the broad range of events, variables and interactions that can influence cover performance and ultimately lead to percolation of water into the waste. Therefore, for management programs to be successful, it is essential to acknowledge and address this complexity during ET cover design, installation, and monitoring program.

Events and mechanisms for which management is realistic and thus, potentially effective, are identified by the model. For example, knowledge of the time-dependent components of the cover allow managers to dedicate resources to components when they are most sensitive to performance failure (i.e., investing resources in establishing a healthy seed bank in cover soils during construction due to the risk of episodic events killing the initial vegetation after construction).

Although the modeling and assessment of some of the events identified in these fault trees would be difficult or unrealistic, it is important to acknowledge them in order to provide a comprehensive risk assessment tool for ET cover performance. Therefore, all of the building blocks on which the model is based must be well considered. It should be noted that, even where risks are largely unknown, difficult to quantify, or reflect stochastic events, this does not necessarily preclude management intervention.

The model, although being general and comprehensive, cannot be universally applied in the form presented here. This was clearly highlighted by the contrast between the Monticello and Burrell case studies. Hence, the model would need to be modified according to the site specific characteristics of the cover and location. However, the method itself is easily adaptable to any site. Therefore, the general conceptual model should be modified to represent the most relevant components, scenarios, and lessons learned. This includes the importance given to each basic event and undeveloped event, which graphically in the model might seen of equal importance but, as explained above, different events would have more or less importance depending on specific circumstances. Similarly, the analysis of the process should focus on those components that could actually play an active role in cover performance. In general, these modifications should reduce the complexity of the model, increase its accuracy and elucidate the steps of the performance process where management may be feasible.

Utility of the Fault or Event Tree Analysis Framework

Although often associated with quantitative analysis, fault tree analysis (or the corresponding event tree analysis) is most often used as a hazard identification technique and to help design mitigation strategies (Hayes, 2002b). In contrast to most hazard identification techniques, fault tree analysis forces the analyst to follow a systematic and reductionist approach not only to identify the components and potential hazards of the system, but also to determine the causal links between them. Without following this approach, the thorough analysis of the performance assessment depicted in this model, where most of the variables and their interactions are identified and organized, would not have been possible. However, as with any hazard identification technique, fault tree analysis has some limitations. The first, and probably the most important limitation, is the reliability of fault tree analysis on expert opinion. The current lack of research and data on the ET cover performance makes expert opinion indispensable when designing and implementing risk assessment and management plans for ET covers.

In industrial systems, fault-trees are often supplemented with quantitative information to derive the probability of the top event. It seems unlikely that they could be used in a similar fashion for ecological systems because of the difficulties in estimating the probability of the basic events in the tree (i.e., the fertility of the soil). The fault tree does, however, identify the important variables and relationships within the system which is one of the most important steps in a quantitative risk assessment.

Model Uncertainty

Uncertainty is an inevitable and important characteristic of modeling and FTA, and usually is divided into linguistic, epistemic, and aleatory (Thacker and Huyse, 2003). In contrast to linguistic uncertainty which arises from the vagueness and context dependency of the natural language, epistemic uncertainty reflects incomplete knowledge that results from variability and incertitude, measurement error, systematic error, natural variation, model uncertainty and subjective judgment (Bae et al., 2004). Aleatory uncertainty accounts for natural variation or randomness in the behavior of a system and in the case of data availability, probability-based approaches are found to be the best choice (Agarwal et al., 2004).

To describe uncertainties in input data (i.e., event likelihood) and propagate them through ETA, probability based approaches such as Monte Carlo simulations (MCS) have been traditionally used (Bae et al., 2004). This approach requires sufficient empirical information to derive probability density functions (PDFs) of the input data, which may not be available (Wilcox andAyyub, 2003). As an alternative to objective data, expert knowledge/judgment is used, especially when the data collection is either difficult or very expensive (Rosqvist, 2003).

Expert judgments are qualitative/linguistic in nature and may suffer from inconsistency if lack of consensus among various experts arises. The classical probabilistic framework is not very effective to deal with vague or incomplete/inconsistent systems, such as the dynamic ecological systems of ET covers discussed in this paper (Druschel et al., 2006).

Reducing uncertainty should be a priority in both modeling and FTA. Often, in an attempt to present quantitative analyses, researchers potentially overlook and underestimate conceptual model uncertainty, which would generate incomplete and inaccurate models with systematic biases. This is especially true for ecological systems that evolve considerably over time and involve highly coupled processes. The event tree approach presented in this paper reduces uncertainty by basing analyses on carefully developed conceptual models and site specific data. Hence, while the absence of quantitative application of the present model can be seen as a short-coming, on the contrary, the model can be regarded as a sound conceptual framework that could underpin future quantitative analyses of ET cover performance with the inclusion of important ecological components and drivers. Perhaps most importantly, the model presented is a first step to draw attention to the fact that there are a range of ecological mechanisms that need to be identified and incorporated into long term performance assessments, and acknowledged as major sources of uncertainty in any qualitative analysis. This is an important contribution to this field, particularly considering that the current literature and assessment methods omit key ecological processes and mechanisms.

CONCLUSIONS

This paper identifies the necessary steps that must occur for water to percolate down through an ET cover and into the waste, and highlights the complexity of the cover performance even when only major components and processes are considered. The diversity of cover components that could contribute to the performance suggests that a focus on engineered components alone could lead to other potential mechanisms and processes being overlooked (e.g., ecological). Even though the role of some ecological mechanisms is not well understood within this context, there is sufficient evidence to highlight their potential importance to ET cover performance and personnel who have important first hand experience. There is a need therefore, for further research and assessment of the potential for each of these ecological components and their related processes to transport water through the ET cover system.

However, absence of such knowledge should not preclude recognition by site managers of these diverse components as potential sources of performance risk. The model described here is a comprehensive conceptual representation of key ecological components and processes in generic ET and conventional cover systems, and has been applied to case studies representing different types of cover constructions and site conditions. Thus, the model is an important starting point for scientists and managers to reach consensus on this method, modify the components according to the specific attributes of different sites and scenarios, and identify key uncertainties and information needs for quantitative risk assessment and model development. The aim of this paper is to encourage site managers and regulatory authorities to adopt these techniques in a continuing effort to improve best practice in performance assessment and risk assessment of engineered covers. The analytical techniques identified in this paper are better at identifying ecological hazards and alternative conceptual models by which they occur than ad hoc checklists and brainstorming.

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OBSERVATIONS AND RECOMMENDATIONS

Fault-tree analysis and the accompanying event tree analyses, are not, an ‘objective’ science –their heuristic potential and usefulness depends on the expertise of the analyst(s). This approach enables the analyst to deconstruct complex systems into their contributing parts, so long as he or she is sufficiently familiar with the system in question. Indeed, this is the principal weakness of this methodology in that it requires substantial expert knowledge, and is ultimately limited by knowledge of the people involved in its construction. Fault-trees are, therefore, most useful when constructed by a team of experts who are able to pool their collective expertise. The fault-trees described in this paper were constructed by the author. However, the ultimate utility of the analyses will be best applied if the conceptual models presented and discussed with ET cover experts, site-managers, or regulators. The trees themselves will evolve through this review process and will undoubtedly be substantially amended since their original inception.

Furthermore, there is no guarantee that a fault-tree will capture all casual pathways that may lead to the top event. Unexpected interactions (outside the experience or imagination of the analyst) could result in additional unidentified hazards or hazard inducing mechanisms. Simply put, there are no such guarantees in any form of hazard analysis or risk assessment (hence the need to continually compare the predictions of a risk assessment with reality). The logical and rigorous structure of fault-tree analysis, however, helps minimize the probability of missing important casual pathways and it performs much better in this regard than simple brainstorming techniques.

Fault-trees also quickly identify areas of knowledge uncertainty. In this example, important areas of knowledge uncertainty are represented by some of the events that are not developed within the tree, notably:

- soil fertility,
- vegetation dynamics,
- geomembrane integrity,
- the effects of episodic/catastrophic events.

These all need additional research before we can fully understand the mechanics of ET cover performance. Research in these areas will help management and regulatory authorities better predict performance objectives and the most cost-effective means of managing performance risks. The event tree approach will also guide the development of post closure monitoring through the identification of those events that need to be monitored.

The fault-tree is in effect a 'snap-shot' of the state of the system – the basic components either occur or they do not. Most biological systems, however, contain very important time-dependant variables that may not be captured by a fault-tree analysis or may not be appropriately parameterized as a probability distribution. Vegetation and soil dynamics are notoriously dependant on timing and difficult to accurately predict future dynamics. Fault trees will always, therefore, have limited application to ecological systems more generally. Nonetheless, they can help identify prioritize the components and detailed risks, and thereby direct the analyst to the important fine-scale processes. This is an interesting heuristic exercise in itself, but as a hazard-analysis precursor to a rigorous ecological risk-assessment and/or quantitative model development is essential.

The methods presented in chapter V will be best utilized in two ways: by allowing cover experts to assign RPNs to a range of FTAs, and to apply this information to develop more robust quantitative models. FTA's present site specific information in a straight forward and streamlined way than can be instrumental in evaluating the common highest risk components of covers across the DOE complex. Similarly, in the case of ET covers that involve complex ecological interdependencies, it would be useful to understand what components derive the highest risks based on the experience of site managers and other experienced personnel. A workshop that specifically focuses on developing additionally event trees, probability assignments, and RPNs for ET covers would be a important exercise leading to better inform quantitative model development.

Risk Communication

ETA can be a useful communication tool between site managers and regulators, as well as with members of the general public, to clearly illustrate the design criteria for a cover based on site specific risks and hazards. Site managers are the individuals who are in charge of overseeing daily operations of a cover at each site. The event trees developed in this paper will be a useful tool for managers to prioritize long term monitoring funds and activities, and can assist managers in the decision making process on how best to allocate maintenance funds throughout the period of performance.

Risk communication is possibly the most important aspect of risk management, especially in relation to radioactive waste. Many aspects of risk assessment are difficult to convey, especially if it is communicated through quantitative models within a highly technical engineering context and the audience is untrained in such techniques. Clear, qualitative communication is the only remedy. Moreover, a poor job communicating will only reinforce confusion, suspicion, and resistance. For these reasons, it is critical to design risk communication tools for engineered covers carefully, with attention to the how they could be received and interpreted. ETA's have an advantage over quantitative models in that they are more easily interpreted and visually provide a lot of information that would otherwise require lengthy descriptions, as is the case with quantitative models. The content of an ETA is specific enough to aid in decision making processes, but not so detailed that it obfuscates the message with extraneous technical information.