A Regulatory Perspective of Monitoring and Assessing Performance of Engineered Surface Barriers – 10138

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ABSTRACT

Engineered surface barriers can be significant barriers and may help provide reasonable assurance that statutory requirements involving near-surface land disposal of radioactive waste will be met. The long-term performance of an engineered surface barrier depends on the degradation processes on, and within, the barrier that will modify the barrier from its "as built" performance metrics to its longer-term performance level. Performance of the barrier can be physically monitored with on-site instrumentation or by remote sensing during the institutional or postclosure time periods. The post-institutional period assumes the surface barrier is no longer being monitored nor maintained. Instead, numerical modeling and model support can be used to build confidence in those components of the barrier which provide for a long-term performance that protects the public and the environment. Hydrologic codes for engineered surface covers are evaluated based on their ability to simulate or represent total water balance of the cover, ponding, frozen snow and snow melt, vegetation, lateral diversion and seepage of geomembranes, soil water movement using Richards' equation, spatial variability in the cover properties, and percolation output to other codes. Determining long-term cover performance requires information on degradation processes, changes to local topography, cover geometry, cover material properties, climate, and ecology.

INTRODUCTION

During the 1950's and 1960's, the common practice of disposing of low-level radioactive waste (LLW) was disposal at sea. Based on recommendations by the National Academy of Science (NAS) at the time, commercial wastes were typically disposed in the oceans based on the belief that dilution in sea water and the relatively short half-lives of most of the radionuclides would pose a minimal hazard to mankind. Commercial interest in ocean disposal declined due to public opinion and concern over costs, and ended completely by 1970 [1]. By 1971, a total of six near-surface LLW disposal facilities were licensed and operated to dispose of commercial LLW. The earliest engineered surface barriers, or covers, were earthen mounds created when trenches in which the waste was placed were backfilled using material removed during trench excavation, and subsequently compacted and graded. Due to concerns that the soil and grass covered trenches were not containing the waste material and that radionuclides were being released, the NAS was asked to independently review near-surface disposal practices used. Although the NAS found no serious deficiencies in past federal disposal practices, it made administrative and technical recommendations to improve disposal practices. One of the recommendations made was that engineered barriers be adapted so as to work in tandem with the geological and hydrological systems.

The U.S. Nuclear Regulatory Commission (NRC) issued Part 61 of Title 10 of the Code of Federal Regulations (10 CFR Part 61) in 1982 after several years of development. The regulations covered all near-surface LLW disposals from site selection through facility design, licensing, operations, closure, and postclosure stabilization to the period when active institutional controls end. The regulation requires the use of engineered features in concert with the natural characteristics of the disposal site to contain and isolate the wastes, and included performance objectives and technical criteria. Section 3116 of the National Defense Authorization Act for Fiscal Year 2005 expanded the use of 10 CFR Part 61 as it requires NRC to monitor U.S. Department of Energy (DOE) disposal actions of waste incidental to reprocessing (WIR) of high-level radioactive waste based on the performance objectives found in Subpart C of 10 CFR Part 61.

In addition to licensing LLW near-surface disposal facilities, NRC also regulates uranium mill tailings under the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA). This legislation addresses two types of sites: (1) those that were inactive or no longer being used when UMTRCA was passed, referred to as Title I sites; and (2) sites that were active or issued a license after UMTRCA was passed; referred to as Title II sites. Title II sites are regulated under the provisions of 10 CFR Part 40. Appendix A to 10 CFR Part 40 establishes technical and other criteria for Title II sites relating to siting, operation, groundwater protection, decontamination, decommissioning, reclamation of mills and of tailings at mill sites, and long term site surveillance. Criterion 6 of Appendix A requires an earthen cover (or approved alternative) over the tailings or waste to increase control of radioactive hazards and limit release of radon-222 from uranium and radon-220 from thorium to the atmosphere. Title I sites are regulated under the requirements of 40 CFR Part 192 and have a general license under 10 CFR 40.27.

NRC guidelines on engineered barrier performance or on monitoring disposal sites of various waste types can be found in NUREG-1388 for LLW [2], NUREG-1854 for WIR [3], NUREG-1620 for radioactive mill tailings [4], and NUREG-1757 for complex materials decommissioning [5]. NUREG-1623 presents methods, guidelines, and procedures for designing erosion protection, for long term stabilization, with an emphasis on engineered surface barriers at uranium mill tailing sites in accordance with the requirements of 10 CFR Part 40, Appendix A (Title II sites) and 40 CFR part 192 (Title I sites) [6].

THE ENGINEERED SURFACE BARRIER AS PART OF THE ENGINEERED BARRIER SYSTEM

The components of engineered barrier systems (EBS) may include liners, covers or caps, and/or lateral barriers or walls, and may use a variety of natural material such as aggregates, soil, or clay, and synthetic, cementitious, and bituminous materials including polyethylenes, fabrics, mortar, and asphalt [7]. The regulatory disposal requirements, and types of EBS chosen, depend on the waste type. Of all the components from the EBS, the engineered surface barrier, or cover, is the most commonly used barrier and often considered to be one of the most important components. Since engineered surface covers can be significant barriers, they may provide reasonable assurance that one or more performance objectives will be met. For example, covers may greatly contribute to performance so that the following objectives for safe near-surface disposal of LLW as set in 10 CFR Part 61 can be reached: provide physical stabilization of the site (10 CFR 61.44), minimize infiltration and slow degradation of the stabilized wasteform (10 CFR 61.41), and provide an intruder deterrent (10 CFR 61.42).

Function. There are three main functions for covers. The physical presence of an engineered surface cover can retard various environmental processes and enhance the waste's isolation. Thicker covers can provide protection from external radiation while concurrently hindering all but the deepest roots from extracting contaminants from the subsurface and releasing them at the more environmentally active surface. Burrowing animals may damage the cover but are usually impeded from obtaining direct contact by the depth at which the waste is located. For example, the engineered surface barrier currently being considered at the Hanford Site in the State of Washington has a thickness of 5 m [15 ft] while the top of the grout-filled tanks are currently covered with approximately 2 m [7 ft] of backfill. Engineered surface covers are expected to deter future inadvertent intrusion by man including possible excavation during construction of structures. Surface covers can provide physical stabilization especially at uranium mill tailings sites. NUREG-1623 provides guidelines on designing erosion resistant covers for long-term stabilization.

Another function of engineered surface barriers is demonstrated at radioactive mill tailings sites that limit the release of radon-222 from uranium byproduct materials and radon-220 from thorium byproduct materials. These engineered surface covers are designed to reduce radon emissions into the atmosphere. Increased thickness of cover material can be beneficial for reducing radon release by utilizing the increased travel time through the cover and the relative short half-life of radioactive radon.

A critical function for most engineered surface barriers is resistive or divertive in nature and designed to control surface water percolation through the cover. Reducing water contact with the wasteform helps keep the waste environmentally isolated and the contaminants contained while degradation of all barrier components is considerably slowed. Delayed or decreased contaminant transport in the saturated zone fulfills a common requirement of the engineered surface barrier. Many surface covers allow initial water infiltration to occur, however allow only a minimum to percolate out through the bottom of the cover. Covers usually consist of one or more layers so that infiltration through one layer does not equate to infiltration through all cover layers.

Type. Surface covers employ a variety of functional mechanisms to divert water and contain waste, however most covers are of two types: conventional and evapotranspiration (ET). Conventional covers rely on the resistive properties of one or more components of the cover, such as a geomembrane, to halt downward movement of infiltration water and allow a drainage layer with high hydraulic conductivity to channel the water to the sides of the cover where it is discharged from the system. The resistive properties can be used to prevent water from reaching the waste, or radon from escaping into the atmosphere. Examples of materials with resistive properties include compacted soil or clay, sheets of synthetic material such a geomembranes, and geosynthetic clay liners. Geotextiles and geonets are often used in conjunction with granular drainage layers to provide a drainage pathway out of the cover system. Although ET removes water from conventional covers, it is the layers of low permeable material that hinder water from reaching the waste. In contrast, ET covers rely more on natural processes to remove water and would not fully function without vegetation. ET is usually the most important process removing water, sometimes removing over half of the total water input (i.e., precipitation). Water is allowed to enter the outer portion of the cover, a non-compacted soil layer with a saturated hydraulic conductivity value close to that of the surrounding environment, during periods of elevated precipitation and minimal ET. Stored water is subsequently pulled back to the surface by a network of plant roots and removed from the system by ET during drier periods. ET covers are effective when the upper soil layer has sufficient storage capacity and when sufficient evapotranspirative demand exists to remove the stored water [8]. Engineered surface barriers may combine the features of both conventional and ET covers, e.g., installation of synthetic material below the water storage unit of an ET cover.

Engineered surface barriers have evolved from basic earthen mounds to the complex multilayered covers being considered today. Covers can be flat and horizontal, such as the Prototype Hanford Cover found at the Hanford Site or the thick multilayered covers being considered for use at potential WIR sites. Wasteforms for such covers are located in the subsurface allowing relatively horizontal surface covers to be built. However, for most waste lying at the surface, engineered surface covers and the layers of which they are composed usually fit themselves over the waste so that the overall shape of the cover can be quite domed. Although their functional design may vary greatly, most uranium mill tailings covers are shaped to fit the form of the waste.

Time-Dependent Performance. All components of an engineered surface barrier are subject to long-term degradation and some relatively short-term degradation or initial design or emplacement flaws. Increased degradation and diminishing performance could eventually lead to failure of the engineered component as a barrier. Compacted soil or clay has been shown to change their lower as-built saturated hydraulic conductivity to conductivities closer to that of the surrounding environment, sometimes developing cracks due to desiccation, often more than an order of magnitude [9]. For ET covers, the upper storage layer may be designed for the wrong type of vegetation, develop secondary permeability features, or suffer from erosion. Drainage layers may clog due to soil infiltration, biological activity, and/or mineral precipitation [7]. Geomembranes, usually a significant component of an engineered surface barrier, can be emplaced with defective materials or seams, damaged during installation, suffer from punctures due to root penetration, or undergo long-term chemical oxidation changing the polymeric properties over the long-term. Depending on the disposal site’s topography, climate, and waste type, erosion severe enough to reduce performance can occur. Slumping, slope failure, landslides, subsidence, and gully-forming erosion can reduce the thickness of engineered surface covers as well as increase infiltration by shortcircuiting the resistive properties of a low permeable barrier or decreasing the water storage capacity of an ET cover. Climatic conditions at a cover may change during the performance period, including the frequency or magnitude of short-duration, large magnitude events. For engineered surface barriers that are a significant component of the overall EBS, features, events, and processes accelerating degradation and effecting surface cover performance need to be identified before the final cover is constructed and monitored during the postclosure and institutional control period.

APPROACHES TO ASSESSING COMPLIANCE FOR DISPOSAL SITES WITH ENGINEERED SURFACE BARRIERS

As previously stated, engineered surface barriers can help provide reasonable assurance that performance objectives will be met as set out in 10 CFR Part 61, Subpart C, for near-surface disposal of LLW or WIR, as well as fulfill the regulations of 10 CFR Part 40, Appendix A, for radioactive mill tailings. 10 CFR Part 61 establishes the procedures, criteria, and terms and conditions upon which NRC issues, transfers, and terminates licenses for the land disposal of radioactive LLW and covers the preoperational, operational, closure, postclosure, and institutional-control phases of the licensing process. The institutional-control requirements in Part 61.59 state that the disposal site owner must perform environmental monitoring to assure continued satisfactory disposal performance, physical surveillance to restrict access to the site, and minor custodial activities. In addition, the institutional-control period is not intended to last longer than 100 years following transfer of control; however, the determining factor on how long institutional control will remain is compliance with the performance objectives in 10 CFR Part 61.41 through 44, including the protection of the general population, protection of individuals from inadvertent intrusion and during operations, and long-term stability of the disposal site after closure so that active maintenance of the disposal site is not required. Depending on the disposal site and the waste characteristics, the institutional control period may last longer or be shorter than the suggested 100 years. NRC believes that the disposal facilities should be robust, and institutional controls should not be relied upon in order to rebuild temporary or substandard disposal components.

The disposal site owner could be found noncompliant with the performance objectives of 10 CFR Part 61, Subpart C, if either 1) there are sufficient indications that the requirements of 10 CFR 61.41 through 44 are currently not being met, or 2) there are sufficient indications that there is no reasonable assurance that the performance objectives will be met in the future (e.g., assumptions relied upon to demonstrate compliance are no longer supported). Compliance with the performance objectives during the lifespan of the disposal site license would rely on monitoring and performance assessment. Compliance after the lifespan of the site license would rely on performance assessment. For example, if a reviewer is determining whether a site will remain in compliance with the performance objectives 800 years after a disposal facility's closure, performance assessment would be used to support such a determination.

Institutional Control: Monitoring and Performance Assessment. During a period of institutional control, the owner must perform environmental monitoring to assure continued satisfactory disposal performance, physical surveillance to restrict access to the site, and minor custodial activities. Short-term performance of the disposal site can be physically monitored with various onsite instrumentation or by remote sensing. Monitoring may detect early significant release of contaminants and may be used to verify the correctness of assumptions made and the accuracy of the results of numerical modeling, thereby reducing uncertainty. Assumptions, parameters, and features that have a large influence on the performance and/or have relatively large uncertainties should be an important part of a monitoring plan. For example, a planned cover for a waste disposal site may be an important barrier in keeping waste isolated from the environment; however, uncertainty regarding the performance of the planned cover during a potential drought-heavy rainfall cycle could not be reduced during the performance assessment process. It could not be excluded that the planned cover might fail during such conditions, either due to degraded geosynthetic clay liners or reduced evapotranspiration. A 100-year institutional control period could allow observations to be made, data to be gathered, and uncertainties to be reduced.

Monitoring is a good mechanism to manage uncertainties and to evaluate new information obtained during the institutional period. Additional information gained through various sources can reduce uncertainties and support previous predictive modeling. Monitoring is not to be used as a substitute for development of an adequate database, but rather to support the previous determination of adequacy considering uncertainty. When there is uncertainty associated with the waste disposal system, monitoring can maintain confidence in the performance demonstration. However, if the uncertainties are too large and associated with significant processes, the performance objectives will not be met and the facilities remain in the postclosure phase. In this case, a disposal site would not be allowed to enter the active institutional control period. The institutional control period should not be an opportunity to do fundamental characterization, but a time to support the compliance decision and build confidence.

Post-Institutional Control: Performance Assessment. NRC does not assume institutional controls, environmental monitoring, or maintenance will continue indefinitely into the long-term future, but does assume that degradation processes do continue. NRC staff typically derives reasonable assurance that the performance objectives will be met in the future (up to 10,000 years) through the use of performance assessment. Typically, a LLW disposal site relies on a number of engineered features (e.g., grout, concrete vaults, specialized covers) to close their facilities. It may be several decades or centuries before any radioactive materials are expected to be released from the disposal facility, and thereafter be detected. Performance assessment establishes an acceptable methodology to demonstrate compliance with the performance objectives through the use of systematic risk analyses and numerical modeling. However, for periods of performance over hundreds or thousands of years, numerical models cannot be validated in a traditional sense. Assessing compliance with the Part 61, Subpart C, is expected to include adequate support of the model necessary to maintain confidence in the results of performance assessment. Model support and confidence building are important in demonstrating that, even with the inherent uncertainties, radioactive waste disposal will not endanger public health and safety. Model support should use multiple sources and various types of information such as the results of environmental monitoring, tests, information, experience with similar systems, component process models, natural and anthropogenic analogs, or independent peer reviews.

Long-Term Institutional Control: Radioactive Mill Tailings Disposal Sites. Appendix A of Subpart C, 10 CFR Part 40, include detailed regulations pertaining to the siting and design of tailings impoundments, disposal of tailings or wastes, decommissioning of land and structures, groundwater protection standards, testing of the radon emission rate from the impoundment cover, monitoring programs, airborne effluent and offsite exposure limits, inspection of retention systems, financial surety requirements for decommissioning and long-term surveillance and control of the tailings impoundment, and eventual government ownership of the tailings site under an NRC general license. Unlike land disposal sites for LLW, institutional control does not end for radioactive mill tailings sites since there is no termination of the general license for custody and long-term care of uranium and thorium byproduct material disposal sites. The custodian may perform environmental monitoring, physical surveillance of the site, and minor custodial activities. However, continued satisfactory disposal performance should not rely on active maintenance to preserve the site. 10 CFR Part 40, Appendix A, Criterion 4 provides guidelines on siting and designing the tailings disposal sites. The slopes of the surface cover and the embankment must be relatively flat to minimize erosion potential and to provide conservative factors of safety assuring long-term stability. A full self-sustaining vegetative cover must be established. Where a full vegetative cover is not likely to be self-sustaining due to climatic or other conditions, a final rock cover must be employed to reduce wind and water erosion to negligible levels. It must be designed to avoid displacement of rock particles by human and animal traffic or by natural process and to preclude undercutting and piping. 10 CFR Part 40, Appendix A, Criterion 6 states that the covers and final design to close the waste disposal area shall provide reasonable assurance of radiological hazards control for 1000 years, to the extent reasonably achievable, and in any case, for at least 200 years. The surface cover must be designed to limit radon emissions into the atmosphere. 10 CFR Part 40, Appendix A, Criterion 5B states that contaminants entering the groundwater from a licensed site must not exceed a specified concentration limits in the uppermost aquifer beyond the point of compliance during the compliance period. The NRC shall identify hazardous constituents, establish concentration limits, set the compliance period, and may adjust the point of compliance if needed in accord with developed data and site information, when the detection monitoring established under Criterion 7A indicates leakage of hazardous constituents from the disposal area. 10 CFR Part 40, Appendix A, Criterion 7A establishes a detection monitoring program that will detect leakage of hazardous constituents from the disposal area so that the need to set groundwater protection standards is monitored, and secondly, to generate data and information needed for the Commission to establish the standards under Criterion 5B. 10 CFR Part 40, Appendix A, Criterion 12 states that annual site inspections must be conducted by the government agency responsible for long-term care of the disposal site to confirm its integrity and to determine any need for maintenance and/or monitoring. In summary, compliance with 10 CFR Part 40 during the lifespan of the general license (in perpetuity) would rely on short-term and long-term monitoring and modeling at the approval stage.

APPROACHES TO MONITORING ENGINEERED SURFACE BARRIER PERFORMANCE AND DEGRADATION

Monitoring is considered important to obtain confidence that barrier components are performing as intended and is an important tool in detecting early release of contaminants in the environment. Past practices have relied on traditional environmental monitoring, particularly in the saturated zone, which emphasized detection of contaminants that have already been released by the waste disposal system. Advancement in technology and understanding, however, may allow the disposal site owner an opportunity to detect potential problems and potential releases before they happen. Recently, monitoring to detect problems within barriers has gained increasing interest. Monitoring systems developed in conjunction with conceptual models of the waste-isolating disposal system have not been used as frequently as the standard groundwater monitoring wells. Monitoring systems are often designed for the sole purpose of meeting statutory requirements and seldom to directly monitor barrier performance. However, since it may take several decades or centuries before contaminants are actually released and detected in the environment, any early indications of barrier degradation before radionuclides are released into the groundwater builds confidence that uncertainties related to the EBS would be manageable. In lieu of increased understanding of potential shortcomings with engineered surface barriers, monitoring of engineered systems is being recognized as a powerful tool that has the potential to yield valuable data. For example, clay surface covers and clay liners are now known not to be as effective in isolating waste from water as originally believed. Cracking due to shrinking and swelling, freezing and thawing, root penetration, and differential settlement have all been found to reduce performance. A monitoring design incorporating such knowledge and specifically aimed at detecting shortcomings in a defective layer would give advance warning of potential releases far earlier than the traditional environmental monitoring program. A well-conceived monitoring system for engineered surface barriers would provide information to assess barrier performance and level of degradation.

A water budget for covers can be used to understand how a cover is expected to perform. Components of the water budget are precipitation (usually the sole input), surface runoff, lateral internal drainage, water storage change, ET, and downward percolation exiting the cover. NRC staff looks for risk-informed approaches which tie the support for the effectiveness of the surface cover with the risk that the wasteform poses. A water budget showing ET as the dominant process for removing water from a surface cover would require a monitoring plan focused on obtaining information on water storage data properties, development of preferred pathways, the health, abundance, and type of vegetation at the surface, and potential disruptive climate shifts. A water budget demonstrating geomembrane performance as a significant factor preventing deeper percolation would indicate the need of a monitoring program concentrated on collecting data of physical and chemical property changes of the geomembrane.

Methods and instruments for measuring features and processes associated with covers have expanded. These can include lysimeters, tensiometers, gas monitoring probes, neutron-moisture probe, nuclear magnetic resonance, numerous geophysical methods, and remote sensing [7]. Pan lysimeters can be used for obtaining direct measurements of infiltration over relatively large areas, i.e., larger than 10 m by 10 m [8]. Heterogeneity in hydraulic and vegetative properties and preferred flow through cracks and other secondary features require a large area to be measured in order to capture these features and their effects on the infiltration rate in the upper cover. Pan lysimeters provide a direct measurement of infiltration while water-content sensors have been used to monitor the temporal variations of water stored in the soils layer. This would be extremely important for maintaining performance in ET covers as information could be collected on potential wetting fronts near the base of the soil layer or conditions too dry to support the vegetation needed to produce the necessary ET [8]. Various instruments and sensors could be placed in covers during construction such as wire grids to detect leaks or temperature to better estimate the service environment of significant barrier components [7]. In-situ sensors could detect physical, chemical, and biological processes such as heat, pressure, moisture, gas signature, and organic and inorganic material. Electrical resistivity, electromagnetic surveys, tomographic imaging, and seismic velocity surveys have the potential to detect changes in physical properties of barrier components.

Airborne and satellite-based remote monitoring techniques are able to efficiently monitor particular aspects of the engineered surface covers. For example, remote sensing may detect vegetative change that can affect ET. This change in the ET will change the water budget of the cover so that the rate of water percolating through to the waste material will change. Sensor development has rapidly advanced so that sensors are becoming not only quicker and more reliable, but smaller, more automatic, wireless, and more sophisticated and powerful while at the same time lasting longer. Changes in vegetation, soil water content and temperature are obtainable through multispectral imaging. Ground penetrating radar, LIDAR, and other remote sensing techniques may detect stabilization problems at the very early stages due to its high resolution output [7]. Automated sensors may someday be placed throughout the different components of the cover to monitor those features and process demonstrated to be significant.

APPROACHES TO ASSESSING LONG-TERM ENGINEERED SURFACE BARRIER PERFORMANCE AND DEGRADATION

Model Support. Engineered surface barriers can be significant barriers and may help provide reasonable assurance that statutory requirements will be met. Numerical models for radioactive waste disposal cannot be validated in a traditional sense if the performance period extends over hundreds or thousands of years. Since performance assessment results are only as good as the input and support provided for the models, model support and confidence building are important in demonstrating that reliance on model results with inherent uncertainties will not endanger public health and safety. Together, numerical modeling and model support can be used to build confidence in engineered surface barriers that take credit for long-term performance. Codes used to model cover performance and degradation should be appropriately used in applications for which they were designed and account for known important processes. For example, some basic code requirements for modeling processes with ET covers would include the ability to solve Richards' equation, to simulate soil-atmosphere interactions, and to integrate climatic data into the solution. Technical bases and model support are needed to demonstrate the durability and longevity of a surface cover for its intended purpose, as well as build confidence in its long-term performance despite uncertainties associated with assumptions made and input parameter ranges. Processes that significantly contribute to diverting water away from the wasteform and mitigating radionuclide release should be supported at a level commensurate with the risk-significance of the assumed level of performance taken credit for in the performance assessment. Model support can use multiple types and sources of information and may include site specific tests, information on previous experience with similar systems, process models of barrier component performance, natural and anthropogenic analogs, independent peer review (expert elicitation), or plans to develop additional model support for engineered surface barrier system performance. Adequate technical bases are needed so that the modeling is appropriately accounting for uncertainties or is sufficiently conservative based on the model support. Technical bases and model support can help provide the knowledge needed to understand interrelationships between processes, e.g., between the extent of cover erosion and the infiltration rates into the cover, and provide reasonable assurance the coupled processes are adequately understood.

Model support could include results and conclusions of studies that lessen uncertainties associated with long-term performance of the erosion and infiltration. Model support requires that processes inside and on the cover that minimize water flow to the waste be known so as to understand the workings of the engineered cover system. Before numerical modeling, a conceptual model of the water budget and water circulation in and on the engineered cover at various stages during the compliance period would be critical, as would the capacity of the engineered cover system to cope with a large amount of rainfall. Experiments or field studies on engineered surface covers with similar composition and comparable vegetation in the expected climate could provide information on infiltration. For example, literature reviews may obtain data on the root depth and penetration strength of trees or other expected flora under different settings and in different strata. Additional supporting evidence might include the results of field studies on surface covers having undergone some form of accelerated degradation. Various components or layers of an engineered surface cover may be represented in nature as a natural analog. Natural analogs can provide the basis for designing engineered surface barriers that mimic favorable natural settings and provide insights into the response of the barrier to future conditions and the effects on barrier performance.

Modeling. Assessment of the future engineered surface barrier performance may assume a period of monitoring and maintenance, and institutional control lasting in perpetuity as stated in 10 CFR Part 40.28, or not longer than one hundred years as intended in 10 CFR Part 61.59. If there is a post-institutional control period, active maintenance and monitoring stops and the surface cover is assumed to be under the influence of natural processes and events. Three phases can be considered to assess long-term engineered surface barrier performance and degradation [10]: 1) performance of the as-built cover, 2) degradation processes that are undetected and not remediated during the institutional-control period (e.g., clogging of geosynthetic drainage layer), and performance of the as-is cover, and 3) degradation processes after the institutional control period and performance of the as-is cover. Modeling as-built engineered surface barrier performance would require input values from various areas. The type of cover would need to be known including physical and hydraulic properties of each layer. Sensitivity analyses would later identify significant barrier components that may require more detailed input. Hydraulic properties would include saturated hydraulic conductivity, van Genuchten parameters, and soil water characteristics curves. In addition, field-measured onsite meteorological data (i.e., precipitation and temperature) would be needed, as would information on plant phenology and field-measures of leaf area index and density/depth distribution. Components of the water budget would be used as input parameters as well as to define initial boundary conditions. Uncertainty of material properties and construction defects should be evaluated, especially for synthetic materials and their installation. Studies have shown geomembranes with installation defects [11] and geosynthetic clay liners installed during unsuitable weather conditions. Modeling engineered surface barrier performance over ten's and hundred's of years would include uncertainties associated with potentially undetected and unmitigated degradation. Compacted soils and other resistive barriers have been shown to change their physical and hydraulic properties to better match those properties of the surrounding materials [12] [9]. Modeling long-term cover performance of hundred's and thousand's of years needs additional information on changes to local topography and cover geometry and changes to cover material properties, climate, and ecology (e.g., flora).

The 2007 Walter and Dubreuilh report [10] reviewed a considerable number of codes related to surface cover performance and degradation. Codes examined consisted of hydrologic codes for evaluating deeper percolation, generalized and localized erosion codes for evaluating long-term stability of the cover, and additional codes for evaluating various processes of covers (e.g., ecological evolution). Hydrologic or water percolation codes were evaluated based on their ability to simulate or represent total water balance, ponding, frozen snow and snow melt, vegetation types and coverage, lateral diversion and seepage of geomembranes, soil water movement using Richards' equation, spatial variability in the cover properties, and percolation output to other codes. Erosion and mass wasting codes were evaluated on physics-based wind and water processes, database of soil properties, representation of hydrologic and vegetative influence, topographic changes, and engineered controls.

SUMMARY

Engineered surface barriers can be significant barriers and may help provide reasonable assurance that statutory requirements will be met. Engineered surface barriers for near-surface disposal of radioactive waste are to limit release of radionuclides from the wasteform to the environment and can be intended to discourage human intrusion into the waste. These types of barriers are basically designed to limit contact of infiltrating rainwater with the waste, but sometimes designed to limit release of gaseous radionuclides, such as, radon. In addition, most are designed to reduce and slow the erosion rate of the surface barrier itself and the underlying disposal site.

The long-term performance of an engineered surface barrier depends on the degradation processes on, and within, the barrier that will modify the barrier from its "as built" performance metrics to its longer-term performance level. For radioactive wastes disposal sites, performance of the barrier can be physically monitored with on-site instrumentation or by remote sensing. Regulations for disposal of LLW specify that active institutional controls can only be relied on during the design and building stage and maintained for 100 years after facility closure. During a period of active institutional controls, monitoring and maintenance can be carried out in addition to predictive modeling. Monitoring can be used to verify the correctness of assumptions made and the accuracy of the results of numerical modeling, thereby reducing uncertainty. Monitoring would allow instruments to be set up and data to be collected at various sites and through various means. Unlike land disposal sites for LLW, institutional control does not end for radioactive mill tailings sites since there is no termination of the general license for custody and long-term care of uranium and thorium byproduct material disposal sites. The custodian may perform environmental monitoring, physical surveillance of the site, and minor custodial activities. However, continued satisfactory disposal performance should not rely on active maintenance to preserve the site.

Under 10 CFR 61.59 and 10 CFR 61.7, the LLW disposal site, in addition to the surface barrier, is assumed to be unattended and physical, chemical, and biological processes are allowed to change the hydraulic properties of the original barrier components unimpeded by anthropogenic intervention after the 100-year period of active institutional controls has ended. The post-institutional-control period assumes the surface barrier is no longer being monitored nor maintained. Instead, numerical modeling and model support can be used to build confidence in those components of the barrier which provide for a long-term performance that protects the public and the environment. Adequate technical bases are needed so that the modeling is appropriately accounting for uncertainties or is sufficiently conservative based on the model support. For periods of performance over hundreds or thousands of years, numerical models simulating radioactive waste disposal sites cannot be validated in a traditional sense. For this reason, model support and confidence building are important in demonstrating that even with the inherent uncertainties, the disposal action will not endanger public health and safety. Model support should use multiple sources and various types of information such as the results of site-specific tests, information on previous experience with similar systems, process models of barrier component performance, natural and anthropogenic analogs, or independent peer review (expert elicitation). For example, model support could include results from experiments or field studies on engineered surface covers with similar composition and comparable vegetation to the barrier being reviewed. In addition, natural analogs could provide the basis for designing engineered surface barriers that mimic favorable natural settings and provide insights into the response of the barrier to future environmental conditions and the effects on barrier performance.

Three phases are considered to assess long-term engineered surface barrier performance and degradation: 1) performance of the as-built cover, 2) degradation processes that are undetected and not remediated during the institutional-control period (e.g., clogging of geosynthetic drainage layer), and performance of the as-is cover, and 3) degradation processes after the institutional control period and performance of the as-is cover. The application of hydrologic codes should be based on the codes ability to simulate or represent total water balance, ponding, frozen snow and snow melt, vegetation types and coverage, lateral diversion and seepage of geomembranes, soil water movement using Richards' equation, spatial variability in the cover properties, and percolation output to other codes. Erosion and mass wasting codes evaluated based on their ability to simulate physics-based wind and water processes, hydrologic and vegetative influence, topographic changes, engineered controls, and on the code's database of soil properties.

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