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Near-Surface Engineered Environmental Barrier Integrity

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Abstract– *The INEEL Environmental Systems Research and Analysis (ESRA) program has launched a new R&D project on Near-Surface Engineered Environmental Barrier Integrity to increase knowledge and capabilities for using engineering and ecological components to improve the integrity of near-surface barriers used to confine contaminants from the public and the environment. The knowledge gained and the capabilities built will help verify the adequacy of past remedial decisions and enable improved solutions for future cleanup decisions. The research is planned to (a) improve the knowledge of degradation mechanisms (weathering, biological, geological, chemical, radiological, and catastrophic) in times shorter than service life, (b) improve modeling of barrier degradation dynamics, (c) develop sensor systems to identify degradation prior to failure, and (d) provide a better basis for developing and testing of new barrier systems to increase reliability and reduce the risk of failure. Our project combines selected exploratory studies (benchtop and field scale), coupled effects accelerated aging testing at the meso-scale, testing of new monitoring concepts, and modeling of dynamic systems. The performance of evapo-transpiration, capillary, and grout-based barriers will be examined.*

I. INTRODUCTION

Removal and subsequent treatment of wastes at many Department of Energy (DOE) sites is technically difficult, expensive, and hazardous, exposing workers and the environment to chemical and radiological contamination. Alternative approaches that incorporate "robust containment and stabilization technologies will be a key factor in the success of DOE's strategy to manage subsurface contamination… DOE's management commitment potentially extends for many thousands of years."[1]

The National Research Council (NRC) conducted a review of barrier technologies for interim and long-term containment of contaminants[2] in 1997 and concluded that "barriers such as surface caps and subsurface vertical and horizontal barriers will be needed as important components of remediation strategies." Identified issues included the following:

- Existing barrier performance data are inadequate; we should learn more from how existing barriers are performing.
- Knowledge to predict lifetimes of selected barrier materials and resultant barrier systems is inadequate.
- The full range of ecological and engineering factors needs to be considered to predict and enhance long-term performance.

The NRC further reviewed the long-term institutional management of DOE legacy waste sites in 2000[3] and cited the need for a much broader-based, more systematic approach for contaminant reduction, isolation, and stewardship. The report stated that "the objective is to achieve a barrier system that is as robust as reasonably achievable," given the current limitations. However, they went on to state that "the most important consideration in the use of engineered barriers and waste stabilization approaches in waste management is the fact that there is limited experience with most, if not all, of the systems being considered." They concluded that improvements are needed to enhance scientific and engineering understanding of barrier materials and designs.

One approach to assessing long-term barrier performance is to use experience gained at field sites. With few exceptions (applied water simulating precipitation), effects are only manifest at the same rate as a barrier in actual service. This approach provides limited understanding of a barrier's performance at a different site, under different climatic conditions, or with a modified design at a similar site.

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Another approach is to conduct small-scale, short-duration, single-effect tests such as ultraviolet degradation of synthetic materials, freeze-thaw cycling on concrete, etc. The long-term aggregate effect of these processes is typically modeled by linearly combining the effects of the individual processes. Such an approach does not address the dynamically coupled effects of these processes that can affect long-term barrier performance. This limitation is increasingly important, as barriers become more complex with multiple layers and functions.

To meet these needs, the INEEL is working to improve understanding in the linkages between how classical engineering can be merged with scientific principles from areas such as ecology, chemistry, materials, sensors, and hydrology. This focus will help us improve how barriers can be designed and managed, using an ecological engineering approach[4] to better understand and evaluate possible long-term changes in barrier performance. This work will focus on tasks to improve understanding of what constitutes failure and improve experimental and modeling approaches that can increase capabilities to address the inevitable uncertainties inherent in current barrier performance measurement.

This project combines selected exploratory studies (benchtop and field scale), coupled effects testing, accelerated aging testing, and modeling of dynamic systems. Testing of coupled effects and accelerated aging effects are generally done at intermediate ("meso") scales where multiple effects can be simulated, preferably at rates much faster than field service. These efforts, combined with other past and current work, will increase understanding of how engineered environmental barriers will evolve over time. The project complements other programs' emphasis on field and benchtop studies by emphasizing testing at intermediate scales —the "meso-scale" —where coupling of effects can be observed. We provide a capillary barrier example below to illustrate how processes must be evaluated at appropriate scales (benchtop, meso, field).

This paper summarizes our understanding of the situation and our initial path forward. We welcome suggestions and possibilities for collaboration.

This project is part of the ESRA program, which provides core-capability and problem-driven research leading to solutions to the DOE's cleanup and stewardship mission. The research targets science and technology needs and gaps and serves as a bridge between basic research programs and cleanup operations.

II. BACKGROUND

A wealth of information on cap and barrier design exists. However, performance data are less available and usually in the form of knowledge derived from a combination of the following:

- Field data from existing barriers regarding effects of stressors since construction (at most a few decades of experience),
- Field studies of new surface cap designs,[5]
- Small-scale laboratory data on individual effects,
- Performance assessments for the deep geological waste disposal projects, which are isolated from the near-surface environmental changes that drive many of the degradation mechanisms critical to near-surface barriers.

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.) Figure 1 illustrates the current methodology – design a barrier for some fixed lifetime, reach agreement with regulators to determine performance requirements, and monitor for failure of the barrier (rather than monitor the internal performance of the barrier prior to failure).

A common approach to evaluating contaminant containment is to monitor groundwater. Finding increased contamination in groundwater means that the barrier has already failed – and failed so long ago that contamination has migrated to groundwater, thereby expanding the volume to be remediated. The effectiveness of groundwater monitoring is especially weak (and relatively costly) when there is a thick

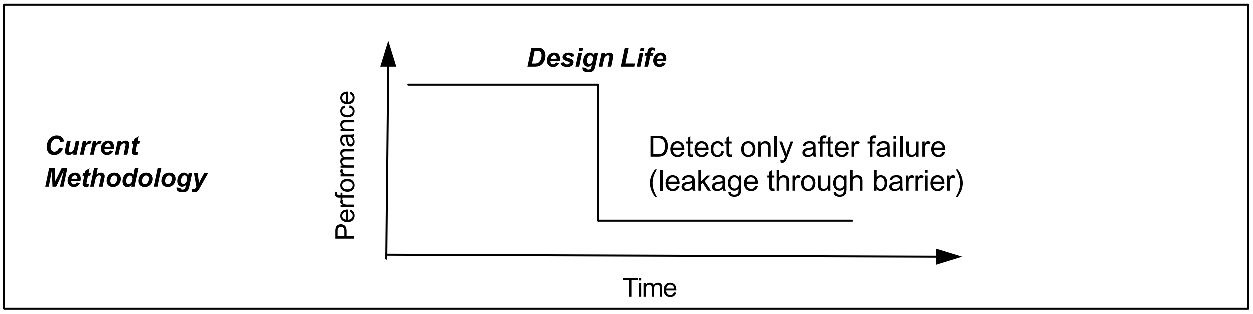

Figure 1. Current methodology for designing and regulating near-surface barriers

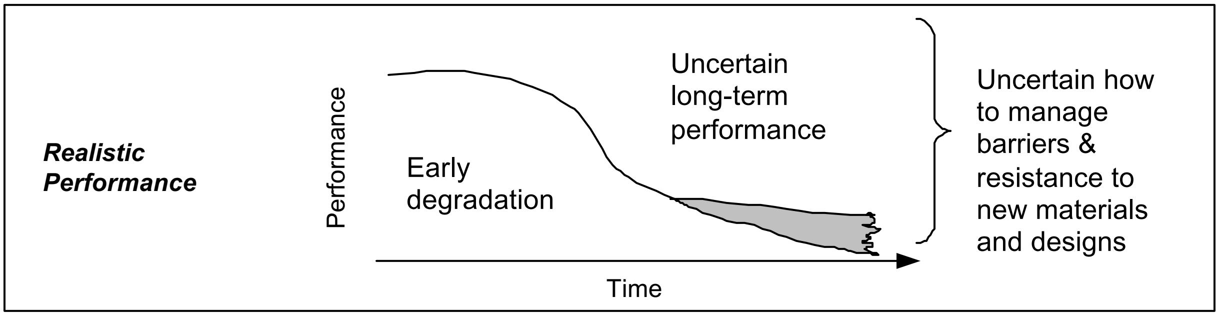

Figure 2. More realistic expectation of how barriers evolve; uncertainties grow with time

unsaturated (vadose) zone between barrier and groundwater. In arid and semi-arid systems, this zone can be thick (hence long transport times) and can have localized preferential flow paths that may be difficult to detect by a finite set of monitoring wells.

New cap and barrier systems include the use of a leak collection and detection layer incorporated under barriers to monitor performance. (This is generally impractical if the barrier is installed above buried waste without moving the waste.) This strategy reduces the time between failure and detection, but the barrier has still failed before detection.

Current knowledge[1,2] is helping us to understand that existing barrier failures generally appear to demonstrate slow degradation rather than catastrophic failure. Thus, understanding of barrier degradation dynamics can provide a basis for monitoring and managing barriers before failure.

The real performance of barriers rarely follows the simple step-function pattern in Figure 1. Barrier performance generally degrades gradually as illustrated in Figure 2. The short-term performance of barriers (i.e., less than 10 years) is fairly well understood and is currently the focus of numerous studies.[1,2,3,5] We hypothesize that the uncertainty of barrier performance is embedded in slowly developing coupled processes. These will change the barrier structure and performance. Indeed, the relative importance of processes likely changes as the barrier itself evolves. Identification of these processes and the coupled interaction of these processes are not fully understood. Furthermore, the quantitative analysis of the interaction between these processes and their effects has not been performed.

DOE and the Nation are facing many tough challenges in assuring that contaminated materials are isolated and that risks to humans and the environment are as low as achievable. To help address these challenges the INEEL has assembled a multi-disciplinary team that will be seeking to ally with other Federal (e.g., EPA, NRC, DoD, DOI) and State agencies, universities, other National labs, and the international community to bring together current ideas and minimize duplication. One of the challenges facing DOE is to conduct R&D in a manner that addresses cleanup program needs.

III. APPROACH

A holistic approach will be used to help evaluate the performance of barriers for hazardous waste management. This approach will evaluate individual effects upon barriers, how individual effects couple, and the relative importance of effects – as a function of time. By considering coupled interactions we hope to significantly advance the understanding of barrier performance and build important new R&D capabilities. The coupled approach is illustrated in Figure 3.

The key questions to be addressed include:

- What are the physical, chemical, and biological

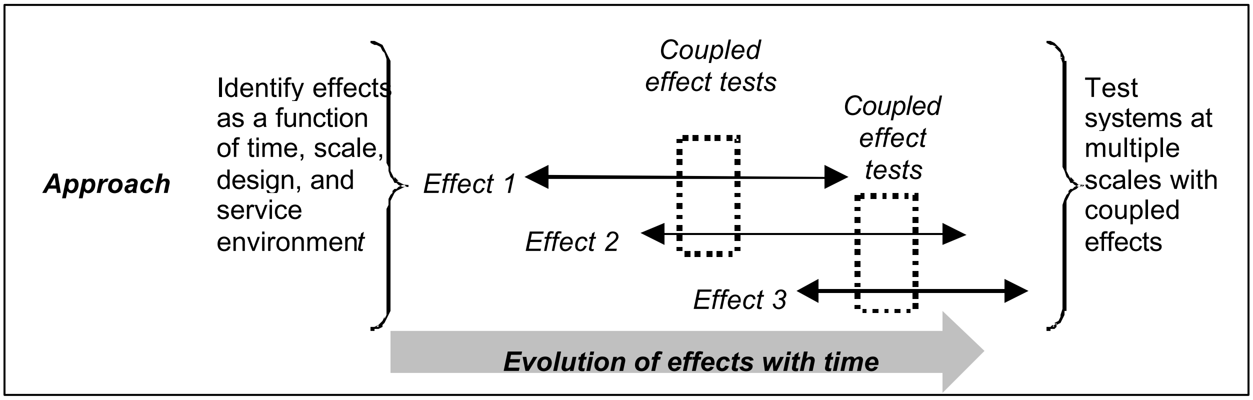

Figure 3. Approach to studying how barriers degrade with time

processes that can compromise barriers (surface caps, liners, containerized waste sites, grouted/entombed structures)?
- On what physical scales and time periods are these processes important?
- What is the contribution of each process to the total impact at different times?
- How might combinations of these processes magnify the impact to the barriers?
- How can the effects of multiple processes be examined within a laboratory setting to develop their fundamental relationships?
- What environmental variables can be monitored to detect these processes in the field?
- How can processes that degrade barriers be minimized, and processes that enhance barrier performance be encouraged, in existing and new barriers?

By addressing these questions we hope to improve:

- understanding of the technical basis for managing barriers as they degrade,
- predictive capabilities by incorporating coupled processes in models, and
- knowledge needed to create and test new materials and designs.

The project has five main components: a) understanding the processes that affect the cap and barrier integrity, b) examining the acceleration and coupling of processes affecting barrier performance, c) sensing barrier changes, d) modeling barrier degradation dynamics, and e) integration.

III.A. Understanding Processes

The purpose of this component is to develop a better understanding of the impacts of various forces on the integrity of caps and barriers (figure 4). Our initial tasks focus on biological phenomena, especially in capillary barriers. Better understanding at normal exposure rates is necessary before knowing the importance of the effects and whether it is needed and possible to accelerate effects.

Soil cores will be examined to study relationships between microbial growth and hydrologic properties within capillary barriers systems. This effort will evaluate two conceptual models of microbial distribution. The first model assumes that the microbes are uniformly distributed throughout the surface layer of the capillary barrier. The second conceptual model hypothesizes that the fine/coarse media interface will exhibit enhanced growth. Such fundamental understanding should clarify whether microbial effects are positive (increase resistance to water infiltration such as by plugging) or negative (decrease resistance by changing surface tension).

A closely related task expands the capability of nuclear magnetic resonance (NMR) imaging at the

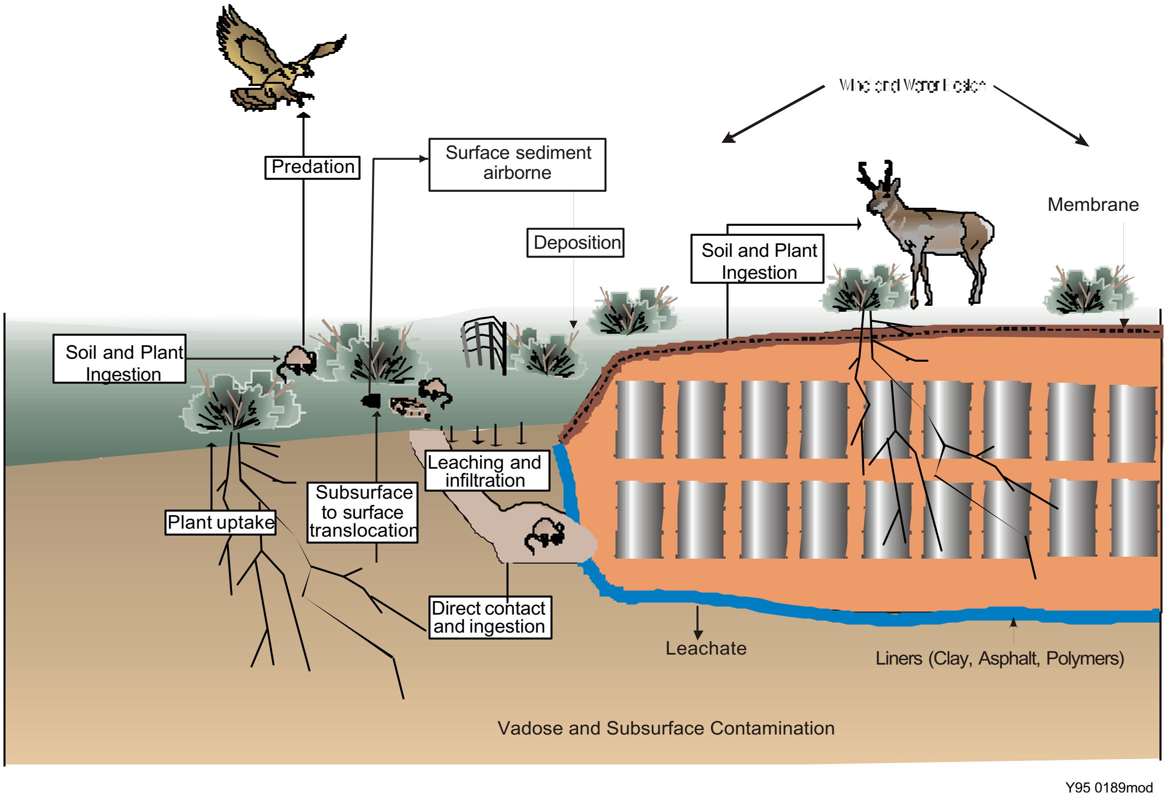

Figure 4. Conceptual model of interactions affecting barrier degradation dynamics

micrometer and millimeter scale to improve understanding of how microbiological growth in subsurface material influences how water moves through complex flow paths that approach those anticipated to develop in caps over centuries. The imaging technique will be evaluated for its potential to relate the impact of bacterial accumulation in preferential flow paths on water flow properties such as dispersion coefficient, local mean velocity and propagators relevant to spatial and temporal correlations.

When soil-based caps are constructed, the material is generally homogeneous (in each layer). Biological processes (e.g. soil formation) are expected to produce gradients in the new cap. The formation of such gradients provide clues to how biological processes are affecting the capillary barriers or evapo-transpiration (ET) properties of the cap. To improve understanding of this effect, we will evaluate the stratification of carbon (C) and potassium (P) concentrations in soil cores at the Protective Cap Barrier Experiment site at the INEEL. The comparison of the vertical stratification of C and P in the surface cap to surrounding native communities, will provide information to help better predict subsequent changes in vegetation and microbial communities growing and their influence on caps performance.

III.B. Acceleration and Coupling of Processes

This component explores acceleration and coupling of processes at benchtop and meso-scales and will have several tasks that will be worked together to ensure consistent approaches to accelerated aging.

Much of this work will be conducted at the existing INEEL Engineered Barrier Test Facility (EBTF). This facility has ten cells, each approximately 3 m x 3 m x 3 m, about 28 m^3. At this location we will conduct larger-size meso-scale experiments for our project. The initial tasks will study the effects of accelerated precipitation on coupled process and interaction among the following; a) cap performance, b) vegetation, c) soil microbiology, and d) small animal burrowing.

The next smaller scale is ~1 m^3. Compared to EBTF, we lose the ability to have colonies of animals and therefore cannot test animal intrusion. However, we gain ability to manipulate the environment to evaluate accelerated effects on barriers. We will build upon the data for capillary barriers at the field scale[5] and EBTF scale. However, we wish to use this meso-scale to explore behavior in long-term data and help provide data to support analytical predictions. Specific mechanisms to be evaluated include seismic/subsidence activity, freeze-thaw, and water infiltration at meso-scale.

Another acceleration of process study will evaluate two specific engineered materials of direct relevance to INEEL cleanup needs – geosynthetic clay liners (GCLs) and grout. These will be studied first at the benchtop scale, and as appropriate, we will proceed to larger-scale, multiple-effects. Because the INEEL has a cold, semi-arid climate, freeze/thaw cycles are particularly important.

The GCLs will be tested to develop a better understanding of the long-term physical and hydraulic performance of GCLs as affected by freeze thaw cycling. Testing will be performed at both bench and meso-scales to determine the performance and hydraulic integrity of various GCLs when subjected to long-term freeze-thaw cycling (with varying moisture conditions).

Grouts currently being considered to meet INEEL cleanup needs will be subjected to bench-scale testing to investigate the degradation of grouts and surrogate waste materials as a result of thermal cycling both with and without water present.

III.C. Sensing Barrier Changes

This area focuses on developing the science and engineering to fill technical gaps in the capabilities to sense changes in the integrity of barrier systems. These tests will be conducted at the most appropriate scale – those focusing on animal and plant intrusion are incorporated into EBTF tests; those focusing on proof-of-concept for cementitious materials are being conducted at the benchtop scale.

At the meso-scale (EBTF), we will design and test fast and cost-effective methods using soil tracers incorporated into the cap design to determine the existence of biointrusion by burrowing mammal and the level of damage inflicted upon the cap as a consequence of their activity. This will also identify potential tracers that could identify the existence of plant root intrusion into the cap.

Also at EBTF, we will evaluate the use of non-intrusive geophysical techniques to identify biointrusion (plants or animals) within caps and barriers. The effort will use an automated imaging system and test different sensors including ground penetrating radar and electromagnetic induction. This effort will incorporate lapse time 3D or 4D geophysics. The underlying notion of 4D geophysics is simply to collect multiple identical data sets, remove the complexity of the background, and produce time-dependent changes in physical properties.

Benchtop testing will provide the proof-of-concept to determine if electrochemical impedance spectroscopy can be used to identify failure modes in cementitious caps and barriers. The task will help provide the capabilities necessary for complete interpretation of the impedance spectra of cementitious systems. These data should be used to describe the various physico-chemical processes presumed to be important to system performance. The work will also identify the application of the techniques to other non-cementitious cap and barrier systems.

III.D. Modeling of Barrier Degradation Dynamics

Our approach to modeling involves different scales, but the different scales refer to the dimensionality and sophistication of the models, not physical size. The long-term multi-year objective of this effort to develop a suite of models that incorporates stressors and effects that assesses and predicts barrier risk as a function of time. The models need to be able to assess uncertainties in a probabilistic sense and provide insights to the value of information, e.g., by reducing the uncertainty in parameter X, we reduce the uncertainty in calculated risk by Y at a future time period Z. Often the nature and amount of uncertainty change with time as the barrier evolves and the relative importance of stressors/effects therefore changes. This will guide both R&D and operational management of barriers and complement and enhance existing risk/uncertainty analyses.[6]

We are exploring barrier degradation dynamics for ET caps, capillary barriers, and grouted systems. The first generation system dynamic models will not track 2- and 3- dimensional spatial changes but will help understand the dynamics of how barriers degrade and set the stage for more sophisticated modeling. It matters both how long a barrier will last and how fast the degradation may occur. Slow or graceful degradation is more likely to be detected and acted upon. It also spreads subsequent human exposure out in time, decreasing the maximum exposure to any individual. This is particularly helpful where health effects (and/or regulations) exhibit a threshold effect; exposures may be reduced below harmful thresholds. In contrast, a barrier system that exhibits little degradation followed by rapid degradation invites a false sense of security followed by the need for rapid action.

Many multi-dimensional hydrological barrier models exist. These are generally static in the sense that the structure and material properties are constant. However, to track barrier degradation, calculational tools need to reflect changing material properties and structure (adaptive meshes). Thus, we are exploring to add a soil/atmosphere boundary condition to a existing multi-dimensional unsaturated flow and transport model. This extended capability model will also be used to incorporate the physics of important processes identified by other research in the project.

III.E. Integration

The above tasks will be grounded using a logical approach compiled into a Technical Constraints Document (TCD) and risk/performance-based prioritization of the importance of different failure modes and effects. (These are focused on R&D gaps for long-term behavior and are not intended to duplicate existing efforts such cap design guidance.) As needs and opportunities are identified and updated through the development of the TCD and risk/performance prioritization, additional projects will be initiated, modified, or terminated. The TCD effort will focus on defining the technical issues that limit the application of barrier technologies. This includes clearly defining the state of the technology, the technical limitations and constraints, and recent and ongoing research. Gaps in technology and science will be identified and attempts will be made to prioritize them. This effort will build on existing efforts that have been performed by both EPA[7,8] and DOE.[5] Early in the process the EPA Office of Research and Development, the DOE Office of Environment, Safety, and Health, and the Nuclear Regulatory Commission will be consulted; first to understand their ongoing activities and assessment and second to gain their concurrence on the resulting priorities for presort of products. Emphasis will be given to assuring relevance to EM Operations needs at the INEEL and elsewhere in the DOE Complex.

One measure of the success of containment systems is the ability for them to maintain their integrity over long periods of time. Models validated with experimental data can be used to extrapolate natural processes. The limitations of existing methods (EPA, ASTM, and others) and technology will be identified along with any ongoing research. Risk assessment methodologies will be used to prioritize the gaps in knowledge with a focus on those specifically needed to support DOE. The need for additional tasks will be examined by first identifying risk-prioritized needs and then deriving needs. This could be brought together in the form of Bayesian Decision Networks or other value-of-information approaches that depend on risk. Our focus will be to emphasize activities that decrease the uncertainty in those parameters that dominate risk.

V. CAPILLARY BARRIER EXAMPLE

The capillary barrier example will be used to illustrate how this project plans to coordinate interactions between physical, chemical, and biological effects from both man and nature induced stresses. A capillary barrier depends on surface tension in a “fine” layer that overlays a “coarse” layer. This keeps water in the upper layer. The performance of such a barrier depends on maintaining a sharp gradient at the interface. Several phenomena may degrade capillary barrier performance as illustrated in Figure 5. (We recognize that other effects such as wind and water erosion are important but believe we can adequately leverage other programs to obtain data on these processes.) The current focus of this part of the project will be organized into three tasks (A to C). Additional tasks may be added as additional needs are identified or teaming arrangements with other agencies are established. Task A looks at plant/animal biointrusion

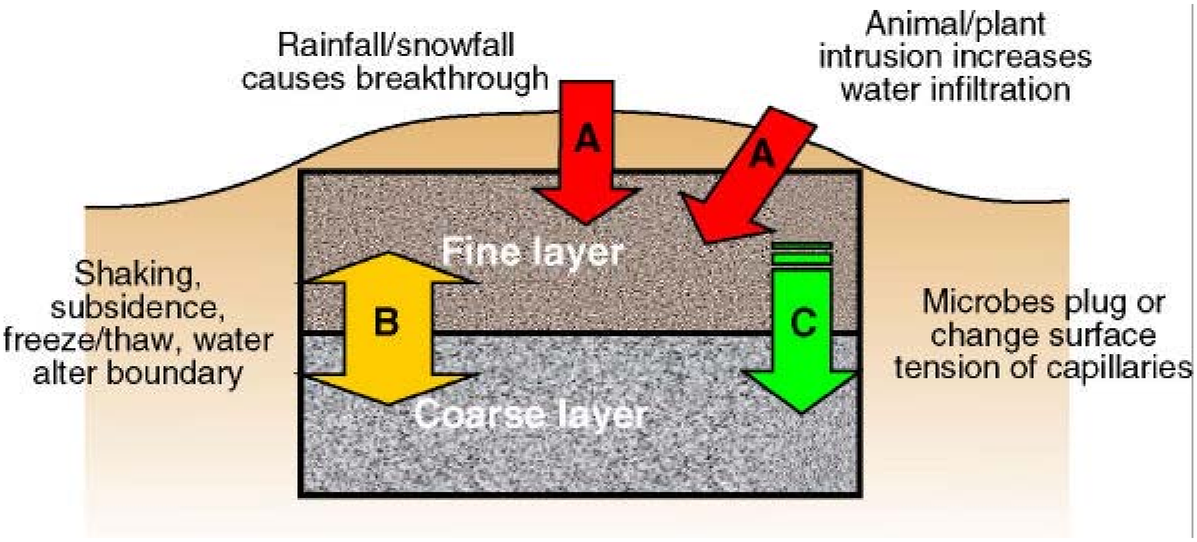

Figure 5. Major types of threats to capillary barriers requiring research (letters refer to tasks, see text)

and precipitation. Task B is investigations into mechanical and soil-forming changes to profiles, recognizing that the sharp fine/coarse boundary in capillary barriers produces the capillary effect itself [9,10]. Task C evaluates potential microbial effects that could plug capillaries or change the capillary surface tension, especially at the fine/coarse boundary. Because much is known from field studies about the processes explored in task C, it starts at the meso-scale (in this case, ~28 m^3 cells). Most of the processes in task B are difficult or impossible to test (in short times) in the field, so it also starts at the meso-scale (~1 m^3); however, microbial processes in task C are more exploratory. We plan to identify the phenomenon starting at the field scale and evaluate it at the benchtop scale, working toward later meso-scale tests as appropriate.

Together, we hope that these tasks (plus existing knowledge from other programs) allow us to mechanistically understand scenarios that start with a combination of the following effects increasing the amount of moisture getting into the coarse layer: excessive rainfall/snowmelt, animal/plant intrusion, mechanical effects, and microbial effects on capillaries. Normally, plants have no incentive to send roots into the coarse layer because it is dry; similarly, there should be little moisture to foster microbe communities. (This stimulates the question of how much moisture for how long a time?) If roots and microbial activity impact the capillary layers, the barrier could be subject to a cascading or propagating failure. The processes and the coupling of these processes must be understood to have confidence in the long-term robustness of capillary barriers.

VI. PATH FORWARD

The research and capabilities built in this project will benefit the DOE by improving confidence in existing barriers, providing improved technical basis for managing existing barriers, and improving the basis for designing and testing new barriers. DOE is quickly driving toward achieving as much cleanup as possible by 2012. At many DOE facilities, caps and barriers will play a major role in cleanup strategies and need to be designed with maximum integrity to minimize future risk.

Designers would like to increase use of engineered materials to improve performance or reduce overconservatism. Avoidance of engineered materials is a factor in using separate layers for each function. Sometimes that is optimal. But, we observe that surface caps are becoming thicker, partially as a result. When designing a new facility, it is often practical (but expensive) to dig deeper so that the cap top does not project too far above the surrounding terrain, thereby increasing risk of exposure to wind and water erosion (figure 6). This is generally impractical when applying a surface cap as part of closure of an existing contaminated site. Excess conservatism in addressing some factors can lead to increased vulnerability to other factors such as wind.

Specifically, the project incorporates research that will benefit near-term cleanup operations, e.g., the final design of the INEEL CERCLA Disposal Facility (ICDF), cleanup and closure at the INEEL Subsurface Disposal Area (SDA) and the Idaho Nuclear Technology and Engineering Center (INTEC). Each of these sites will eventually be capped. The ICDF cap will, and SDA and INTEC caps may, include evapo-transpiration and capillary barrier functions. (A surface cap is likely

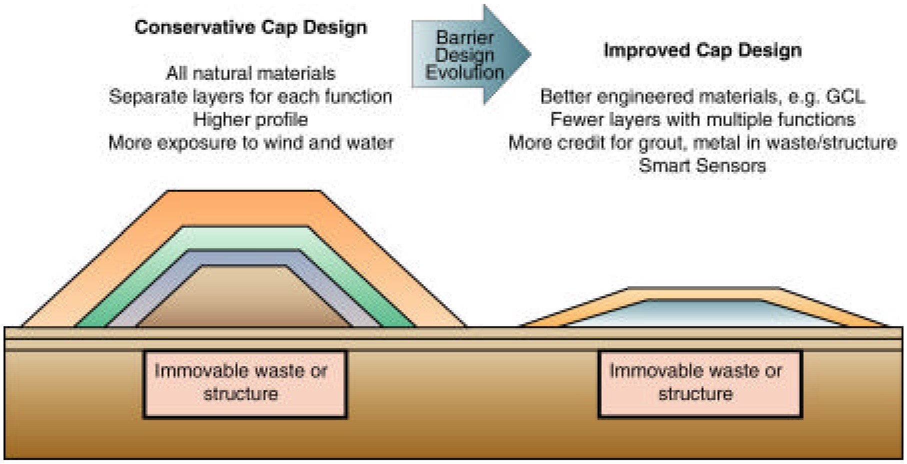

Figure 6. Improved confidence in long-term barrier performance will improve barrier design

needed even for portions of the SDA where buried waste will be removed; residual hazards will remain and water should not be allowed to infiltration into the rest of the SDA.) Portions of the SDA and INTEC will probably have grout and even concrete caps. For example, the Waste Calcining Facility at INTEC has been entombed (filled with grout) and capped with concrete.

Similar examples exist throughout the DOE Complex and private sector. Often the duration of hazards is long. This project will help provide the basis for managing and improving performance of these barriers.

VIII. ACKNOWLEDGMENTS

We stress that we are only spokespeople for the entire project and gratefully acknowledge the rest of the team.

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