

## TESTING, MODELING, AND MONITORING TO ENABLE SIMPLER, CHEAPER, LONGER-LIVED SURFACE CAPS

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### ABSTRACT

Society has and will continue to generate hazardous wastes whose risks must be managed. For exceptionally toxic, long-lived, and feared waste, the solution is deep burial, e.g., deep geological disposal at Yucca Mtn. For some waste, recycle or destruction/treatment is possible. The alternative for other wastes is storage at or near the ground level (in someone's back yard); most of these storage sites include a surface barrier (cap) to prevent downward water migration. Some of the hazards will persist indefinitely. As society and regulators have demanded additional proof that caps are robust against more threats and for longer time periods, the caps have become increasingly complex and expensive. As in other industries, increased complexity will eventually increase the difficulty in estimating performance, in monitoring system/component performance, and in repairing or upgrading barriers as risks are managed. An approach leading to simpler, less expensive, longer-lived, more manageable caps is needed.

Our project, which started in April 2002, aims to catalyze a **Barrier Improvement Cycle** (iterative learning and application) and thus enable **Remediation System Performance Management** (doing the right maintenance neither too early nor too late). The knowledge gained and the capabilities built will help verify the adequacy of past remedial decisions, improve barrier management, and enable improved solutions for future decisions. We believe it will be possible to develop simpler, longer-lived, less expensive caps that are easier to monitor, manage, and repair. The project is planned to: a) improve the knowledge of degradation mechanisms in times shorter than service life; b) improve modeling of barrier degradation dynamics; c) develop sensor systems to identify early degradation; and d) provide a better basis for developing and testing of new barrier systems.

This project combines selected exploratory studies (benchtop and field scale), coupled effects accelerated aging testing at the intermediate meso-scale, testing of new monitoring concepts, and modeling of dynamic systems. The emphasis on meso-scale (coupled) tests, accelerated effects testing, and dynamic modeling differentiates the project from other efforts, while simultaneously building on that body of knowledge. The performance of evapo-transpiration, capillary, and grout-based barriers is being examined. To date, the project can report new approaches to the problem, building new experimental and modeling capabilities, and a few preliminary results.

### INTRODUCTION

The Department of Energy (DOE) and the world face tough challenges in assuring that contaminated materials are isolated and that risks to humans and the environment are maintained legally acceptable, over long time periods. Removal and treatment of wastes at many contaminated sites is technically difficult, expensive, and hazardous, exposing workers and the environment to chemical and radiological contamination. "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 reviewed barrier technologies for 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 how existing barriers are performing;
- Knowledge to predict lifetimes of selected barrier materials and resultant barrier systems is inadequate; and
- All ecological and engineering factors need to be considered to predict and enhance long-term performance.

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The National Research Council then reviewed the long-term management of DOE legacy waste sites in 2000 (3) and cited the need for a much broader, 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.

More recently, the Nuclear Regulatory Commission staff has stated that longevity assumptions in current barrier performance assessments “*have no basis in the scientific and technical literature and experience.*” (4) The Environmental Protection Agency has studied barriers (5, 6) and concluded that data from barriers in service are often not adequate to know if the barrier is providing adequate protection; worse, rarely is there information on the **internal** condition of the barrier. RCRA and CERCLA caps are often designed for 30-year lifetimes, yet often the hazards will remain toxic. On what basis will cap lifetimes be extended or barriers be upgraded?

Numerous studies have been to improve the design of landfill caps. The DOE’s alternative landfill cover demonstration project at Sandia National Laboratory (Albuquerque, NM) provided data necessary on cost, construction, and performance to the public and regulatory agencies so that design engineers could have alternatives to conventional cover designs that cost less, but conform to regulations. S. Dwyer (7) was the technical lead on this activity in which six covers were evaluated for moisture flux rates over 4 years - Subtitle D RCRA Cover, Geosynthetic Clay Liner Cover, Subtitle C Compacted Clay Cover, Capillary Barrier Cover, Isotropic Barrier, and Evapotranspiration (ET) Cover. Flux rates over the four-year time period indicated that barrier performance did change with time. Long-term behavior is less understood. Our workscope is intended to complement the existing alternative cap studies. Meanwhile, DOE is designing caps with long lifetimes, such as the INEEL CERCLA Disposal Facility (ICDF) designed for 1000 years.(8) Caps are an integral part of DOE’s cleanup strategy.(9, 10)

To illustrate the challenge, consider the dominant barrier monitoring approach - sample groundwater. Finding groundwater contamination means that the barrier system has failed – and failed so long ago that contamination has migrated to groundwater, thereby expanding the volume to be remediated (at higher cost). The effectiveness of groundwater monitoring is weaker when there is a thick unsaturated (vadose) zone between barrier and groundwater. In more arid systems, this zone can be hundreds of meters 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. Newer cap and barrier systems include the use of a leak collection and detection layer under the barrier. (This is generally impractical if the barrier is installed above buried waste without moving the waste.) This reduces the time between system-level failure and detection, but the barrier system has still failed before detection. The trend in other industries is to detect degradation *prior to failure* to decrease lifecycle cost, extend lifetimes, increase performance, etc.

The development of barrier analytical models have focused on hydrologic models with limited evaluation of other mechanisms of contaminant transport and barrier changes over time. We have not found a peer-reviewed model that defines “failure” and associated processes and events controlling the aging of barrier systems, barrier components and materials, and resulting mobilization and transport of contaminants.

Most accelerated aging barrier work has focused on single components acted on by a single force, such as freezing/thawing, erosion. The testing standards also focused on single components; standards for accelerated aging of barrier systems were not identified. Most work has centered on answering single questions, e.g., what is the effect of freeze/thaw of geosynthetic clay liners? We did not find any coordinated laboratory or meso-scale accelerated tests focused on validating analytical models estimating the changing integrity of barriers.

To meet these needs, the INEEL is exploring linkages between classical engineering and scientific principles from areas such as ecology, chemistry, materials, sensors, and hydrology. This focus will help improve how barriers can be designed and managed, using an ecological engineering approach (11) to better understand and evaluate possible long-term changes in barrier performance. This work will improve understanding of what constitutes degradation, improve experimental capabilities of understanding of long-term degradation processes, establish a dynamic model of long-term degradation, and suggest improved ways to monitor degradation prior to system-level failure.

## WHAT WE NEED: REMEDIATION SYSTEM PERFORMANCE MANAGEMENT

Most environmental remediation problems are multi-faceted and require multi-component solutions. For example, closure of even simple landfills requires design and construction of caps, liners, leachate collection systems, and monitoring systems. Remediation of more complicated contaminated sites can also require design and construction of pump and treat systems, vapor vacuum extraction systems, and various *in situ* and *ex situ* treatment and disposal operations. The components of a remedial system must work together to protect human health and the environment, so analysis of remedial action effectiveness must focus on the system as a whole rather than a single component.

This distinction has many important implications. For example, systems that incorporate multiple barriers to water and contaminant movement (e.g., caps, grouts, liners, thick vadose zones, and long distances to receptors) can be designed to allow leakage through each barrier. As long as the system as a whole meets regulatory requirements, one or more of the barriers can fail without causing an unacceptable system response. Under a systems analysis focus, degradation modes for each component must be investigated to identify positive and negative feedback effects on neighboring components. Furthermore, experiments that are designed to test various components of a remedial system must consider physical processes that are controlled by neighboring components. For example, investigation of vapor phase contaminant release from a treated waste form might have to consider the transport enhancement effects of vapor vacuum extraction and the diffusion retardation effects of an extensive cap. Tests of a physical process in isolation may produce incomplete or erroneous data.

Fig. 1 illustrates the concept of remediation system performance management,(12) with the following elements:

- Determine how remedial systems will degrade and eventually fail. For our purposes, **system failure occurs only if/when regulatory dose limits are exceeded.**
- Identify the indicators of degradation.
- Designing a monitoring system that is guaranteed to detect the degradation indicators.
- Incorporating positive feedback loops that will allow systems to self-heal to the maximum extent possible, i.e., beneficial dynamic processes compensate for harmful processes to the extent possible.

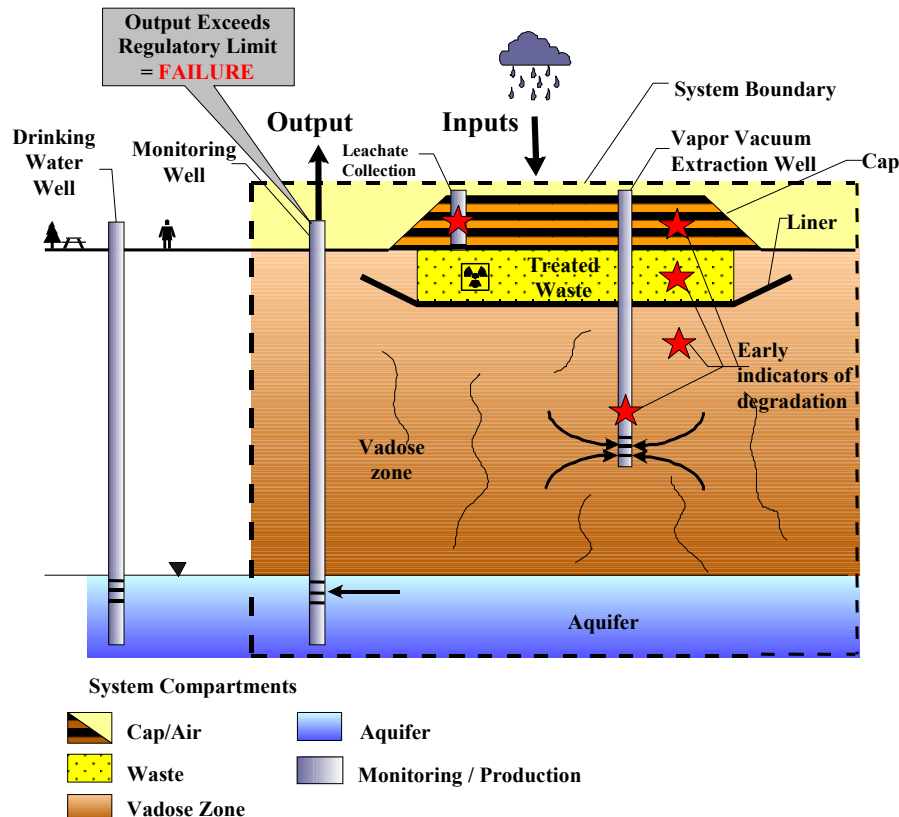


Fig. 1. Remediation System Performance Management (12)

This project is working toward such an integrated system. However, we caution that this project does **not** have the objective (nor resources) to substantially increase data monitoring, collection, and analysis of field data for the hundreds of caps already in service. However, we see this project as encouraging and enabling such a development.

The first of the four elements is the most critical since a clear understanding of how a system will fail is needed before effective mitigating measures can be planned. Unfortunately, analysis of remedial systems can be very complicated. Questions such as a) What is failure? b) What may cause system-level failure? and c) What is the probability of occurrence for each contributing event or process? must be answered before completing a list of degradation indicators. Likewise, positive and negative feedbacks caused by varying modes for components must be investigated before a complete understanding of the potential for system failure can be developed.

Clarification of system failure enables the other three, interrelated elements. For example, the types and placement of the detectors to be used in a monitoring system are dependent on the physical indicators that must be measured. Yet, limits on detector sizes, sensitivities, cost, and placement restrict the type of indicators that can be selected for monitoring. Similarly, monitoring system response might be required before self-healing steps can be taken. The monitoring system should determine if a response has occurred and measure the degree of response effectiveness.

There are at least two benefits to emphasizing system performance analysis during the design of remedial actions. First, evidence suggests that, in complex systems, simplifying component design tends to improve system performance; complicating component design tends to hurt system performance. If this evidence holds for remediation systems, it could support development of simpler and less expensive cap and waste treatment designs. Second, designing remedial investigations using a systems analysis perspective will improve efficiency of the investigations and reduce the cost of rework. Investigations that consider all variables impacted by operation of a remedial system will avoid shortcomings that result from consideration of only a subset of important variables.

In most engineered or biological systems, in the absence of aging/weathering, the failure rate of components does not change with time. Failures are controlled by episodic (acute) events. For example, ignoring aging, the probability of damage from seismic events does not change with time. Two other failure types are critical – initial failures due to poor quality assurance (design and/or construction) and failures due to aging. The former typically shows a decreasing failure rate over time; the latter increases with time.

The combined failure rate curve has the classic “bathtub” shape with relatively high failures both early and late in life. This curve is observed in a very wide range of systems including human death rates as a function of age, bridges, and nuclear power plants. Several critical observations ensue:

- The relative importance of the three failure types - initial (QA), episodic, aging - depends on the system, the design, the service environment, and the care given to QA during design and construction.
- Over time, the importance of QA problems decreases; the importance of aging related failure increases. This can be expected of waste barriers as well.
- The contribution of underlying failure causes change as a function of time.
- Assessment of the remaining lifetime of the system requires consideration of aging and episodic effects.

This project focuses on aging and episodic failure modes as they determine system lifetime.

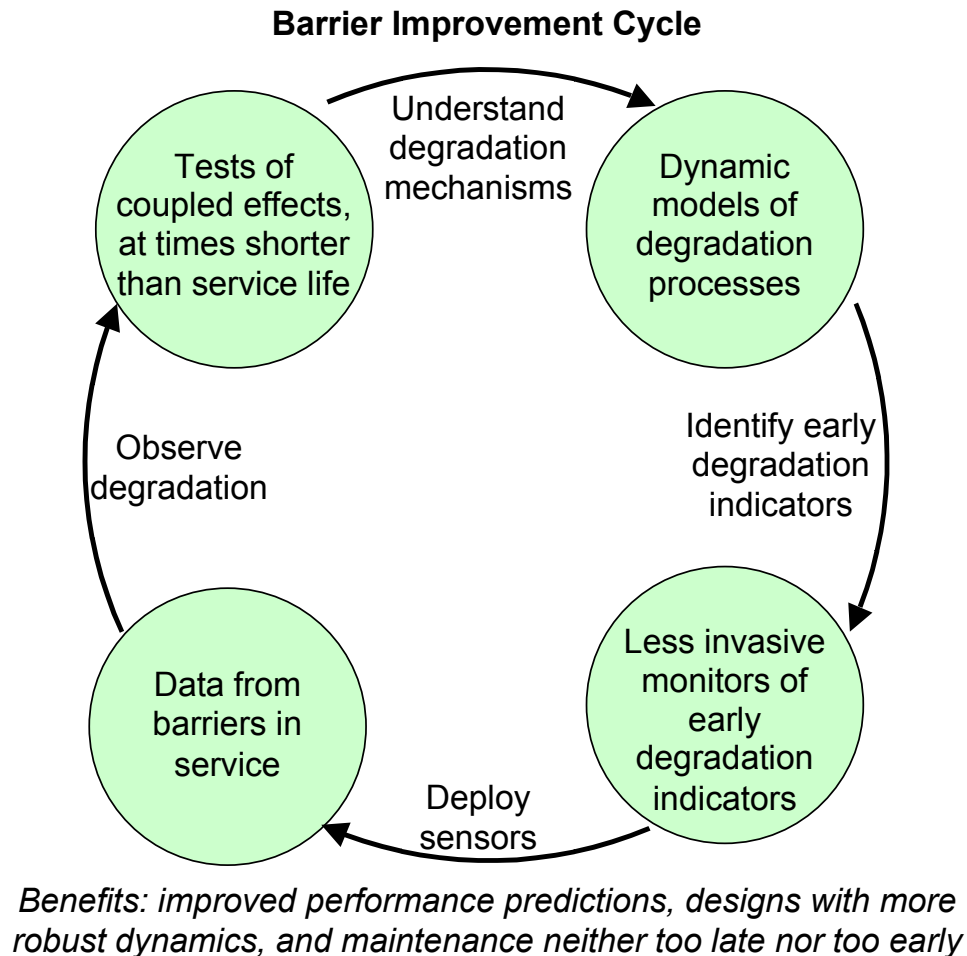
## **GETTING THERE: BARRIER IMPROVEMENT CYCLE**

As outlined above, our analysis of past work and future cleanup strategies suggests that a more comprehensive, systematic approach is needed to continuously improve barrier performance prediction, design, and management/maintenance, see fig. 2. Fortunately, much of the needed knowledge, models, and monitoring techniques exist. This project is aimed at providing additional parts to enable a barrier improvement cycle. Accordingly, the project combines:

- Selected data from the field - specifically looking at microbial behavior because microbes are central to ecology and apparently understudied at present. Plant ecology is extremely important to barrier performance and is likely to change over the life of a cap. Changes in plant ecology, microbial ecology, water balance, and soil-building processes are interrelated.
- Tests at multiple physical scales to bridge the gap between field and benchtop tests. This meso-scale regime allows examination of coupling among effects, control of those effects, and sometimes acceleration of effects.

- Dynamic modeling of barrier degradation processes - building on existing hydrological models that assume the barrier structure is static (weather inputs are dynamic).
- Selected exploration of new, non-invasive monitoring techniques that may lead to field deployment. (They also help diagnose tests within the project.)
- Integration of the above parts.

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 bench top studies by emphasizing (a) testing at intermediate scales - the "meso-scale" - where coupling of effects can be observed and sometimes accelerated and (b) modeling of dynamic processes.



**Fig. 2. Using knowledge of dynamic processes and meso-scale tests (coupled effects, acceleration) to better predict performance, improve design, and improve maintenance.**

Product improvement cycles similar to fig. 2 are found in many other industries. Indeed, the practicality and effectiveness of such improvement cycles is improving as the information age is making it easier to collect and process data and understanding of degradation processes is combined into appropriate dynamic models. "Complex systems foreshadow their failure with subtle changes in performance."(13) To avoid mistakes of replacing components too early or too late, "Ultimately, improvements and cost reductions in sensors and computing power will enable remote maintenance and diagnostics to move to consumer products. Refrigerators, washers and other appliances will receive instructions and report operating conditions over the Internet."(13)

Similar concepts are being developed in medicine, looking ever earlier for patterns that would indicate new diseases (or bioterror attacks). Similarly, at the individual level, for decades doctors have stressed the value of early detection of illnesses. The likelihood of cure goes up, and the cost tends to go down, as illnesses are detected earlier in individual patients. In contrast, the tendency in barrier monitoring (consistent with regulations) is to only detect contamination in groundwater, by which time the barrier has failed, contamination has spread, and further cleanup become more difficult (if not impossible). We describe this as detecting dead patients (barriers) years after they died (failed). Might it be cost effective and more protective of the public to detect barrier degradation prior to failure?

Similar trends exist at nuclear power plants, where understanding of system and component aging has allowed 50% increase in the authorized lifetime (40 to 60 years) of at least 10 U.S. nuclear power plants. Increased understanding, modeling, and monitoring of degradation has resulted in better power plant maintenance and billions of dollars of economic benefit from power plant lifetime extension.

If this type of improvement cycle can be envisioned (indeed implemented) for engines, aircraft, consumer products, medicine, nuclear power plants, etc., why not barriers that protect people from chemical and radiological hazards?

### **RATIONALE FOR APPROACH**

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

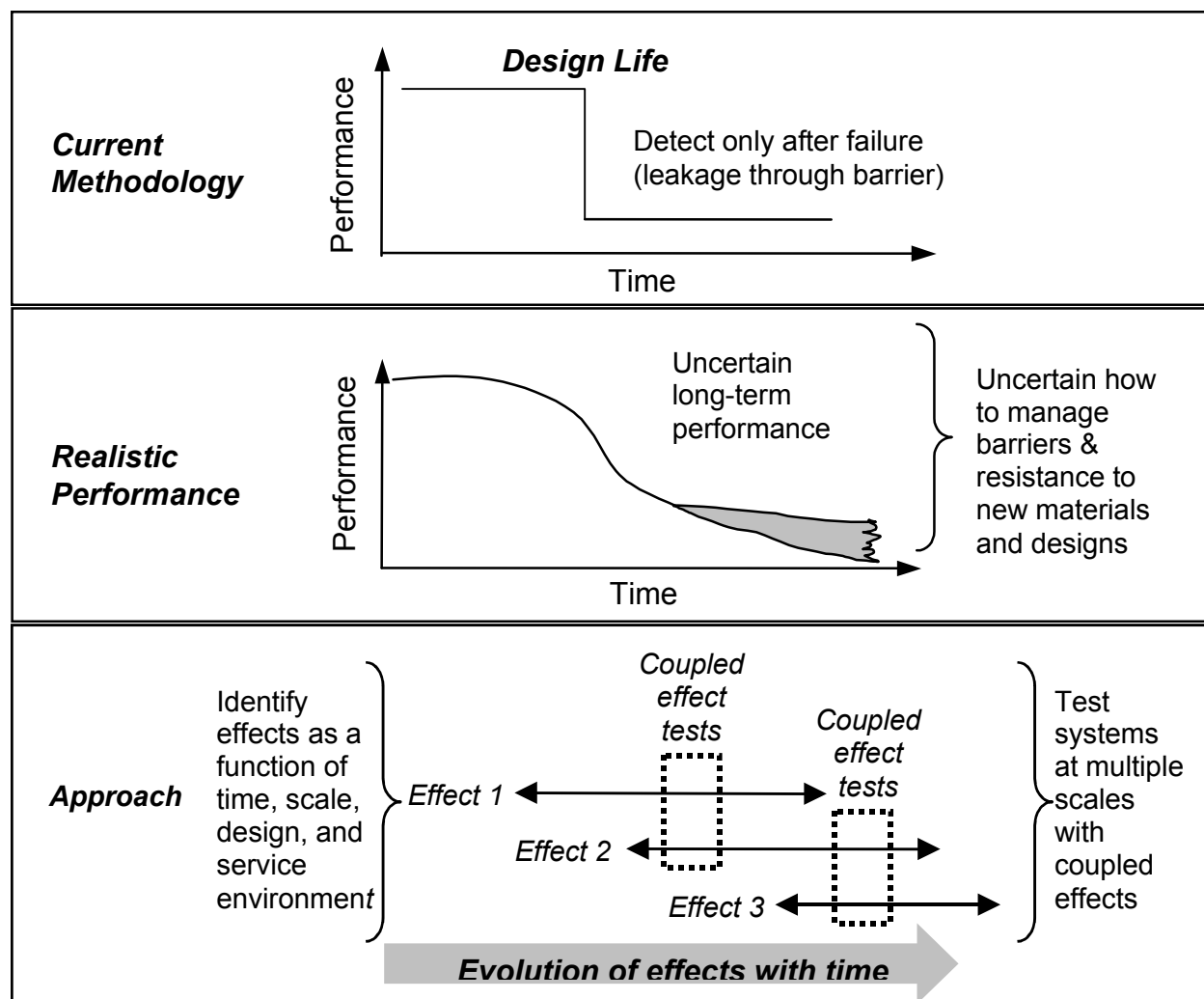
- Field data from existing barriers regarding effects of stressors since construction (a few decades of experience),
- Field studies of new surface cap designs,(7)
- Small-scale laboratory data on individual effects, and
- Performance assessments for the deep geological waste disposal projects, which are isolated from the near-surface environmental changes that drive many of the degradation mechanisms critical to near-surface barriers.

One approach to assessing long-term barrier performance is to use experience gained at field sites. With few exceptions (applied water simulating precipitation), effects on barrier performance are usually limited by the rates that natural environmental processes (e.g. number of freeze/thaws per year) associated with the barrier occur. 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.

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.

These approaches have not been sufficient to establish understanding of the relevant dynamic processes for the entire system. Indeed, current barrier models and regulations assume that barriers can be designed, built, and perform at a nearly 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 system failure rather than barrier degradation. (In some places, caps are visually inspected for signs of erosion or subsidence, which could lead to barrier system failure.) Fig. 3a illustrates the current methodology – design a barrier for some fixed lifetime, reach agreement with regulators to determine performance requirements, and monitor for barrier system failure - rather than monitor the internal performance of the barrier prior to failure.

The real performance of barriers rarely follows the simple step-function pattern in fig. 3a. Barrier performance generally degrades gradually as illustrated in fig. 3b. The short-term performance of barriers (i.e., less than 10 years) is fairly well understood and is currently the focus of numerous studies. 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 their coupling are not fully understood. Furthermore, the quantitative analysis of the interaction between these processes and their effects has not been performed.



**Fig. 3. Evolution of barrier performance approaches: (a) current methodology for designing and regulating near-surface barriers, (b) more realistic expectation of how barriers evolve; uncertainties grow with time, (c) practical approach to studying how barriers degrade with time.**

We use a holistic approach to 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 fig. 3c.

We have considered the range of potential stressors, degradation mechanisms, and effects and then considered which effects can be tested at what physical scale and with what degree of “acceleration”, see Table I. We have considered which effects might combine and thus which combination of effects should be tested together. The result is a mosaic of tasks, described below. We have initiated tests (Table II) at specific physical scales for mechanisms that may influence earthen cap performance, with some supplemental tasks for grout and geosynthetic clay liners (GCL).

Table I. Factors Considered in Assessing Which Testing Scales are Appropriate for Each Degradation Process

Consideration	Field	Meso-scale (28 m <sup>3</sup> ), EBTF	Meso-scale (0.3 m <sup>3</sup> ) BADTL	Benchtop
Which effects are possible to test at this physical scale	All that occur during the period of service, but determining the role of each effect is difficult and sometimes impossible	Possible to test most effects	Impractical to test plant or animal intrusion	
Which effects can be controlled	Only control of precipitation is possible (over a limited area)	Can control precipitation, animals, and plants	Practical to control temperature, water influx, soil moisture, mechanical disturbances, colonization of microbes, etc.	
Which effects can be accelerated?	Only control of precipitation is possible	Acceleration of water flux possible, but not biological	Acceleration of most effects is possible	Acceleration of most effects is possible
Relative ease of monitoring effects	Low	Generally high		High
Relative duration	Service time (decades)	Years	Months to years	Weeks to months
Relative cost	High cost for many years	Intermediate costs		Low
EBTF = Engineered Barrier Test Facility BADTL = Barrier Accelerated Degradation Testing Lab				

Table II. Project Test Matrix Showing Which Processes are Being Tested at Which Physical Scales

Degradation processes	Field	Meso-scale (28 m <sup>3</sup> ), EBTF	Meso-scale (0.3 m <sup>3</sup> ) BADTL	Benchtop
Microbial influence on soil formation and water transport	Cores		<i>Being considered for future work</i>	Analyze cores
Plant intrusion		Coupled effects (precipitation accelerated)		
Animal intrusion				
Precipitation and wet/dry cycles			Coupled and accelerated effects	
Freeze/thaw cycles				GCL & Grout long-term data
Differential subsidence, etc.				
Illustrative acceleration ratio = rate of testing/rate of service time (a)	Ratio = 1 (by definition)	Ratio = 1 (except accelerated precipitation at up to 3x normal)	Ratio = 10-1000 (b)	Ratio ~ 33 (c)
a. Compare to goal (ref 3) of acceleration by 5x to 50x, so that 100-year life could be simulated in 2 to 20 years. b. For capillary barriers our current test protocol suggests acceleration ratios of approximately: Wet/dry to field capacity: ~100 test cycles/year versus 0.1-10/year in service (?) gives ratio of 10-1000. Wet/dry to wilting point: ~10-25 test cycles/year versus 0.1-1/year in service (?) gives ratio of 10-250. Freeze/thaw: ~50 test cycles/year versus 0.1-1/year in service (?) gives ratio of 50-500. c. For GCL testing, about ~100 cycles/year versus ~3 cycles/year for GCL used in the ICDF evaporation pond liner, gives a ratio of ~33.				



## **DATA FROM THE FIELD - IMPROVE UNDERSTANDING OF MICROBIAL PROCESSES**

We start the description of the barrier improvement cycle (fig. 2) here. We identified one particular class of processes that may be both important but also understudied - microbes in earthen caps. As microbes are fundamental in ecological processes, understanding what they are doing in earthen caps would appear essential. We identified two key questions:

- How fast are soil formation processes in earthen barriers?
- Are microbes influencing the hydrology of earthen caps?

### **How Fast are Soil Formation Processes?**

Caps for the disposal of radioactive or hazardous wastes are often constructed of homogenized sub-soil material from the local area. Over time, these materials are subjected to natural soil-forming processes, such as weathering and the activities of plants and animals. These processes result in the development of strata within the cap material, which may ultimately influence cap performance. The objective of this subtask is to evaluate the changes in the vertical distribution of carbon (C) and phosphorus (P) concentrations in soil cores collected from the INEEL Protective Cap Biobarrier Experiment site (PCBE) and to compare these features with those of soil cores collected from a nearby, undisturbed (mature) site. Organic C and available P play important roles in the structure and function of the soil ecosystem.(14) The PCBE was established in 1993 to examine different surface cap designs under different vegetation types and under different moisture regimes.(15) Because the PCBE caps have been in place for eight years, the comparison will provide insight into plant-soil interactions within the surface cap and how these interactions progress over time. Ultimately, this information will help with the current assessment of impacts on surface caps due to plant/soil interactions and it will enhance models used to predict cap performance.

During September 2001 (by a different study), 144 soil cores were collected at PCBE, which is located on the Experimental Field Station. In June 2002, 24 soil cores were collected from an undisturbed site located about 0.5 miles north of Experimental Breeder Reactor (EBR) 1. In each subplot (PCBE site) or plot (undisturbed site), a soil core was collected from beneath a sagebrush canopy and a bunchgrass canopy and in an open area adjacent to that plant. Each soil core was collected to a depth of 150 mm and was cut into segments at certain distances from the surface, which are as follows: 12.5 mm, 25 mm, 37.5 mm, 50 mm, 75 mm, and 125 mm, yielding a total of 1008 samples. Organic C will be determined according to the tube digestion/heating block method,(16) a modification of the Walkley-Black method,(17) which has been found to improve the recovery of organic C. For plant-available soil P, samples have been extracted with a buffered alkaline solution of sodium bicarbonate (18) and the solution will be analyzed using an Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP/AES) analyzer.

### **Are Microbes Influencing Hydrology of Earthen Caps?**

We hypothesize that earthen caps, especially those with capillary breaks, can enhance the growth of microorganisms leading to secondary effects on the hydraulic properties of the soils within these caps. Depending on the magnitude of microorganism growth and distribution within the barrier, the barrier performance could be enhanced or degraded. We are examining two conceptual models of microbial distribution within capillary barriers. The first model assumes that the microbes are uniformly distributed throughout the fine soil layer overlying the capillary break whereas the second model hypothesizes that the fine/coarse media interface will exhibit enhanced growth. Because of microbial growth within a barrier, the unsaturated moisture characteristic relationship of the barrier layers is not solely a property of the soil matrix itself, but is also dependent upon the microbial magnitude and distribution. Note that the data are applicable to near-surface contaminant transport outside of barriers as well.

Core samples were collected from two INEEL sites for microbiological-hydrological-geochemical analyses. The first site was the Engineered Barrier Test Facility (EBTF), built in 1996. Both the thick soil design and the capillary/biobarrier design were sampled. The thick soil design can be used as a base case to examine if the capillary barrier interface is a significant growth area for subsurface microbes. The second site is the PCBE, built in 1993. This site had three barrier designs to study that had established natural vegetation on its surface. In total, five barrier designs were evaluated from these two sites.

Microbial cell density and activity were analyzed as a function of depth to determine their distribution within the capillary barrier. Relationships between microbial biomass and activity and other physical/chemical parameters were estimated by correlation matrix analysis. The preliminary results indicate:

- Microbes do exist in fine soils of capillary barriers at an average density of  $1 \times 10^{+7}$  cells per gram;
- Soil-formation processes appear to be taking place within the barrier affecting the hydraulic properties;
- Under the current management practices at the EBTF, the microbial communities do not appear to be affecting the performance of the barrier; PCBE data are not yet available; and
- In general, the microbial density is fairly uniform throughout the barrier; however, conventional sampling techniques may not be acceptable for microbial interfacial analyses. More work is needed to clarify microbial community succession (community structure, species distribution, abundance) and resulting effects on performance.

Also, a 2-channel flow cell - channel with diameters of 100  $\mu\text{m}$  and 300  $\mu\text{m}$  - has been imaged on the INEEL Nuclear Magnetic Resonance (NMR) imaging instrument. This is a major accomplishment since we were not initially certain that an image could be obtained through the flow cell's epoxy matrix. Work is now focusing on determination of the resolution that can be obtained with the instrument.

## TESTS OF COUPLED EFFECTS AT TIMES SHORTER THAN SERVICE LIFE

This is the second step in the barrier improvement cycle (fig. 2). These tasks explore acceleration and coupling of processes at benchtop and meso-scales. Per previous Table II, these tasks include the following:

- Meso-scale testing ( $28 \text{ m}^3$ ) of animal Intrusion, plant Intrusion, and precipitation
- Meso-scale testing ( $0.3 \text{ m}^3$ ) of wet/dry, freeze/thaw, and mechanical cycles
- Benchtop testing of long-duration freeze/thaw cycles for GCL and grout

### Meso-Scale Testing ( $28 \text{ m}^3$ ) of Animal Intrusion, Plant Intrusion, and Precipitation

Animals and plants can have both beneficial and harmful effects on earthen caps, for example:

- Animal burrows
  - ⊗ Increase downward water flux
  - ⊙ Increase upward evapo-transpiration
- Plant roots
  - ⊗ Increase macropores, allowing downward water flux
  - ⊙ Increase upward water siphoning from deeper into the cap
  - ⊙ Increase upward evapo-transpiration

The harmful effects are mitigated by design, but the beneficial effects tend to be ignored with the exception of plant evapo-transpiration. It is thus desirable to better understand both harmful and beneficial processes. This requires knowing more than the magnitude of each effect. We must also know the timing of the effects and what influences their magnitude (and timing). For example, for animal burrows, the relative importance of downward water flux and upward evapo-transpiration depends on the time of year - possibly a net negative during high precipitation periods but net positive during hot, dry periods where ET is maximal. In either case, eventually the burrows will collapse, truncating the important effects in time.

This subtask will determine the dynamics (individually and coupled) of plant intrusion, animal intrusion, and accelerated precipitation. Accelerated testing will be implemented by artificially increasing the precipitation level experienced by the test caps, based on the fact that water is a significant driver of processes in the cap including microbial and plant root depth. Increased levels of precipitation will represent possible future (worst-case) environmental conditions and worst-case conditions in a given year (heavy snow layer followed by rapid melting). We will test the hypothesis that cap performance resulting from the multiple interactions among soil cap processes and accelerated environmental conditions differs from cap performance observed under single effects testing.

This work is being conducted at the EBTF (fig. 4). This meso-scale facility has ten cells (six used in this study), each about 3 m x 3 m x 3 m, about  $28 \text{ m}^3$ . Mockups of an evapo-transpiration-storage type soil cap have been constructed and instrumented to measure soil moisture, soil moisture tension, soil temperature, and drainage. There



**Fig. 4. Meso-Scale Engineered Barrier Test Facility (EBTF)**

is 1.5-m of indigenous soil (fine zone above capillary break) and ~0.2-m of pea gravel (coarse zone for capillary breaks. (In the current experiments, the bottom half of the cells are unused.) Overall soil cap performance will be evaluated in terms of the cap's water balance. Dividing walls used to create two test plots in each test cell were installed. Plumbing systems for test plot drains were installed and tested for water flow continuity. The geomembrane liners used to seal the bottom of the test plots were installed. The calibration of new Time Domain Reflectometers (TDRs) and heat dissipation sensors for installation in the test plots was completed. Thermocouples recovered from the previous experiment were checked for proper functioning in preparation for installation in the new test plots. Instrument towers for buried instruments were constructed and installed as test plot construction progresses. The automated data acquisition system has been designed and will be installed during the winter.

#### **Meso-Scale (0.3 m<sup>3</sup>) Testing of Freeze/Thaw, Wet/Dry, and Mechanical Cycles**

This subtask is conducted at the Barrier Accelerated Degradation Testing Lab (BADTL) to evaluate the susceptibility of capillary barriers to degradation over time in response to various stressors such as freezing/thawing cycles, wetting/drying cycles and shaking - individually and combined. The first test articles have about 0.6-m of fine soil above a capillary break; 0.2-m of pea gravel underneath. Later, articles with GCLs and grout will be considered. The study is based on the hypothesis that repeated exposure of the barrier to these stressors will alter the physical structure of the barrier, thus altering the barrier's hydraulic properties and affecting subsequent performance. We seek to accelerate the application of the stressors to address long term performance concerns. This requires the test barrier to be subjected to numerous cycles in a relatively short time. The application of stressors also needs to be applied in a manner that will mimic field conditions. Translation of these requirements to testing at the field- or EBTF-scale is difficult if not impossible, so this subtask focuses on the use of meso-scale test barriers that provide the ability to manipulate the environment to evaluate accelerated effects on barriers.

The BADTL scale is ~0.3 m<sup>3</sup>, compared to ~28m<sup>3</sup> at 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 and EBTF scale, to use this meso-scale to explore behavior in long-term data and help provide data to support analytical predictions. Mechanisms to be evaluated include seismic/subsidence activity, freeze/thaw, and water infiltration at meso-scale.

#### **Effects of Long-Term Freeze/Thaw Cycling on the Hydraulic Integrity of Geosynthetic Clay Liners**

GCLs are geocomposites that typically consist of a thin layer of dry bentonite between two layers of geotextiles or attached with an adhesive to a geomembrane. An important issue or concern in areas of the country with cold

climates is whether freeze/thaw cycling affects the hydraulic integrity of GCLs. Laboratory studies on GCLs have shown that they retain their hydraulic characteristics when subjected to short-term freeze/thaw cycling, up to 20 cycles.(19, 20) Given that evaporation ponds, landfills, and other cap/barrier structures are being constructed with anticipated or required functional life spans of tens or even hundreds of years, some regulatory agencies are requiring overly conservative designs to make up for the lack of long-term data. Thus, the objective of this subtask is to test and determine the performance and hydraulic integrity for a variety of commercial geosynthetic clay liners when subjected to long-term freeze/thaw cycling.

The scope of the first phase of the research is to perform laboratory freeze/thaw tests of three GCL materials using a flexible wall permeameter. Samples of three commercially available GCLs have been obtained from CETCO (Brand name does not suggest endorsement of product), including those to be used in current designs at the INEEL. These include Bentomat ST, which will be used for the ICDF evaporation ponds at the new INEEL CERCLA Disposal Facility (ICDF) landfill; Bentomat DN, which will be used for ICDF landfill and evaporation ponds; and Claymax 600CL, which will be used for comparison with previous studies, e.g., Hewitt and Daniel.(19)

We are measuring hydraulic conductivity of the specimens before freezing and thawing to establish base hydraulic conductivities, and then measure hydraulic conductivity after a given number of freeze/thaw cycles. Hydraulic conductivity tests are being performed on 70-mm diameter test specimens in a flexible wall permeameter. After determining the specimen's hydraulic conductivity, the specimen is placed in a freezer for 24 hours. The GCL then thaws for 24 hours prior to being either re-tested or re-frozen. We will increase the number of cycles to at least 150, and as much as 300, to provide a sound base for determining if long-term freezing and thawing affects the hydraulic performance of the GCLs. If so, the data will support using GCLs in long-term applications.

The methodologies used to conduct the freeze/thaw cycling and the hydraulic conductivity tests are a compilation from several different sources, including ASTM (21, 22, 23), Geosynthetic Research Institute's GCL-2 Test procedure for determining hydraulic conductivity of GCLs,(24) and operating instructions for the system.(25)

A working assumption is that three freeze/thaw cycles will equal one calendar year. The hydraulic conductivity will be measured after the number of freeze/thaw cycles representing 0 (control), 1, 3, 5, 7, 10, 15, 25, 50, 75, and 100 years. A total of three individual specimens of each of the specific GCLs will be measured for the total number of freeze/thaw cycles. This requires 99 individual samples (33 of each GCL).

The next phase of the research will be to evaluate the effects of repeated freeze/thaw cycling at the meso-scale. The general approach will be to incorporate GCLs into a typical evaporation pond liner design with varying freeze/thaw, wet/dry, and possibly stress state. The entire system will then be subjected to repeated cycling and the GCLs hydraulic conductivity measured. A three-cell flexible wall permeameter was procured, tested and calibrated and is now being used to perform hydraulic conductivity measurements on test samples. Two meso-scale 1-m x 1-m x 1-m freeze/thaw chambers were procured and are now being prepared for experimentation.

### **Long-Term Performance of Grout**

This subtask studies the degradation of grout and surrogate waste materials from thermal cycling with and without water at the bench scale. Grout is used at some buried waste and decommissioned facilities to stabilize contaminated materials, prior to covering with a cap (either earthen or cement). Prior to covering - or at long times in the future - the grout will be subjected to Idaho's cold, semi-arid climate. Related cement caps will be subjected to such freeze/thaw cycles for their service life. Actual grouted contaminants are highly heterogeneous - either mixtures of grout, soil, waste, waste containers (cardboard, drums, etc.) or mixtures of grout, discarded process equipment, demolition debris, etc. Therefore, the objectives of this work are to characterize the negative effects of freeze/thaw cycles on the mechanical integrity of grout systems - with and without water - in heterogeneous geometries. Simplified cement based materials are being used to establish baseline experimental data to compare directly with formulations slated for deployment. A range of sample sizes are being used to determine optimal test procedures and identifying geometry-sensitive processes, 102 to 305-mm high and 51 to 152-mm diameter.

A 0.3-m<sup>3</sup> environmental chamber is being used to conduct precise thermal tests of grout and related materials under controlled conditions. The complete progression of damage accumulation will be characterized by sample sectioning at known damage states. These data will then be used to refine a test matrix involving remote sensing

capabilities and to make direct durability evaluations of specific grouts. Simulations of modest temperature changes results in significant stresses that predict grout degradation.

## **DYNAMIC MODELS OF DEGRADATION PROCESSES**

This is the third stop in the barrier improvement cycle (fig. 2). More information on the dynamic modeling efforts is reported at this conference.(26) The long-term objective is to develop a suite of models that incorporate stressors and effects that assess and predict barrier performance as a function of time. The models must 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.(27, 28)

### **Preliminary ET/Capillary Barrier Dynamic Model**

This subtask explores the design and evaluation of relatively simple but very flexible system dynamic models to explore the dynamics of barrier performance. This research provides a tool to map out the underlying feedback loop structure of the system and explore the relationships between the various components. This modeling is designed to quickly explore the structure and behavior of the system under a variety of scenarios whereas more sophisticated models are strong tools for exploring sensitivities to parameter uncertainties. A thorough understanding of the structure of these complex systems can lead to an explanation of their performance over time and in response to both internal and external perturbations. By understanding a system's underlying structure, predictions can be made relative to how the system may react to perturbations and changes.

System Dynamics models are descriptive by nature. All the elements in the model correspond to actual entities in the real world. The decision rules in the model must conform to actual practice and real world phenomena. Thereby, adjusting an element in the model corresponds to a physical change in the real system. The purpose of the model is threefold: 1) a visual diagram of the system encourages discussions on the various elements of the model and elicit input from interested parties; 2) initial simulations promote insights into the dynamics of the system; and 3) calculations after benchmarking/calibration provide a tool for the analysis of long-term performance.

Our first illustrative barrier model (26) is a single layer soil cap with a vegetative cover and underlying capillary break. The model tracks the soil moisture content in the cap as well as deep drainage into the waste level. The change in moisture in the cap layer is dependent on the inflow of moisture from precipitation, run-on and irrigation, field capacity of the soil, current moisture level of the soil, and extraction from evapo-transpiration and deep drainage. The system includes feedback loops. For example, excess moisture in the soil (above the current transpiration capacity) causes an increase in plant growth thus plant root density which in turn increases transpiration which reduces the excess moisture in the soil until the two elements (transpiration, moisture) are in equilibrium.

The model will eventually allow simulations such as the following:

- Time-dependent balance for animal intrusion burrows between harmful open porosity versus beneficial increased evaporation.
- Time-dependent balance for plant intrusion between harmful macropores versus beneficial increased wicking and evapo-transpiration.
- Time-dependent system response as the water storage layer thickness changes due to soil erosion.
- Response to fire - plants providing evapo-transpiration are destroyed, cap is initially less protective, time and water allows plants to reestablish
- System response to fluctuating precipitation (one or more abnormally wet or dry years will cause plant changes, thereby changing evapo-transpiration; long-term wet or dry periods will cause ecosystem changes)
- Hypothetical long-term capillary break degradation.
- Hypothetical long-term GCL degradation.

#### **4-Dimensional Hydrology Performance Assessment Model Development**

The subtask looks beyond the preceding preliminary dynamic model, toward an all-inclusive dynamic barrier simulation code (or suite of codes) for evaluation of long-term performance. The code will be developed using modularity and will potentially incorporate all barrier degradation mechanisms identified as significant.

The approach includes the following: a) survey the available barrier simulation codes; b) survey the “state-of-the-art” computational techniques used in hydrology and other fields such as computational fluid dynamics; c) identify the “state-of-the-art” computational techniques amenable to unsaturated/saturated groundwater flow and contaminant/energy transport simulation in near surface barriers and select a preferred method; d) develop the simulation code using this method in a progressive sequence starting with a one dimensional code and continuing to 2 and 3 dimension; and e) verify, validate, and benchmark the code with analytical models, experimental results, and comparisons with other codes, respectively.

There are currently no multi-dimensional codes available to simulate the full range of physics occurring in barriers. The current codes available for simulating evapo-transpiration and the physics of unsaturated flow (capillarity) are two-dimensional. There are numerous multi-dimensional models available that rigorously solve the unsaturated flow problem, but they only offer simple surface boundary conditions and do not include atmospheric energy and water transfer at the surface from continually changing atmospheric conditions. Furthermore, the current two-dimensional barrier and multi-dimensional unsaturated flow codes use the Darcy flow assumption, which neglects the convective components in the momentum equations. The validity of Darcy flow is questionable for many subsurface environments such as fractures/macro pores and surface water/subsurface interactions.

Currently, the barrier models for water, energy, and contaminant transport in unsaturated porous media are based on Richard's equation, which describes unsaturated liquid water flow; Fick's Law, which describes water vapor movement; Fourier's Law, which describes conductive heat flow in the soil profile; the convection-diffusion equation, which describes energy movement with the pore water; and the advection-dispersion equation, which describes contaminant transport in the subsurface.

Alternatively, water movement in a porous medium can be described by the conservative form of the Navier-Stokes equations. These equations will reduce to Richard's Equation when the convective components are neglected. This is the case for most flow in a porous medium because the velocity is very small and inertial forces play a very minor role. The advantage of employing the Navier-Stokes equations is that the code will have a wider range of applicability and could include overland water flow, flow in fractures and macro pores and atmospheric conditions into the computational domain. The main strength of this approach will be barrier simulation code that valid in both porous media and free surface flow regimes.

#### **LESS INVASIVE MONITORS OF EARLY DEGRADATION INDICATORS**

This is the fourth and final stop in the barrier improvement cycle.(fig. 2) We are exploring three ideas that facilitate some of the above testing tasks and that may lead to field deployable monitors:

- Animal and plant intrusion by non-invasive techniques - tested at the EBTF meso-scale.
- Soil moisture, temperature, and pressure by a wireless sensor platform - tested in the field.
- Degradation by electrical impedance spectroscopy - tested at the benchtop scale.

#### **Monitoring of Animal and Plant Intrusion Monitoring by Non-Intrusive Techniques**

The subtask is evaluating the use of non-intrusive techniques to better understand animal and plant intrusion dynamics. Three non-intrusive techniques are being studied at the EBTF:

- Tracers, which if validated could be used in actual caps in service;
- Ground penetrating radar, which could be used as needed in service;
- Electromagnetic induction, as a proof of principle.

Integration of the soil tracer study with the two geophysical techniques allows us to crosscheck results among the three methods. These monitoring studies are integrated with the EBTF testing described above, providing the opportunity to evaluate the techniques under different environmental (precipitation) and surface cover conditions.

A trapping survey performed last year near the EBTF indicates that deer mouse and pocket mouse are the most abundant rodent species available at the periphery of those sites, followed by chipmunk, kangaroo rat and ground squirrel.(30) Since deer mice will be used for this study, a protocol was written to ensure that all the safety issues of handling rodents that are potential Hanta virus carriers were taken into consideration. This protocol follows the guidance and regulations established by the Center for Disease Control and Prevention. In addition, a detailed protocol was prepared by Stoller Corporation describing proper handling and maintenance of rodents in semi-captivity; this protocol is in the process of being presented to local veterinaries for review. Finally, a method developed by Washington State University in collaboration with Stoller Corporation (31) to motivate rabbits to dig into the soil will be tested with the mice. In spring 2003, pregnant females will be placed in the plots. The placement of pregnant females, which have a bigger disposition for digging and nesting, in addition with the placement of PVC shallow holes, should accelerate the construction of tunnels and burrows in the testing plots.

The mixture of sand/soil is such that in the event of animal intrusion, detection will be evident by the presence of soil tracers brought to the surface of the cap as a result of burrowing. Colored sand was selected since it can be thoroughly mixed with a variety of soils commonly used in caps designed with natural materials. This type of sand is non-toxic and insoluble in water. It also has good stability and weatherability. Before emplacing the colored sand, we tested the amount needed to be incorporated with the soil mix, and determined an appropriate proportion suitable for easy detection. To test the proportion of sand/soil required, we prepared a titration of different colored sands mixed with the soil. Then a group of volunteers were asked to identify the samples, indicating color of the sand and difficulty in detecting the grains. Based on their responses, we selected the three easiest colors to identify: pink, green and blue. We found the best proportion of sand/soil to be roughly 1 to 1.5%. The colored sand has been placed in the fine soil in layers of 22 mm. The pink sand was placed at 1.48-m deep, green sand at 1.0 m, and blue sand at 0.58 m. The capillary break is 1.5-m deep. Results will not be available until later in 2003.

An automated imaging system and different sensors including ground penetrating radar and electromagnetic induction will be set in place. This effort will use time-lapse 4D geophysics, to collect multiple data sets at fixed 3D spatial coordinates, remove the complexity of the background, and produce time-dependent changes in physical properties (density, electromagnetic) denoting penetrations in the soils. The design has the following characteristics:

- The gantry system will ride over all plots, and will retreat into a protected housing. As the weather conditions at the site are such that continued exposure of electronics would be detrimental to system performance of a rack and pinion system, a design was chosen in which the acquisition unit and motors ride over the rack. Thus, the only exposed component of the system will be an anodized aluminum rail. The system design was completed and system components have been received.
- The control system allows remote operation and control of the gantry system as well as the geophysical instrumentation. It is modular, i.e. it allows for integrating multiple instruments in a straightforward way. Deployment of the system will be weather dependent. A software program was written which pulls weather data off the Internet continuously and writes it to a local database, which will be used both for interpretation of results and for decision making on whether to collect data. Another element is integration with a remote controllable camera that will allow researchers to get real time access to site conditions.
- Data processing, visualization and interpretation software must drive the whole system. We have identified appropriate visualization software (EVS) and designed a software infrastructure, driven by a centralized piece of controller software (written in Labview/Visual C).

### **Remote Monitoring of Soil Moisture, Temperature, and Pressure by a Wireless Sensor Platform**

Unusual changes in soil moisture, temperature, and pressure could signal that the cap was not performing as anticipated, i.e., that degradation could be occurring. Typical monitoring techniques require electrical power and signal transmission lines, thereby necessitating invasive and costly lines to and from the sensors. It would be helpful to develop a sensor platform that could provide information without such complications.

The INEEL has previously developed a versatile micro-power sensor interface platform for the purpose of periodic, remote sensing of environmental variables such as subsurface moisture, temperature, or radiation.(32) The key

characteristics of the platform architecture are that the components are passive thereby requiring no internal power source and that it communicates with a reader via short-range telemetry. Other attributes include the potential for a long service life and compact size that makes it well suited for retrofitting existing structures. Functionally, the sensor package is read by a short-range inductive coil that both activates/powers the sensor platform and detects the sensor output via a radio frequency signal generated by the onboard programmable interface/controller microchip. Inherent to this approach is an operational depth limit and power budget in which sensors must function. Operational depths will be limited to the distance the induction field can be projected into the ground as defined by the electrical/physical characteristics of the antenna systems and electromagnetic properties of the soil. The practical operating depth is about two meters. (This illustrates that thicker caps are generally more difficult to monitor.) Almost any low power sensor can be integrated that fits within the operating parameters of the analog to digital converters in the controlling microchip and the platform's power budget.

This subtask provided for the installation of the sensor platforms at the Gilt Edge Gold Mine in South Dakota, providing an opportunity to install and demonstrate the capabilities of the INEEL wireless sensor platform. Sensor packages were assembled, transported to the site, and buried in the gravel layer below the liner. The liner is presently being put into place and covered with topsoil. Three sensor packages were assembled and installed. Assuming the sensor platforms survived final barrier construction, they will be demonstrated at a later date.

### **Monitoring of Degradation by Electrochemical Impedance Spectroscopy for Monitoring Performance**

This subtask develops electrochemical impedance spectroscopy for monitoring the long-term performance of caps and barriers. Benchtop testing will provide proof-of-concept to see if electrochemical impedance spectroscopy can be used to detect and monitor the progress of various degradation modes in cementitious caps and barriers.

Impedance spectroscopy methods are based upon the well-established theory of electronic AC circuit analysis. The fundamental approach of impedance spectroscopy is the application of a spectrum of small-amplitude sinusoidal voltage excitations to interrogate the system of interest and the measurement of that system's response. In theory, any intrinsic property that influences the conductivity of a material (e.g. permeability, porosity, ionic conductivity, etc.) can be examined by impedance measurements. Techniques based on impedance spectroscopy offer the possibility of providing a reliable and cost-effective means of characterizing and monitoring cap/barrier integrity. The development of such techniques addresses the need for low-maintenance, long-lived, non-invasive sensors.

This study will provide the knowledge needed for the interpretation of the impedance spectra of cementitious systems. Because it is likely that many engineered caps and barriers will be constructed using cementitious materials, initial impedance studies are being carried out on concretes and cement composites. The data will be used to describe the various physical-chemical processes presumed to be important to these systems. Initial efforts will develop electrochemical impedance methods designed to: a) detect and monitor water intrusion into concrete, b) detect stress/strain on a concrete slab, c) detect deterioration of cap integrity due to micro cracking.

### **INTEGRATION AND DATA MANAGEMENT**

The information from the various parts must be integrated. One way is to develop a system capable of accessing existing data sources, acquire and organize relevant data, enter data or findings to assess the performance and/or integrity of surface or near-surface barriers. Thus, here we describe initial efforts to initiate such a system.

A survey was conducted among the organizations likely to have developed such a system (EPA, NRC, DOE, DoD, NSF). This survey showed the existence of numerous studies and reports on this type of research but no searchable databases were found. This may seem surprising at first, however, the variety of interests and designs being pursued by the above organizations and the lack of consistency in terminology and testing methodology prevent the integration of the body of knowledge into a single tool available to all. An analysis of the potential users of this system was performed and the following are some of the most prominent groups: scientific community at large, regulators and state officials, civic and environmental groups, and impacted individuals/stakeholders.

We surveyed related tools available or in development to evaluate the potential value of using all or parts of them to save time and money in the development of such a data management system. This survey resulted in a number of databases dealing with other features of the same sites where these caps and barriers may exist. For example, the



INEEL developed a database for the Long Term Stewardship Program in FY01/02, that contains information on the DOE sites, location, contaminants, stakeholders, volumes, end state, etc. It provides a basis for further development and includes the additional information about those sites related to the performance of the caps and barriers in them.

Development of such a prototype was initiated. The interface could eventually allow the user to:

- Find out what has been done to date;
- Who is performing tests for what, when the results will be available, etc.;
- What approach has been taken and found to be good/bad in the design of tests to evaluate performance of caps in a “wet” environment, semi-arid climate, etc.;
- What performance indicators have been determined to yield reliable information to establish a strong correlation between cause and effect, which would lead to the identification of degradation mechanisms – the beginning of the true understanding of the science behind the engineering of caps and barriers.

## **PATH FORWARD**

The information obtained and capabilities built in this project will benefit the DOE, nation, and world by improving confidence in existing barriers, providing an improved technical basis for managing barriers, and improving the basis for designing and testing new barriers. 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. Specifically, the project incorporates research that will benefit INEEL near-term cleanup operations, e.g., cleanup and closure at the Subsurface Disposal Area (SDA) and the Idaho Nuclear Technology and Engineering Center (INTEC). Each of these sites will eventually be capped, probably with evapo-transpiration and capillary functions. (A surface cap is likely 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 may have grout or 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.

The project addresses the tendencies to make caps thicker and more complex, which in turn makes them more expensive, harder to manage, harder to monitor, and more difficult to upgrade/repair.

- Increased thickness by itself can be counter-productive. For example, 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. 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.
- Designers want to increase use of engineered materials to improve performance or reduce over conservatism. 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 and more complex, partially as a result. The project should increase knowledge of engineered component behavior in the total system, facilitating their use.
- The project should also increase the understanding of both harmful and beneficial ecological processes, with the long-term intent of discouraging the former while promoting the latter. Focusing only on the harmful effects is also tending to make caps thicker and more complex. Since nature will win in the long run, we advocate better understanding ecological processes and, where possible, using them.

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