Risk Analysis, Vol. 24, No. 3, 2004

Engineered Containment and Control Systems: Nurturing Nature

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The development of engineered containment and control systems for contaminated sites must consider the environmental setting of each site. The behaviors of both contaminated materials and engineered systems are affected by environmental conditions that will continue to evolve over time as a result of such natural processes as climate change, ecological succession, pedogenesis, and landform changes. Understanding these processes is crucial to designing, implementing, and maintaining effective systems for sustained health and environmental protection. Traditional engineered systems such as landfill liners and caps are designed to resist natural processes rather than working with them. These systems cannot be expected to provide long-term isolation without continued maintenance. In some cases, full-scale replacement and remediation may be required within 50 years, at an effort and cost much higher than for the original cleanup. Approaches are being developed to define smarter containment and control systems for stewardship sites, considering lessons learned from implementing prescriptive waste disposal regulations enacted since the 1970s. These approaches more effectively involve integrating natural and engineered systems; enhancing sensors and predictive tools for evaluating performance; and incorporating information on failure events, including precursors and consequences, into system design and maintenance. An important feature is using natural analogs to predict environmental conditions and system responses over the long term, to accommodate environmental change in the design process, and, as possible, to engineer containment systems that mimic favorable natural systems. The key emphasis is harmony with the environment, so systems will work with and rely on natural processes rather than resisting them. Implementing these new integrated systems will reduce current requirements for active management, which are resource-intensive and expensive.

KEY WORDS: Environmental stewardship; waste management; engineered systems; containment and control; natural processes

1. INTRODUCTION: PRESCRIPTIVE REQUIREMENTS FOR WASTE MANAGEMENT

Thousands of sites across the country face challenges in effectively managing wastes and related environmental contamination over the long term. Containment approaches have been an integral part of remediation strategies for contaminated sites beginning with the pre-Superfund efforts of the 1970s. For land-based systems, the key performance factor

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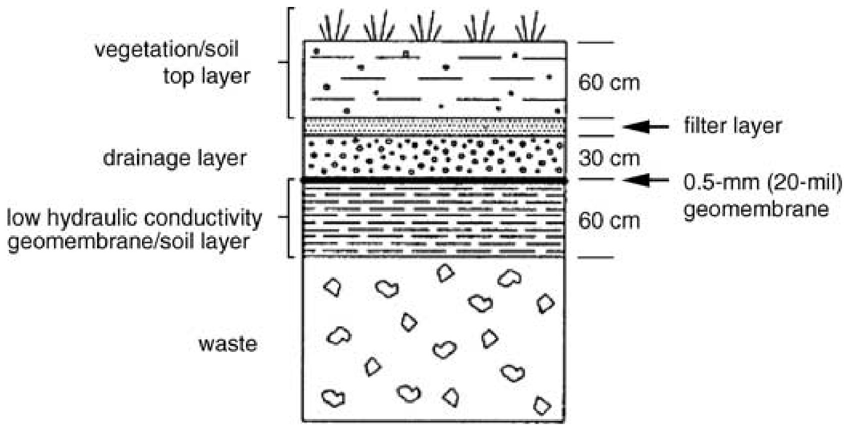

Fig. 1. U.S. Environmental Protection Agency recommended cover design.[3]

has always been, and most likely will continue to be, an ability to prevent infiltrating rainwater and underlying groundwater from contacting the contaminated materials that are being isolated. The default design paradigms for accomplishing these objectives are landfill caps and liners and vertical barriers or treatment systems. The hydraulic conductivity of the engineered barriers themselves became the overarching performance criterion in the design and regulatory acceptance for *in situ* containment and control approaches and for new contamination isolation facilities.

Many early approaches and some prescriptive standards were found to be especially inappropriate for arid and semi-arid climates in that reliance was placed on compacted clay soils, which would desiccate and crack, thereby losing their ability to prevent infiltration. Compacted clay barriers could be expected to eventually fail in other climatic settings as well, due to a combination of natural physical and biological processes, including desiccation, freeze-thaw phenomena, and penetration by plant roots and burrowing animals.[1,2] Regulations promulgated under the Resource Conservation and Recovery Act (RCRA) incorporated prescriptive, one-size-fits-all designs that rely on a combination of compacted clay soils and geosynthetic barriers and natural and geosynthetic drainage media that are also subject to degradation due to natural processes (see Figs. 1 and 2).[3]

As experience was gained with early designs, it became clear that not only was it necessary to use low-permeability materials such as clay and synthetics to provide the needed hydraulic isolation, but it was also necessary to ensure that these materials were protected from potential damage due to erosion, plant and animal intrusion, and other natural processes such as freeze-thaw cycles. Thus, over the years, "layer cake" cover systems emerged with a variety of components designed to prevent damaging events and to provide drainage of infiltrating rainwater away from the primary low-permeability barriers.[4–6]

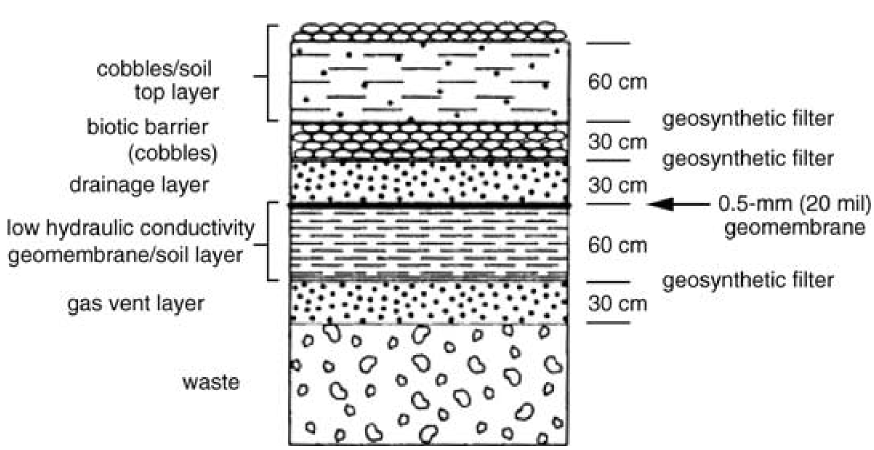

Fig. 2. U.S. Environmental Protection Agency recommended cover design with options.[3]

However, many of these more sophisticated designs were still driven by prescriptive RCRA regulations, and, as such, they often failed to be responsive to different environmental settings and long-term environmental change.

Remediation of contaminated sites also often requires control of contamination that has already entered the subsurface environment. Most subsurface containment approaches that have emerged are based on proven construction techniques, such as slurry-wall construction, with a reliance on low-permeability soils and synthetics. Control of contaminated groundwater also usually requires hydraulic controls, typically including pumping of contaminated water, which then must be treated. Over time, it has become clear that subsurface barriers are also subject to degradation due to natural processes and that site-specific groundwater chemistry and waste compatibility are important performance factors for these systems. Furthermore, experience with the hydraulic control of contaminated groundwater has led to the realization that many pump-and-treat operations must continue for decades or even centuries in order to meet their objectives.

2. LONG-TERM ENVIRONMENTAL STEWARDSHIP AND TIME HORIZONS

The designs for engineered systems that have been developed and implemented over the past couple of decades appear to be providing containment and control to the extent that new releases are being prevented in most cases and existing groundwater contamination is not increasing. However, the in-service durations of containment systems so far have been very short compared to the long times required for performance, based on the toxicity and persistence of the hazardous chemicals and long-lived radionuclides being contained. For example, uranium mill tailings cover systems have a prescribed design life of 1,000 years. Given the realization that current traditional designs will eventually fail, barring perpetual maintenance,[7] a serious need exists for alternative designs that are more resilient and reliable in the long term.

To illustrate, the U.S. Department of Energy (DOE) is one of a number of agencies currently developing and implementing plans for environmental management and long-term stewardship (LTS) of contaminated sites. Beginning more than 50 years ago, DOE's predecessor agencies developed an industrial complex to conduct basic and applied research that extended from nuclear energy and biomedicine to weapons development and testing in support of the nation's defense program. Operations were conducted at more than 100 sites across 30 states and territories. Facilities ranged from uranium mines and mills to chemical plants, metal machining plants, maintenance shops, research laboratories, and nuclear reactors.

With the end of the Cold War in the late 1980s, the focus of activities at many facilities shifted from production to environmental restoration and waste management. Across various sites, past processing and disposal activities that were conducted in accordance with extant practices resulted in considerable amounts of buried and stored wastes and associated environmental contamination. Systems to contain and control contamination are a key element of long-term waste management for these sites. Such systems have already been installed at many DOE sites and are planned for a number of others, and they will need to operate effectively for tens to hundreds and in many cases thousands of years to assure long-term health and environmental protection.

Contamination containment and control systems are a key part of the overall environmental stewardship program to be implemented across the DOE complex, following the completion of active remediation measures at individual sites. A considerable number of contaminated areas within the former nuclear weapons facilities and other properties under the Department's jurisdiction will require effective stewardship following completion of the active remediation period, as illustrated in Fig. 3.[8]

The authors of this article constitute one of four working groups, the contamination containment and control (CC&C) working group, engaged in developing a science and technology (S&T) roadmap for LTS as part of an effort sponsored by DOE through the Idaho National Engineering and Environmental Laboratory (INEEL). The process that was followed to develop the CC&C component of the stewardship roadmap is briefly summarized below.

3. APPROACH FOR IDENTIFYING SCIENCE AND TECHNOLOGY RESEARCH NEEDS

A formal science and technology roadmap process was implemented to identify issues and needs related to the long-term environmental stewardship of contaminated DOE sites as well as capabilities and targets for a sound stewardship program. The general framework for this process was defined by

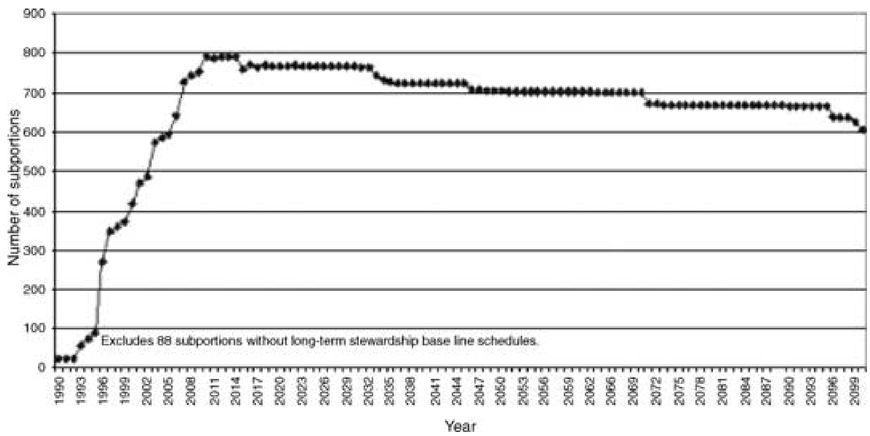

Fig. 3. Estimated number of DOE areas (subportions) requiring stewardship by year.[8]

the lead integrator of the stewardship roadmap effort, INEEL. As a member of the technical team supporting this effort, the CC&C working group was asked to concentrate on meeting immediate stewardship needs by identifying key gaps in existing capabilities for containing and controlling contamination at DOE sites and how those capabilities could be improved through strategic research and development initiatives.

That is, the roadmap development effort aimed to lay out how the Department could "get from here to there" with regard to an improved LTS program that incorporated the best science and technology has to offer. Under the first step in developing this roadmap, the working group identified what activities were essential to designing, implementing, and maintaining an effective CC&C system for a contaminated site. For example, one major aim of CC&C systems is to limit the future migration of contaminants beyond the containment and control system. Under the second step, capabilities associated with these activities were identified, together with specific targets for improving those capabilities. For example, one key capability is being able to design the system in a manner that considers the environmental setting at a given site, and another capability is being able to verify that the containment and control system is working as designed. Targets simply represent endpoints to be achieved within a reasonable science and technology development time that could significantly improve the status quo for CC&C systems.

Through the roadmap process, the working group identified general science and technology investments that could be pursued to strengthen DOE's LTS program. Over several meetings of several days each, the team made a concerted effort to incorporate current knowledge gained from various past and current applications of CC&C systems into the development of strategic science and technology research and development opportunities for the Department. Results of this process and a selected illustration of how field knowledge and experience were incorporated into the results are presented below.

4. RESULTS AND DISCUSSION

The CC&C working group identified the following activities, associated capabilities, and related targets as essential for the effective long-term performance of CC&C systems (Table I).

The first of the four activity areas, engineering of the thermobiogeochemical environment, illustrates the potential contributions of both of these thematic areas. Improved engineering of the thermobiogeochemical environment could reduce stewardship requirements by allowing more aggressive remediation. This is already happening to some extent, but additional research and development could enable available technologies to be deployed more widely. For example, demonstrated technologies for destroying organic contaminants in source zones and groundwater plumes exist, including thermal desorption and enhanced bioremediation. However, additional development efforts to improve capabilities for emulating Mother Nature are needed to apply these technologies to complex contaminant mixtures and to overcome practical limitations associated with the great depths, low permeabilities, and geologic complexity of the settings where contamination occurs at some DOE sites.

Other biological techniques such as engineered wetlands, phytoremediation, and monitored natural attenuation also show promise for reducing contaminant volumes and water treatment needs at locations

Table I. Activities, Capabilities, and Targets Developed for the Science and Technology Roadmap, Considered Essential for the Long-Term Performance of CC&C Systems

Activity	Capability	Target
Limit contaminant toxicity and mobility	Engineer the thermobiogeochemical environment—source contaminants	Deploy alternative technologies that detoxify or immobilize risk-driving contaminants at the source
	Engineer the thermobiogeochemical environment—groundwater environment	Deploy alternative technologies that reduce the volume of groundwater that would otherwise be pumped and/or treated
Limit intrusion, transport, release, and exposure	Design, build, and operate alternative containment systems—covers	Deploy cover systems that mimic natural processes and accommodate environmental change
	Design, build, and operate alternative containment systems—subsurface barriers	Deploy subsurface containment systems that mimic natural processes and accommodate environmental change
Predict, monitor, and evaluate system performance	Conceptualize and predict system performance and potential modes and levels of failure	Deploy a "toolbox" of techniques and technologies (e.g., models, natural analogs, guidance, performance indicators, and failure criteria) to improve planning, design, monitoring, maintenance, and interpretation of monitoring data
Maintain system performance	Identify and implement improved responses to change (via routine and preventive maintenance that nurtures system performance) and failure (via corrective repair, retrofit, and replacement)	Deploy technologies and protocols that significantly reduce the need for maintenance intervention of installed CC&C systems

contaminated with organic compounds or nutrient-rich explosive compounds (e.g., energetics containing fixed nitrogen). These techniques also are generally limited to relatively shallow depths, and their successful application depends on improved understanding of natural processes, including site-specific feasibility studies to verify their applicability and intensive observation of deployed systems to promote confidence in predictions of their long-term performance.

The thermobiogeochemical manipulations that offer the greatest promise for immobilizing and detoxifying metals and long-lived radionuclides are those that emulate natural systems in which similar materials have remained stable over extensive periods, including permeable reactive barrier systems and *in situ* redox manipulation by chemical or biological means. These approaches can stabilize contaminants by creating geochemical conditions that favor formation of stable compounds, either directly or by stimulating microbial communities to create such conditions. Thermal treatment techniques can reduce contaminant mobility by altering the physical setting, as in thermal desorption or vitrification, as well as by altering the rate of chemical changes.

As with other thermobiogeochemical manipulations, improved capabilities for emulating nature are needed to overcome the practical limitations on the depths and geologic settings in which currently available techniques can be deployed. In order for these techniques to be effective in reducing the costs, risks, and uncertainties of LTS, additional investigations are needed to more fully understand Mother Nature, specifically the natural chemical, physical, and biological processes that contribute to observed system performance or could degrade this performance over time. For example, effective prediction of the long-term performance and maintenance needs of permeable reactive barriers requires an understanding of biofouling and other ways that subsurface microbiological processes can enhance or degrade the effectiveness of these systems.[9] Also, an improved understanding of the differentiation of metals within the melt zone is needed to support predictions of the performance of *in situ* vitrification.[10]

Again, the ability to predict, monitor, and verify system performance is essential for effective LTS. Current approaches, such as those relying on groundwater monitoring data, typically treat CC&C systems as black boxes, providing only confirmation of system performance (for now) or failure. They do not provide the ability to determine (or predict) when events that could lead to failure are occurring and thereby do not permit responses (intervention) that could extend the period of performance. Improved knowledge of the best leading indicators of potential failure ("precursors to failure") for critical system components is needed as well.

For all types of CC&C systems, improvements in the ability to predict system performance over long periods of time will require refinements in our understanding of the fundamental natural physical, chemical, and biological processes that contribute to the observed behavior of CC&C systems, the evolution of these systems over time, and the external factors and events that act on these systems.

Finally, improved analytical tools for system performance prediction and improved monitoring capabilities to verify system performance and our models of system performance will greatly enhance our future ability to design and implement systems that are more readily and more effectively monitored and maintained.

Over time, we know that natural processes such as ecological succession and pedogenesis will prevail. Furthermore, the nature, magnitude, and rate of these processes will be influenced by climate change.[11] These processes must be anticipated and factored into system planning and design if long-term environmental management programs that involve waste containment and control are to succeed. The importance of accommodating environmental change into system design, implementation, and maintenance is illustrated by Fig. 4.

In fact, over the past few years considerable progress has been made in understanding the relationship of environmental processes to CC&C systems by studying natural analogs and incorporating them into system planning, design, and performance evaluation.[12–14] Natural analogs give us information about what has occurred and increase our ability to look forward in time. Significant advancements have occurred with regard to developing alternative cover systems that mimic the geomorphology, soils, and ecology of natural settings having favorable attributes for long-term containment. For example, a cover constructed for a uranium mill tailings disposal cell at the Monticello, Utah, Superfund site relies on a thick loam soil to retain water during the wet season and a diverse native plant community to remove stored water during the growing season.[15] Gravel and cobble mixed into the surface mimic the erosion protection

Fig. 4. Sycamore, tree-of-heaven, and Japanese knotweed growing on a disposal cell cover. Root intrusion increased the hydraulic conductivity of the compacted clay layer by two orders of magnitude.

of desert pavements in the area and act as a mulch to enhance plant establishment. Progress has also been made in the use of natural analog studies to better project the long-term performance of existing cover systems. For example, investigations of the morphology of natural and archaeological soil profiles provide clues about rates of pedogenesis and possible future changes in the hydraulic properties of engineered soil covers.

Subsurface containment and control systems can also be designed to mimic natural analog processes. Natural ore deposits are one source of insight into how natural processes can effectively immobilize toxic materials in the subsurface. For example, the bog iron deposits that humans first exploited in the Iron Age were formed when iron and manganese that were dissolved in groundwater entered ancient wetlands and were precipitated there by a combination of reducing chemical conditions and bacterial activity in the wetland environment. Engineered wetlands create an analogous situation, providing an anoxic and biologically active zone for the biodegradation of organic contaminants or the capture and transformation of inorganic contaminants in discharging groundwater.

As another example, the sandstone-hosted uranium ore deposits found in the western United States formed from chemical precipitation at locations where flowing groundwater that contained small amounts of dissolved uranium encountered reducing conditions, sometimes due to buried organic material. The dissolved uranium was converted from the oxidized state, in which it is relatively soluble, to a reduced state, in which it forms stable insoluble compounds.

A technology that mimics this natural phenomenon is the permeable reactive barrier.[16] This barrier is typically a vertical slurry wall constructed of a permeable and chemically active material, such as metallic iron filings (a reducing agent) or an ion-exchange medium. As flowing groundwater passes through this region, contaminants are broken down or immobilized by chemical reaction with the reactive material. If systems such as these, which take advantage of natural processes, can be successfully tailored to specific contaminated sites, they should reduce both the uncertainties and the operating and maintenance costs of long-term subsurface containment and control of contaminants.

The bottom line for all types of CC&C systems is that the second law of thermodynamics will prevail. In any contest, nature will win—it is just a matter of time—unless we abandon the contest and adopt engineered systems that exploit or accommodate natural processes rather than combating them, develop the ability to perform longer-term forecasting, incorporate change into our designs, and revise as we learn (meaning that an ability to remain flexible is also required).

Although a few alternative cover system designs have been proposed and are being tested, and although a handful of these designs have been implemented at full scale,[17] a regulatory constraint still exists in that RCRA requires any alternative design to be "equivalent" to the prescriptive designs that have been promulgated. Equivalency for several approaches is being demonstrated by the DOE[18] and the U.S. Environmental Protection Agency.[19] Permeable reactive barriers, engineered wetlands, and other innovative subsurface CC&C technologies also are being tested and piloted at several sites and have been found to have substantial promise.[9] Successful implementation of these concepts will depend on a solid scientific understanding of site-specific conditions, contaminant behavior, and the natural processes that interact with these systems and can either enhance or undermine their performance. For example, observation of installed systems is needed in order to accurately anticipate how soil invertebrates will affect cover systems in a particular ecological setting, or how subsurface bacterial activity will enhance or degrade the performance of a permeable reactive barrier.

5. SUMMARY AND CONCLUSIONS

Long-term environmental stewardship is best approached by defining a stewardship system that has several key core functions. Those identified by the Science and Technology Roadmap Team for DOE's long-term environmental stewardship program were *contain*, *monitor*, *communicate*, and *manage*, or $S = (MC)^2$.[20] Necessary capabilities and associated targets developed by topical working groups were organized within these four core functions; the CC&C working group focused on systems for containing and controlling contamination at DOE sites.

The challenge of designing a CC&C system that must perform for hundreds to thousands of years is daunting and unprecedented. This sobering endeavor is best viewed from a very different perspective. The working group determined that rather than "fighting Mother Nature" (which is just what we have been doing), we must learn to work with nature and find ways to accommodate environmental forces and change.

This requires an ability to predict change as well as to integrate prediction, monitoring, risk assessment, and evaluation results into improved planning and design through an iterative process. Enhanced analytical tools that permit an evaluation of potential events, consequences, and response costs for the contemplated system designs are needed to allow actual LTS requirements to be estimated before decisions are made.[21]

Achieving these targets will require developing and demonstrating a variety of techniques. No single technology, model, or maintenance protocol could address the full range of situations encountered at sites that will require LTS. The research and development needs related to these technologies can be thought of as belonging to two thematic areas: improved understanding of Mother Nature and improved capabilities for emulating natural processes.

In summary, the challenge posed by the need to ensure prevention of harmful exposures to hazardous and radioactive residuals contained at sites for hundreds to thousands of years is daunting and unprecedented. Our best hope lies in developing an ability to forecast and accommodate the effects of environmental changes on the systems we design and install. Major progress has been made already through rethinking our approach to use natural analogs and other tools in our planning and design rather than fighting nature. To be successful in implementing CC&C systems that accommodate environmental change, we will need good science—a good understanding of site-specific conditions, contaminant behavior, and the natural processes that affect containment and control systems over time. Flexibility will also be needed so we can most productively incorporate the improved knowledge and understanding that will come from our efforts.

ACKNOWLEDGMENTS

The authors gratefully acknowledge support from the U.S. Department of Energy, Office of Assistant Secretary for Environmental Management; leadership and management of the overall roadmap project from representatives of Idaho National Engineering and Environmental Laboratory, particularly Steve Kowall, Bruce Halbert, and Kevin Kostelnik; excellent facilitation with the roadmap process from Doug Hamelin and Brian Parker; valuable insight from Bob Katt of Robert Katt & Associates, Inc.; and inspiring and fruitful interactions with the other working group members and their chairs, Dave Borns, Bill Freudenburg, and Jim Mohatt. Portions of the work were performed at Vanderbilt University, Argonne National Laboratory, Department of Energy Grand Junction Office, Oak Ridge National Laboratory (ORNL), and the Idaho National Engineering and Environmental Laboratory. Vanderbilt efforts are supported by the Consortium for Risk Evaluation with Stakeholder Participation (CRESP) through U.S. Department of Energy Grant DEF628-00NT40938. Work at Argonne National Laboratory is performed under U.S. Department of Energy contract W-31-109-Eng-38. GJO is managed by S. M. Stoller Corp. under contract DE-AC13-02GJ79491, ORNL is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

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