DESIGN, PERFORMANCE, AND SUSTAINABILITY OF ENGINEERED COVERS FOR URANIUM MILL TAILINGS

W. Jody Waugh

Environmental Sciences Laboratory*
S.M. Stoller Corporation
2597 B ¾ Road
Grand Junction, Colorado 81503
970–248–6431
jody.waugh@gjo.doe.gov

Final remedies at most uranium mill tailings sites include engineered covers designed to contain metals and radionuclides in the subsurface for hundreds of years. Early cover designs rely on compacted soil layers to limit water infiltration and release of radon, but some of these covers inadvertently created habitats for deep-rooted plants. Root intrusion and soil development increased the saturated hydraulic conductivity several orders of magnitude above design targets. These covers may require high levels of maintenance to sustain long-term performance. Relatively low precipitation, high potential evapotranspiration, and thick unsaturated soils favor long-term hydrologic isolation of buried waste at arid and semiarid sites. Later covers were designed to mimic this natural soil-water balance with the goal of sustaining performance with little or no maintenance. For example, the cover for the Monticello, Utah, Superfund site relies on a thick soil-sponge layer overlying a sand-and-gravel capillary barrier to store precipitation while plants are dormant and on native vegetation to dry the soil sponge during the growing season. Measurements of both off-site caisson lysimeters and a large 3-ha lysimeter built into the final cover show that drainage has been well below a U.S. Environmental Protection Agency target of less than 3.0 mm/yr. Our stewardship strategy combines monitoring precursors to failure, probabilistic risk-based modeling, and characterization of natural analogs to project performance of covers for a range of possible future environmental scenarios. Natural analogs are needed to understand how ecological processes will influence cover performance, processes that cannot be predicted with short-term monitoring and existing numerical models.

Introduction

The U.S. Department of Energy Office of Legacy Management (DOE–LM) is responsible for long-term stewardship of disposal sites for uranium mill tailings (www.gjo.doe.gov/LM/). Final remedies at most sites include engineered covers. Cover design and performance evaluation guidelines are prescriptive in nature and fail to consider consequences of inevitable changes in ecological settings (1,2). In contrast, the DOE–LM Environmental Sciences Laboratory (ESL) in Grand Junction, Colorado, combines monitoring, modeling, and natural analog studies to evaluate the long-term performance of covers. Below are examples and lessons learned over many years of experience monitoring existing covers, designing alternative covers that accommodate ecological change, and using natural analog studies in combination with monitoring and modeling to project the long-term performance of covers for uranium mill tailings.

Monitoring Existing Covers

Disposal cell covers designed to satisfy the Uranium Mill Tailings Radiation Control Act of 1978 (UMTRCA) have evolved in response to regulatory changes and lessons learned (3). Early designs focused on radon attenuation and a 1,000-year longevity standard (4). Early designs basically consisted

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of three layers: 1) a compacted soil layer (CSL) overlying the tailings for radon attenuation, 2) a surface layer of durable rock for erosion protection, and 3) a lateral drainage layer consisting of coarse sand or gravel sandwiched between the CSL and the surface layer (2). The CSLs were later advocated as low-permeability barriers (2).

Plants began growing in the rock-armored, low-permeability covers within a few years after construction (5). Plant encroachment should have been anticipated. Surface layers of rock reduce evaporation (6), increase soil water storage (7), and, consequently, create habitat for deep-rooted plants. Deep-rooted plants may either decrease or increase the likelihood of contaminant releases from disposal cells, thus long-term maintenance has become problematic. Extraction of soil water by plants (transpiration) may significantly decrease recharge through covers. Even in humid climates where precipitation exceeds potential evapotranspiration (ET), water extraction by plants may account for more than half of soil water loss from disposal cell covers (8). Woody vegetation has also been shown to improve the stability of riprap-armored slopes (9).

Conversely, plants rooted in uranium mill tailings may contain elevated levels of U, Mo, Se, ^{226}Ra, ^{230}Th, and ^{210}Po (10,11,12). Radon-222 can be transported into the atmosphere through transpiration water (13). Roots may also alter waste chemistry, potentially mobilizing contaminants (14). Root intrusion can physically degrade covers. CSLs are vulnerable to desiccation and cracking from wet–dry cycles, freeze–thaw cycles, and biointrusion (8,15). Macropores left by decomposing plant roots may act as channels for water and gases to bypass the soil mass in CSLs. Plant roots also tend to concentrate in and extract water from CSLs high in clay, causing desiccation and cracking, even when overlying soils are nearly saturated (16). Furthermore, roots can clog lateral drainage layers (5), potentially increasing percolation rates.

A cover constructed at Shiprock, New Mexico, in 1986, before the U.S. Environmental Protection Agency (EPA) proposed groundwater quality standards for UMTRCA sites, exemplifies the dilemma. The Shiprock area receives an average of about 15 cm precipitation per year. The Shiprock cover consists of three layers: a 198-cm silt loam CSL for radon attenuation, a 15-cm sand drainage layer overlying the CSL, and a 30-cm layer of large, durable cobble sized to prevent erosion. Early laboratory tests suggested that the Shiprock CSL had a saturated hydraulic conductivity (K_{sat}) between 6.4 x 10^{-8} and 2.3 x 10^{-6} cm/s (17). After groundwater standards for UMTRCA sites were promulgated, DOE became concerned that potentially deep-rooted plants observed growing on the cover, including tamarisk, rabbitbrush, and Russian thistle, could increase the permeability of the CSL.

Soil moisture monitoring and in situ measurements of K_{sat} suggest that recharge through the cover is higher than previously thought (18). Neutron hydroprobe measurements from June 1999 through September 2000 show that the CSL and upper tailings were saturated. In situ K_{sat} was measured using air-entry permeameters (19) in pits where tamarisk, rabbitbrush, and Russian thistle rooted into the CSL and in adjacent pits without plant roots. Results were highly variable with a mean K_{sat} equal to 4.4 x 10^{-5} cm/s. Given saturation of the CSL and tailings and a higher K_{sat} than previously assumed, higher than expected recharge through the cover is likely. ESL is investigating methods for direct measurement of water flux from the cover and, as a contingency, for retrofitting the cover to accelerate plant establishment and ET (see “Alternative Cover Design”). Regulatory agreements currently require spraying cover vegetation with herbicides.

Effects of root intrusion on the performance of the cover at the Burrell, Pennsylvania, site were also evaluated (20). Annual precipitation at Burrell averages more than 100 cm/yr. The Burrell cover consists of a 90-cm CSL overlying tailings materials, a 30-cm sand and gravel drainage layer, and a 30-cm rock riprap layer. Within 3 years after construction, woody plants, including sycamore, box elder, black locust, tree-of-heaven, and Japanese knotweed, began emerging from the rock cover. Within 10 years, Japanese knotweed had rooted through the CSL. At Burrell, K_{sat} averaged 3.0 x 10^{-5} cm/s at locations where Japanese knotweed roots penetrated the CSL, but only 2.9 x 10^{-7} cm/s at locations without plants. The weighted-average K_{sat}, calculated using the leaf area index (LAI) (21) for Japanese knotweed, was 4.4 x 10^{-6} cm/s. At a nearby site with a subsoil similar to the material used to construct the CSL, the K_{sat} averaged 1.3 x 10^{-4} cm/s. Earthworm holes, root channels, and pedogenic structure all contributed to macropore flow. The nearby site was considered to be a reasonable analog of a long-term ecological scenario for the Burrell cover (see "Natural Analogs of Long-Term Performance").

Alternative Cover Design

Lessons learned from monitoring early UMTRCA covers contributed to design improvements. DOE and EPA Region 8 collaborated on an alternative design for a uranium mill tailings disposal cell at the Monticello, Utah, Superfund site (22). The goal at Monticello was to design an engineered cover system that enhances beneficial natural processes to help make long-term containment possible (23).

At semiarid sites such as Monticello, relatively low precipitation (P), high potential evapotranspiration (PET), and thick unsaturated soils seem to favor long-term hydrologic isolation of buried waste (24). But simple P/PET relationships inadequately predict recharge that can approach 60 percent of precipitation in arid-land soils denuded of vegetation (25). Recharge can be minimized if disposal cells are covered with thick, fine-textured soil layers that store precipitation in the root zone where ET seasonally removes it (26,27). Capillary barriers consisting of coarse-textured sand and gravel placed below this soil-sponge layer can enhance water storage and limit unsaturated flow (28,29).

The Monticello cover design (Figure 1) relies on the water-storage capacity of a 163-cm fine-textured soil-sponge layer overlying a 38-cm capillary barrier of coarse sand to retain precipitation until it is seasonally removed by vegetation. Gravel mixed into the surface helps control erosion when vegetation is sparse (following construction, fires, drought, etc.), mimicking conditions that lead to the formation of gravel pavements. The gravel admixture can control both wind and water erosion (30,31) and can enhance seedling emergence and plant growth by functioning as a mulch. The soil-sponge thickness is the primary biointrusion deterrent. Water retention in the soil sponge creates habitat for relatively shallow-rooted plants, and the thickness of the sponge exceeds the depth of most burrowing vertebrates in the Monticello area. A layer of cobble-size rock 30.5 cm above the capillary barrier is an added deterrent should deeper burrowers, such as prairie dogs, move into the area in response to climate change. Fine-textured sponge soil fills the interstices of the cobble layer, preventing it from behaving like a second capillary barrier. Physical and hydraulic properties of the topsoil layer, obtained from the root zone of the

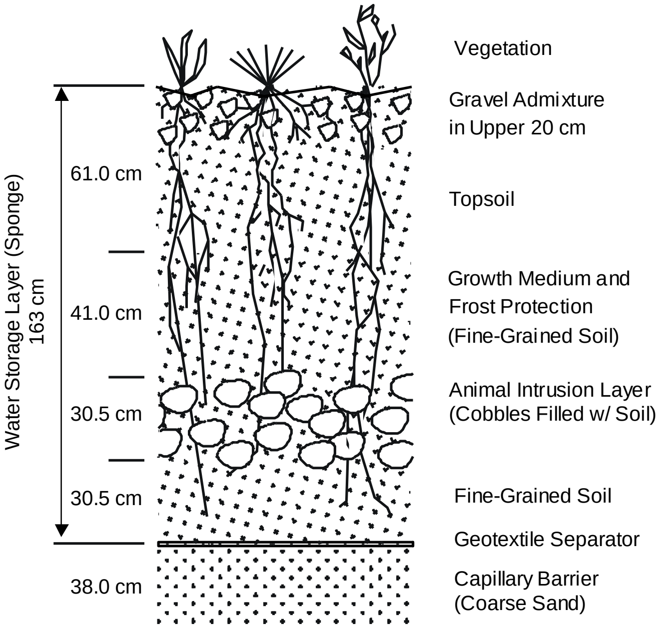

Figure 1. Alternative cover constructed at Monticello, Utah.

borrow area, match the rest of the soil sponge. However, the topsoil also contains available nutrients, propagules, and microorganisms (e.g., mycorrhizae) needed to sustain a diverse and resilient plant community.

ESL personnel conducted a series of field lysimeter experiments to help design and monitor the performance of the Monticello cover. The lysimeter test facility evolved as a sequence of installations, first to test the concept of using an ET/capillary barrier cover design at Monticello, next to evaluate the soil-water balance of the design, and finally to monitor the hydrologic performance of a large facet of the completed cover. In 1990, ESL installed small weighing lysimeters containing intact, 100-cm-deep columns of undisturbed native silt loam soil (monoliths) overlying a pea-gravel capillary barrier and supporting mature native grasses (32). Leaf water potential, leaf transpiration, and whole-plant gas exchange of plants growing in and adjacent to the lysimeters were compared to test the physiological responses of plants to confinement in the small lysimeters. Favorable results led to construction of an array of 15 additional small weighing lysimeters in 1993 to compare drainage, ET, and water-storage capacities of cover designs with varying soil types and soil layer thickness (32). Favorable results this time led to a final cover design for Monticello.

In 1999, ESL teamed with EPA Region 8 on a study using large caisson lysimeters to evaluate the hydrological and ecological performance of the Monticello cover as built. Covers constructed inside the caissons matched the range of conditions as built in the actual cover (33). Finally, in 2000, ESL and the EPA Alternative Cover Assessment Program (ACAP) collaborated on installation of a large drainage lysimeter under a 3-ha facet of the 14-ha disposal cell cover at Monticello. Both the caisson and ACAP lysimeter studies show that plant transpiration has kept drainage flux levels well below the EPA target of 3.0 mm/yr.

Natural Analogs of Long-Term Performance

Understanding how inevitable ecological processes may alter the long-term performance of engineered covers is crucial to designing, constructing, and maintaining cover systems (34). Effective performance modeling requires both current and possible future ecological scenarios (35). Natural analog studies are needed to identify and evaluate likely shifts in cover environments (36), to design covers that mimic favorable natural systems, to bound possible future conditions for input to models, and to provide clues about the possible evolution of engineered covers as a basis for monitoring precursors of failure. Natural analogs also provide tangible evidence of the reliability of numerical predictions. ESL and its partners have collaborated on studies of natural and archaeological analogs to discern likely long-term changes in the environmental setting of cover systems, including climate change, pedogenesis (soil development), and ecological succession (37).

Reasonable projections of possible future changes in climate states and extreme events are needed to design sustainable covers. ESL and its partners are demonstrating methods based on global change models and paleoecological evidence to establish a first approximation of possible future climatic states at DOE–LM sites. A preliminary analysis of paleoclimate data for Monticello yielded average annual temperature and precipitation ranges of 2 to 10 °C and 80 to 60 cm, respectively, corresponding to late glacial and mid-Holocene periods (38). Instrumental records were used as a basis for selecting soil and vegetation analog sites that span a reasonable range of future climate scenarios for Monticello (37).

Pedogenic processes will change the soil physical and hydraulic properties of engineered covers. Pedogenesis includes processes such as formation of macropores and preferential flow associated with root growth, animal holes, and soil structural development; secondary mineralization, deposition, and illuviation of fines, colloids, soluble salts, and oxides that can alter water storage and movement; and soil mixing caused by freeze–thaw activity, animal burrows, and the shrink–swell action of expansive clays (37). ESL and its partners are characterizing natural and archaeological soils considered representative of pedogenic changes in engineered cover soils. For example, key soil physical and hydraulic properties at natural and archaeological soil profiles at climate analog sites were measured to infer possible future pedogenic changes in the performance of the Monticello cover.

Plant communities will establish and change on soil covers in response to climate, soil development, and disturbances such as fire, grazing, or noxious plant invasion. Changes in plant abundance, ET rates, root instrusion, and animal habitat may alter the soil water balance and stability of a cover. ESL and its partners draw evidence of possible future ecological changes using successional chronosequences (a mosaic of plant communities that represent different stages of recovery following a disturbance). For example, at the Lakeview, Oregon, uranium mill tailings disposal site, possible future responses of plant community composition and LAI to fire were evaluated using a regional chronosequence. Similarly, possible future vegetation responses to climate change scenarios were evaluated at regional global-change analog sites. LAI, an index of plant transpiration, ranged from 0.15 to 1.28 for the fire chronosequence and from 0.43 to 1.62 for dry and wet climate analog sites.

Conclusions

The DOE office in Grand Junction, Colorado, has learned several lessons from monitoring, designing, and evaluating the long-term performance of engineered covers constructed to contain uranium mill tailings in the subsurface that could be of benefit to designers of the next generation of covers.

Early rock-armored covers that rely on CSLs to limit water movement into tailings may fall short of permeability targets, and many inadvertently created habitats for deep-rooted plants. Root intrusion and soil development may have increased the K_{sat} several orders of magnitude above design targets in several covers. At Shiprock, New Mexico, ESL is evaluating methods for measuring flux directly to ensure that ongoing efforts to remediate groundwater are not compromised by contaminants seeping from the disposal cell. Saturated flow into tailings is likely occurring in the Burrell, Pennsylvania, disposal cell. But because of low contaminant concentrations, root intrusion and increased saturated flow are not adversely impacting human health or the environment at the Burrell site. Overall, these low-permeability covers attempt to resist natural processes, rather than work with them, and will likely require increasing levels of maintenance or retrofitting to sustain long-term performance.

Relatively low precipitation, high potential ET, and thick unsaturated soils favor long-term hydrologic isolation of buried waste at arid and semiarid sites. The cover constructed at the Monticello site mimics this natural soil-water balance. The Monticello cover relies on a thick soil sponge layer overlying a sand and gravel capillary barrier to store precipitation while plants are dormant and on native vegetation to dry the sponge layer during the growing season. Lysimeter results show that less than 0.05 mm of drainage has occurred since 2000, an amount well below the EPA target of less than 3.0 mm/yr.

Given unprecedented longevity requirements, a stewardship objective should be to design or retrofit covers to accommodate long-term ecological processes with the goal of sustaining performance with as little maintenance as possible. Investigations of natural analogs can provide insights into how ecological processes may influence the performance of engineered covers. Evidence from natural analogs can improve our understanding of meteorological variability associated with possible long-term changes in climate; vegetation responses to climate change and disturbances; effects of vegetation dynamics on ET, soil permeability, soil erosion, and animal burrowing; and effects of soil development processes on water storage and permeability.

Literature Cited

1. U.S. Environmental Protection Agency. Technical Guidance Document, Final Covers on Hazardous Waste Landfills and Surface Impoundments, EPA/530–SW–89–047, Washington, DC, USA (1989).

2. U.S. Department of Energy. Technical Approach Document, Revision II, UMTRA–DOE/AL 050425.0002, DOE UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico, USA (1989).

3. W.J. Waugh, G.M. Smith, D. Bergman-Tabbert, and D.R. Metzler. Evolution of Cover Systems for the Uranium Mill Tailings Remedial Action Project, US. Mine Water and the Environ. **20**:190–197 (2001).

4. U.S. Environmental Protection Agency. Health and Environmental Protection Standards for Uranium Mill Tailings. 48 FR 602, 40 CFR 192, Washington, DC. (1983).

5. U.S. Department of Energy. Vegetation Growth Patterns on Six Rock-Covered UMTRA Project Disposal Cells, DOE UMTRA Project Office, Albuquerque Operations Office, Albuquerque, New Mexico, USA (1992).

6. P.H. Groenevelt, P. van Straaten, V. Rasiah, and J. Simpson. Modification in Evaporation Parameters by Rock Mulches. Soil Technol. **2**:279–285 (1989).

7. W.D. Kemper, A.D. Nicks, and A.T. Corey. Accumulation of Water in Soils Under Gravel and Sand Mulches. Soil Sci. Soc. Am. J. **58**:56–63 (1994).

8. S. Melchior, K. Berger, B. Vielhaber, and G. Miehlich. “Multilayer Landfill Covers: Field Data on the Water Balance and Liner Performance,” in: G.W. Gee and N.R. Wing (eds.), In-Situ Remediation: Scientific Basis for Current and Future Technologies, Battelle Press, Columbus, Ohio, USA, pp. 411–425 (1994).

9. R.P.C. Morgan and R.J. Rickson (eds.). Slope Stabilization and Erosion Control: A Bioengineering Approach. Chapman and Hall, London (1995).

10. D.R. Dreesen, and J.M. Williams. Mobility and Bioavailability of Uranium Mill Tailings Contaminants. Environ. Sci. Technol. **16**:702–709 (1982).

11. L.R. Hosner, H.J. Woodard, and J. Bush. Growth and Selenium Uptake of Range Plants Propagated in Uranium Mine Soils. J. Plant Nutrition **15**:2743–2761 (1992).

12. P.M. Markose, I.S. Bhat, and K.C. Pillai. Some Characteristics of ^{226}Ra Transfer From Soil and Uranium Mill Tailings to Plants. J. Environ. Radioactivity **21**:131–142 (1993).

13. R.C. Morris, and L. Fraley, Jr. Effects of Vegetation, a Clay Cap, and Environmental Variables on Rn-222 Fluence Rate From Reclaimed U Mill Tailings. Health Physics **56**:431–440 (1989).

14. D.A. Cataldo, C.E. Cowan, K.M. McFadden, T.R. Garland, and R.E. Wildung. Plant Rhizoshpere Processes Influencing Radionuclide Mobility in Soil, PNL–6277, Pacific Northwest National Laboratory, Richland, Washington, USA (1987).

15. W.H. Kim, and D.E. Daniel. Effects of Freezing on the Hydraulic Conductivity of Compacted Clay. J. Geotech. Eng. **118**:1083–1097 (1992).

16. T.E. Hakonson. Evaluation of Geologic Materials To Limit Biological Intrusion Into Low-Level Radioactive Waste Disposal Sites, LA–10286–MS, Los Alamos National Laboratory, Los Alamos, New Mexico, USA (1986).

17. U.S. Department of Energy. Moisture Contents and Unsaturated Conditions in UMTRA Radon Barriers, UMTRA–DOE/AL, Uranium Mill Tailings Remedial Action Project, Albuquerque, New Mexico, USA (1989).

18. E. Glenn and J. Waugh. Disposal Cell Cover Moisture Content and Hydraulic Conductivity, Long-Term Surveillance and Maintenance Program, Shiprock, New Mexico, Site, GJO–2001–204–TAR, U.S. Department of Energy, Grand Junction, Colorado, USA (2001).

19. D.B. Stephens, M. Unruh, J. Havlena, R.G. Knowlton, Jr., E. Mattson, and W. Cox. Vadose Zone Characterization of Low-Permeability Sediments Using Field Permeameters. Ground Water Monitoring Rev. **8**:59–66 (1988).

20. W.J. Waugh, S.J. Morrison, G.M. Smith, M. Kautsky, T.R. Bartlett, C.E. Carpenter, and C.A. Jones. Plant Encroachment on the Burrell, PA, Disposal Cell: Evaluation of Long-Term Performance and Risk, GJO–99–96–TAR, U.S. Department of Energy, Grand Junction, Colorado, USA (1999).

21. 25. J.M. Wells and J.M. Norman. Instrument for Indirect Measurement of Canopy Architecture. Agron. J. **83**:818–825 (1991).

22. J. Berwick, T. Meiers, and J. Waugh. Expansive Cover Installed by DOE To Contain Mixed Wastes in Eastern Utah. EPA Tech Trends, May 2000, U.S. Environmental Protection Agency, Washington, DC, USA (2000).

23. W.J. Waugh and G.N. Richardson. “Ecology, Design, and Long-Term Performance of Surface Barriers: Applications at a Uranium Mill Tailings Site,” in: Barrier Technologies for Environmental Management, National Research Council. National Academy Press, Washington, DC, USA, pp. 36–49 (1997).

24. C.C. Reith and B.M. Thompson (eds.). Deserts as Dumps? The Disposal of Hazardous Materials in Arid Ecosystems. University of New Mexico Press, Albuquerque, New Mexico, USA (1992).

25. G.W. Gee and S.W. Tyler (eds.). Symposium: Recharge in Arid and Semiarid Regions. Soil Science Society of America Journal **58**:5–72 (1994).

26. S.O. Link, W.J. Waugh, and J.L. Downs. “The Role of Plants on Isolation Barrier Systems,” in: G.W. Gee and N.R. Wing (eds.), In-Situ Remediation: Scientific Basis for Current and Future Technologies. Battelle Press, Columbus, Ohio, USA (1994).

27. A. Ward and G. Gee. Performance Evaluation of a Field-Scale Surface Barrier. Journal of Environmental Quality **26**:694–705 (1997).

28. J. Stormont and C. Anderson. Method To Estimate Water Storage Capacity of Capillary Barriers. Journal of Geotechnical and Geoenvironmental Engineering **124**:297–302 (1998).

29. M.V. Khire, C.H. Benson, and P.J. Bossher. Capillary Barriers: Design Variables and Water Balance. Journal of Geotechnical and Geoenvironmental Engineering **126**:695–708 (2000).

30. M.W. Ligotke. “Control of Eolian Soil Erosion From Waste-Site Surface Barriers,“ in: G.W. Gee and N.R. Wing (eds.), In-Situ Remediation: Scientific Basis for Current and Future Technologies, Battelle Press, Columbus, Ohio, USA, pp. 545–559 (1994).

31. J.B. Finley M.D. Harvey, and C.C. Watson. “Experimental Study: Erosion of Overburden Cap Material Protected by Rock Mulch,” in: Proceedings of Seventh Symposium on Management of Uranium Mill Tailings, Low-Level Waste, and Hazardous Waste,. Colorado State University, Ft. Collins, Colorado, USA, pp. 273–282 (1985).

32. W.J. Waugh. “Monticello Field Lysimetry: Designing and Monitoring an Alternative Cover,” Proceedings of the Waste Management 2002 Symposium, February 25–28, University of Arizona, Tucson, Arizona, USA (2002).

33. W.J. Waugh, G.M. Smith, and P. Mushovic. “Monitoring the Performance of an Alternative Cover Using Caisson Lysimeters,” Proceedings of the Waste Management 2004 Symposium, University of Arizona, Tucson, Arizona, USA (2004).

34. J.H. Clarke, M.M. MacDonell, E.D. Smith, R.J. Dunn, and W.J. Waugh. Engineered Containment and Control Systems: Nurturing Nature. Risk Analysis (In Press).

35. C.K. Ho, B.W. Arnold, J.R. Cochran, and R.Y. Taira. Development of a Risk-Based Probabilistic Performance Assessment Method for Long-Term Cover Systems, Second Edition, SAND2002–3131, Sandia National Laboratories, Albuquerque, New Mexico, USA (2002).

36. W.J. Waugh, K.L. Petersen, S.O. Link, B.N. Bjornstad, and G.W. Gee. “Natural Analogs of the Long-Term Performance of Engineered Covers,” in: G.W. Gee and N.R. Wing (eds.), In-Situ Remediation: Scientific Basis for Current and Future Technologies, Battelle Press, Columbus, Ohio, pp. 379–409. (1994).

37. J. Waugh, S. Link, E. McDonald, D. Rhode, and S. Sharpe. Characterization of the Environmental Envelope for the Design of Long-Term Covers: Closeout Report, GJO–2003–48–TAC, Environmental Sciences Laboratory, U.S. Department of Energy, Grand Junction, Colorado, USA (2003).

38. W.J. Waugh and K.L. Petersen. “Paleoclimatic Data Application: Long-Term Performance of Uranium Mill Tailings Repositories,” in: W.J. Waugh (ed.), Climate Change in the Four Corners and Adjacent Regions: Implications for Environmental Restoration and Land-Use Planning, CONF–9409325, U.S. Department of Energy, Grand Junction, Colorado, USA, pp. 163–185 (1995).