Williams, L., Hoyt, D., Dwyer, S., Hargreaves, G., and Zornberg, J.G. (2011). "Design Criteria and Construction of a Capillary Barrier Cover System: The Rocky Mountain Arsenal Experience," Proceedings of the *GeoFrontiers 2011 Conference,* Geo-Institute of ASCE, Dallas, Texas, March 13-16, pp. 996-1005.

Design Criteria and Construction of a Capillary Barrier Cover System: The Rocky Mountain Arsenal Experience

L.O. Williams[1], D.L. Hoyt[2], P.E., S.F. Dwyer[3], Ph.D., P.E., G.A. Hargreaves[4], J.G. Zornberg[5], Ph.D., P.E.

[1]US Environmental Protection Agency, Denver, USA; PH: 303-312-6660;
email: williams.laura@epa.gov
[2] Pacific Western Technologies, Denver, USA; PH: 303-274-5400;
email: dhoyt@pwt.com
[3]Dwyer Engineering, Albuquerque, USA; PH: 505-844-0595;
email: dwyerengineering@yahoo.com
[4]US Environmental Protection Agency, Denver, USA; PH: 303-312-6661;
email: Hargreaves.greg@epa.gov
[5]The University of Texas at Austin, Austin, USA; PH: 512-232-3595;
email: zornberg@mail.utexas.edu

ABSTRACT

Capillary Barrier Cover Systems were recently designed and constructed over contaminated materials at the Rocky Mountain Arsenal (RMA) located near Denver, Colorado. The design and compliance of the infiltration control component of the covers at the site are governed by a quantitative percolation criterion . During an initial field demonstration for evaluation of alternative cover systems in achieving the criterion, formation of a capillary barrier was found to play a critical role. This paper discusses design studies, construction criteria and construction approaches that were developed for this capillary barrier cover system, as well as initial information from the long-term monitoring of the cover system performance. The use of index soil properties for the soil storage component of the cover was found to be suitable for construction specifications, but required implementation of a comprehensive borrow source characterization. The use of a laboratory column test program proved relevant to identify the different capillary barriers suitable for the full-scale cover system.

INTRODUCTION

Unsaturated soil covers that feature a capillary barrier are considered "alternative" covers within the US regulatory framework because closure requirements for hazardous waste facilities are generally "prescriptive" (i.e., the cover components are explicitly defined in regulations and/or guidelines). Generally, these regulations allow deviations (or alternatives) from the prescriptive design if the measured alternative cover percolation is "equivalent" to that of a prescriptive cover. Unsaturated soil covers have been used at high-profile sites throughout the world (Dwyer 2003).

The RMA site is regulated under the US Environmental Protection Agency's (EPA) Superfund program and was once considered to contain the "most contaminated square mile on earth" (Frumkin 2005). A primary remedy component at this site involves consolidation of contaminated soils beneath six unsaturated soil covers which span over 183 hectares (ha). The first RMA alternative cover incorporating a capillary barrier, known as the Shell Cover, was constructed in 2007 over an 8.5 ha area in central RMA (Figure 1). Construction of four adjacent covers, known as the Integrated Covers System (133 ha), and the Basin F Cover (42 ha) followed between 2008 and 2010. These covers have a 1.22 m-thick soil layer that was constructed at a comparatively low relative compaction to promote vegetation growth. Below the soil layer is a capillary barrier composed of a nonwoven geotextile in the Shell Cover and of a 25 – 76 mm layer of clean-washed gravel in the other covers. Underneath this is a biota barrier consisting of crushed concrete and coarse gravel (chokestone). The post-construction monitoring program for all alternative covers includes regulatory-required gravity lysimeters to measure basal percolation. The Shell cover is also instrumented with water content reflectometers (WCRs) to measure moisture within the cover soils.

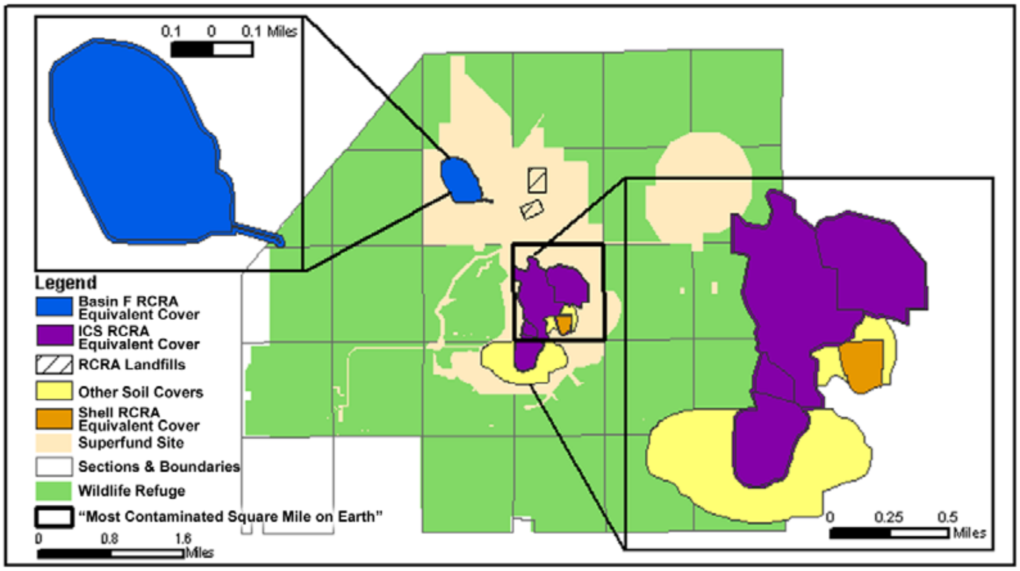

Figure 1. RCRA-Equivalent Cover locations at RMA.

SITE OVERVIEW

The RMA site originally consisted of 6,876 ha and is located 18.5 km northeast of Denver, Colorado, USA. Denver's climate is semiarid, with an average annual precipitation of 396 mm and an average pan evaporation of 1,394 mm. The wettest months of the year (April to October) also have the highest pan evaporation, which makes the RMA site well-suited for the use of unsaturated soil cover systems.

RMA was established in 1942 by the Army, and was used to manufacture chemical warfare agents and incendiary munitions for use in World War II. Beginning in 1946, some facilities were leased to private companies to manufacture industrial and agricultural chemicals. Shell Oil Company, the principal lessee, primarily manufactured pesticides from 1952 to 1982. Disposal practices used during these years resulted in contamination of structures, soil, surface water, and groundwater at levels that posed unacceptable health risks to humans and the environment. As a result, RMA was included on the EPA National Priorities List in 1987 and a remedy to address the on-post contamination was selected in a Record of Decision (ROD) signed in 1996. The ROD formally established the cleanup actions for approximately 1,214 ha of contaminated soil, over 750 structures, and 15 groundwater plumes.

The primary remedy approach was to interrupt the exposure pathways by (a) placing the most contaminated soil and structure demolition debris in two Resource Recovery and Conservation Act (RCRA) Subtitle C landfills constructed on-site; and (b) consolidating less-contaminated soil and structure debris under alternative covers in six highly contaminated areas considered too risky for excavation.

DESIGN OBJECTIVES

A key performance standard in the US for the alternative covers (e.g., unsaturated soil covers) is that they should function equivalently to covers constructed in accordance with Subtitle C of RCRA. EPA guidance (EPA 1991) for the design and construction of RCRA Subtitle C covers has endorsed the use of resistive barriers. Resistive cover systems involve a relatively impermeable liner (e.g., a compacted clay layer) constructed with a low saturated hydraulic conductivity soil (typically 10^{-9} m/s or less) along with a geomembrane to reduce basal percolation. The alternative cover systems originally proposed at RMA included evapotranspiration (ET) and moisture storage components. The novelty of this approach is the mechanism by which basal percolation control is achieved: an ET cover acts not as a barrier but as a reservoir that stores moisture during precipitation events, and then releases it back to the atmosphere as ET or lateral drainage. Based on the site-specific conditions and limited studies available at the time (e.g., Melchior 1997), a quantitative percolation criterion (QPC) of 1.3 mm/year was adopted in 1998 for design of the RMA alternative covers (RVO 1998). In addition to controlling storm water infiltration, the RMA covers must also prevent biointrusion, control erosion, and be compatible with the designated National Wildlife Refuge areas adjacent to the covers (FWENC 1996).

FIELD DEMONSTRATION

The equivalence demonstration project at RMA was conducted over several years, complemented with comparative numerical analyses (Kiel *et al.* 2002), with the goal of establishing a cover profile that met the established QPC. Four test covers, approximately 9.14 m by 15.24 m, were constructed at RMA in the summer of 1998. Data collected for these test plots include basal percolation, precipitation, moisture content, and overland runoff. Basal percolation was collected in pan lysimeters below each test plot, consisting of a geocomposite drainage layer underlain by geomembrane. WCRs measured volumetric moisture content profiles within each test cover and an all-season rain gauge measured precipitation (RVO 1998).

The four cover profiles tested were intended to be monolithic soil covers or ET covers. The covers varied in thickness (from 1.07 m to 1.52 m) and soil type (one profile consisted of coarser-grained soil) to allow for observation of the thinnest profile and best soil type that achieved the QPC. Success of the equivalence demonstration was initially based solely on lysimeter data, which provided a measurement that could be compared directly against the 1.3 mm/year QPC (Kiel *et al.* 2002). With this approach, the lysimeter measurements for all test plots at RMA satisfied the QPC over the demonstration period of 1998-2003. A soil depth of 1.07 m was selected as the thinnest that met the criteria.

However, scrutiny of the WCR data identified that all test plots had achieved the QPC assisted by the formation of a capillary break within the constructed test plots due to the presence of the geocomposite drainage layer below the soil. The capillary break was apparent based on the WCR data that showed wetting fronts moved down toward the base of the cover but were held within the fine soil profile above the geocomposite. The soil moisture content immediately above this geocomposite showed an increase in moisture content approaching saturation prior to measurement of percolation in the lysimeter. The moisture profile measured by the WCRs, placed at various depths within the cover profiles, documented that a capillary break formed between the fine cover soil and geocomposite of the lysimeter.

CAPILLARY BARRIERS

Capillary barriers generally consist of fine-grained soil over coarse-grained soil layers, though fine soil over a geotextile in lieu of coarse soil also produces a capillary barrier (Zornberg et al. 2009). Water is held in the fine soil until ET, horizontal drainage, or percolation removes the water. Differences in pore size distribution between the two layers cause infiltrated water to be retained in the upper soil layer under unsaturated flow conditions, as long as the contrast in unsaturated hydraulic conductivities of the soils in the two layers is sufficiently large (Dwyer 2003). The upper soil layer exhibits greater moisture content than the lower soil layer at the same matric suction. Thus, a capillary barrier effect results when a relatively fine-grained soil overlies a relatively coarse-grained soil or a geotextile. The matric suction in the fine-grained upper soil layer typically must become negligible (i.e., saturated conditions) before any appreciable flow occurs into the lower coarse-grained layer (or geotextile).

The performance of a capillary barrier can be explained by the following: beginning at relatively dry conditions, that is, at high suctions, the fine-grained soil has a significantly larger hydraulic conductivity than that of the coarse-grained soil layer. With increasing water content and decreasing matric suction, the hydraulic conductivity of the fine layer will increase gradually. The hydraulic conductivity of the coarse-grained soil layer will remain comparatively low until suction corresponding to the water entry value is overcome. Before reaching these conditions, water will not move from the fine-grained layer into the coarse layer even though the water content of the fine layer will increase. Breakthrough into the coarse-grained soil layer occurs when the matric suction at the interface equals that of the water entry value of the coarse-grained soil layer.

COVER DESIGN

Fine-Grained Soil Component of the Capillary Barrier

An important criterion for the cover soil was that the soil texture be within an Acceptable Zone (AZ) developed based on testing of the unsaturated hydraulic properties of the soils used in the successful test plots, as well as on the results of unsaturated flow modeling. Unsaturated flow modeling of a soil profile of similar thickness to the test cover profile was performed for the various soil textures within the designated on-site borrow areas. Modeling results that showed the profiles to be equivalent in flux yield to the test cover were deemed acceptable. Based on the modeling, the necessary performance soil properties (e.g. saturated hydraulic conductivity, moisture retention properties) were correlated to index soil properties (e.g. grain size ranges, plasticity index). The AZ was defined using the U.S. Department of Agriculture textural triangle (Figure 2) and identified the soil with percentages of silt, sand, and clay that were suitable to build the RCRA-Equivalent Covers (TTECI 2005).

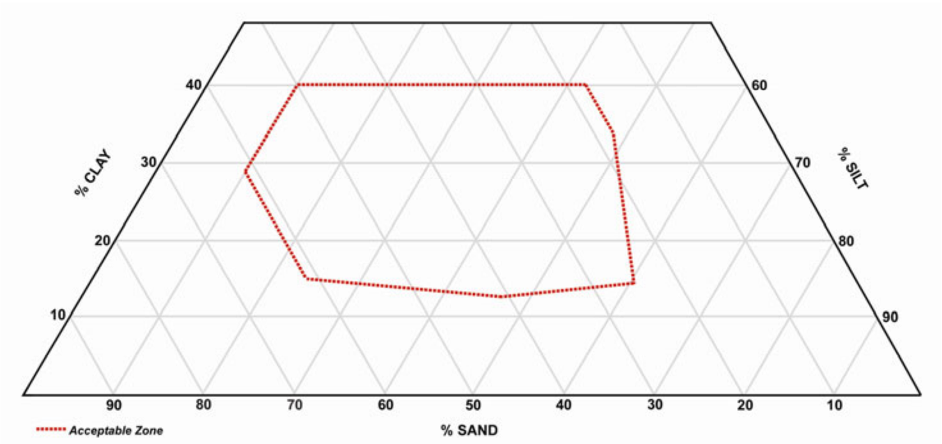

Figure 2. AZ for the fine-grained component of the capillary barrier.

Coarse Layer Component of the Capillary Barrier Design

Since the soil also serves as a rooting medium for native vegetation, it was required to have a degree of compaction ranging from 75 to 85 % of the Standard Proctor maximum dry density, and to meet minimum nutrient and organic matter content. In addition, the soil was required to have less than 15% calcium carbonate, a pH between 6.0 and 8.4, and less than 40% clay.

With these criteria, a detailed borrow area characterization program was implemented to identify soil that was acceptable for cover construction within on-site, RMA borrow areas (TTECI 2007). Almost 3.5 million bank cubic meters (bcm) of soil were evaluated through the excavation of test pits and collection of samples representing each 765 bcm of soil. Each sample was classified using visual/manual methods (ASTM D2488) and one sample per every 1,911 bcm was sent to the laboratory for particle size analysis (ASTM D422) and calcium carbonate equivalency (per USDA procedures) (TTECI 2007). Soil samples were also tested for plasticity, Standard Proctor dry density, and pH. Based on the results from this soil characterization effort, suitable soil that met the geotechnical and agronomic criteria of the AZ was mapped for borrow soil excavation.

Because the appropriate performance of the capillary barrier was critical, a laboratory demonstration project was conducted to evaluate the possible capillary break interfaces that could be proposed for implementation (TTFWI 2005). Each of the capillary break interfaces was built in a laboratory setting (Figure 3). Four columns were tested where fine soil was placed over: (a) geocomposite drainage layer similar to that used in the field test; (b) geotextile with chokestone beneath it; (c) chokestone only; (d) gravel only. Each column was then irrigated at the top of the column until breakthrough through the interface between the fine-grained and the coarse-grained (or geotextile) layers within the profile was recorded. Tipping buckets at the base of each column recorded the volume and time of percolation through each column. Breakthrough of each column occurred at similar suction values in the fine soil layer. The column including the geotextile layer, for example, showed that the soil above the interface had to wet to a matric suction of approximately 10 cm to allow water flow access the interface (Stormont et al. 2008). After infiltration was stopped, the matric suction in the soil above the interface increased until the coarse-grained soil layer (or geotextile) once again became non-conductive. Based on these results, it was concluded that each one of the four proposed interfaces would be adequate to promote the development of a capillary break.

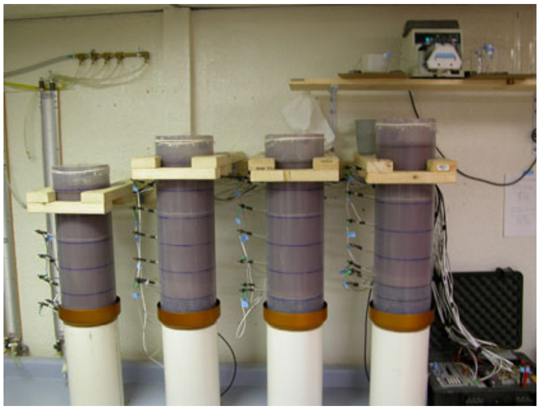

Figure 3. Column tests to simulate capillary barriers, Albuquerque, NM.

Other Design Aspects of the Covers

Much of the RMA is being transitioned to a National Wildlife Refuge; therefore, it is important to prevent the intrusion of wildlife into the waste below the cover systems. The size, weight and thickness of the biointrusion layer serves to prevent burrowing animals from penetrating it and accessing underlying contaminated soils. Another important design goal was that the RCRA-Equivalent covers remain effective throughout its design life while requiring minimal maintenance. As such, the cover materials were designated to be earthen and mimic natural conditions rather than rely on man-made materials. The cover surfaces were sloped to route water to drainage trenches that directed runoff away from the cover systems. A minimum slope of 3% was established, consistent with RCRA guidance (EPA 1991). An additional 15 cm of soil was added to the final cover profiles to offset expected, long-term soil loss due to wind and water erosion, resulting in a minimum soil thickness of 1.22 m.

Cover vegetation was designed with a mix of cool and warm season grasses to provide enhanced transpiration throughout as much of the year. The seed mix was selected to be resistant to drought and produce sufficiently tall vegetation to deter prairie dog invasion. The desired community of vegetation will be compatible with the surrounding prairie grasslands of the designated National Wildlife Refuge.

Final Cover Profile

Before construction of the covers, clean gradefill with a thickness of up to 6 m was placed over the contaminated soil and debris to build a foundation and establish the cover design grades. While all RCRA-Equivalent covers used both ET and capillary barrier concepts to control infiltration, two different materials were used to construct the capillary barrier. As shown in Figure 4, the alternative cover systems include the following components, from bottom to top:

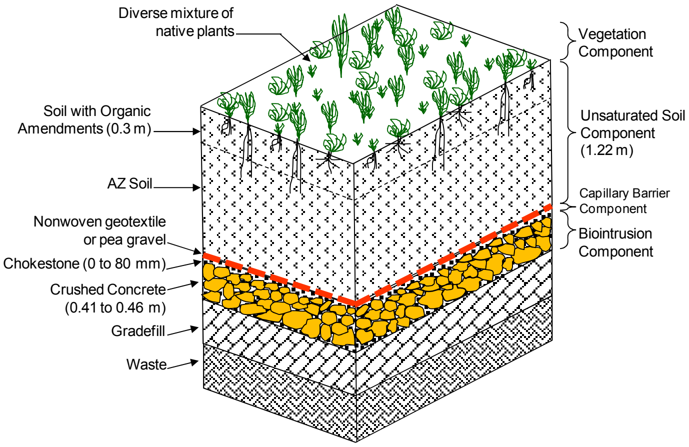

Figure 4. Alternative cover section, RMA

-
- ***Biointrusion Component***, which prevents biota from accessing underlying contaminated soil and constructed of concrete cobbles (at least 0.41 m thick) overlain by a chokestone layer that provides a uniform surface for capillary barrier material.
- ***Capillary Barrier Component***, which consists of a nonwoven geotextile for the cover constructed first (Shell Cover). The design for the ICS and Basin F covers was modified to use a 0.03 to 0.08 m-thick layer of well-graded, washed pea gravel for this component.
- ***Unsaturated Soil Component***, which involves a 1.22 m-thick layer of soil with specific geotechnical and agronomic characteristics, excavated from acceptable onsite borrow areas. The top 0.3 m of this layer was amended to facilitate vegetation growth.
- ***Vegetation Component***, which includes native grasses compatible with the shortgrass prairie habitat of the surrounding National Wildlife Refuge.

CONSTRUCTION

The construction of an effective capillary barrier can be challenging as it requires that soils at the interface of the two layers do not substantially mix and contact between the two layers remain smooth and continuous. The use of end-result specifications allowed good flexibility for contractors to select construction approaches at RMA that fostered innovation and implementation of expeditious construction techniques. In the Shell Cover, it was difficult to construct the overlying, relatively loose soil layer without damaging the underlying geotextile. Based on this experience, the RCRA-equivalent cover design for the other covers at RMA used clean, washed gravel as a capillary barrier. The gravel layer is 25 to 76 mm thick, and required continuous inspection and hand work by laborers during placement to ensure the layer was uniform and clean. Based on the laboratory column testing, the quality of the capillary break in this profile is expected to be equivalent to that produced from a profile that included a geotextile as previously described (TTFWI 2005). The Shell Cover was irrigated after seeding to promote germination and early growth.

PERFORMANCE MONITORING

The ROD requires monitoring of the cover systems to verify that the constructed profiles meet their design objectives and goals, and ensure the remedy remains protective of human health and the environment. Monitoring includes measurement of percolation in 20 lysimeters throughout the ICS, Shell, and Basin F cover systems. Vegetation is assessed and the physical condition of the cover is inspected and maintained.

At the Shell Cover, monitoring includes moisture and water balance evaluation of the cover profiles. Three lysimeters (Lysimeters 1, 2, and 3) are located at the north-facing toe of the cover slope, the top, and the south-facing mid-slope area, respectively. Each lysimeters includes five nests of WCR probes, installed to measure the real-time moisture profiles within the soil. Each of the WCR nests includes eight moisture sensors, as shown in Figure 5. Six temperature sensors were also installed in the Shell Cover at depths corresponding to the locations of the moisture sensors.

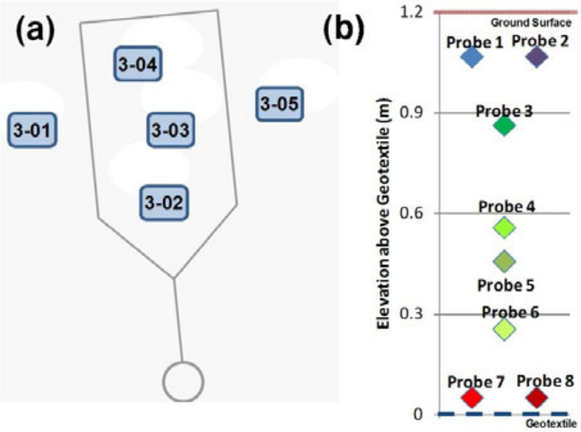

Figure 5: (a) Plan view of nests in Lysimeter 3; (b) Profile of moisture probes

An overview of the monitoring data collected during the 18 months after the Shell Cover was constructed and their implications on the overall cover performance is provided by Williams et al. (2010) and is briefly described here. Their evaluation concluded that the results to date indicate that the comparatively low density of the cover soils appears to have been detrimental to the overall cover performance. As shown in Figure 6, a moisture front advanced from the ground surface to the base of the cover relatively quickly, approximately eight weeks after irrigation began. While a low soil cover density was selected to promote vegetation growth, the low soil density led to high hydraulic conductivity and, consequently, fast infiltration. The capillary break appears to develop when the moisture front reaches the base of the cover as shown by a continued increase of moisture, i.e., the moisture profile 'bulges' at the cover base (Figures 6a and b). After breakthrough, the profiles remain unchanged at a high moisture value and showing no signs of cover recovery for approximately 8 months.

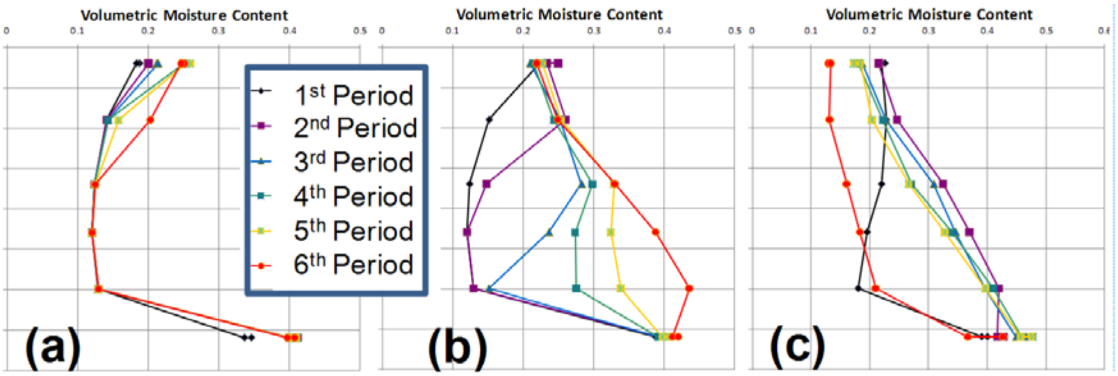

Figure 6: Average moisture content profiles: (a) initial 12 days; (b) initial 12 weeks; (c) initial year

FINAL REMARKS

The design and construction of the alternative covers at RMA have illustrated several important aspects of unsaturated soil covers involving capillary barriers:

- Understanding of the actual storage mechanisms governing the performance of the unsaturated soil cover should not be taken for granted. For example, the formation of a capillary barrier above the lysimeters in the field demonstration was not fully understood until the soil moisture data was fully evaluated.
- Development of acceptable soil criteria based on soil index properties (e.g., grain size ranges for the soil storage component of the cover), combined with a comprehensive characterization of candidate on-site borrow areas proved to be a good compromise to translate the results of analyses into construction specifications. This approach minimized the need of testing of the soil performance properties (e.g., hydraulic conductivity, moisture retention).
- Implementation of a laboratory testing program involving column tests to simulate the development of a capillary break proved important in the selection process of the capillary break materials. Specifically, different fine-grained/ coarse-grained

material combinations had to be conducted in order to identify different capillary barriers suitable for the full-scale cover system.
- The use of end-result specifications allowed good flexibility for contractors to select construction approaches at RMA that fostered innovation and implementation of expeditious construction techniques.
- While post-construction monitoring data available to-date is limited, it has provided information suitable for preliminary assessment of the cover performance. This includes assessment of rates of moisture migration, initial development of a capillary barrier, and cover/precipitation situations resulting in breakthrough.

REFERENCES

Dwyer, SF. (2003). *Water Balance Measurements and Computer Simulations*. PhD Dissertation. University of New Mexico.

Foster Wheeler Environmental Corporation (FWENC). (1996). *Record of Decision for the On-Post Operable Unit*.

Frumkin, H. (2005). *Environmental Health: From Global to Local.* Jossey-Bass, 1108 pp.

Kiel, R.E., Chadwick, D.G., Lowrey, J., Mackey, C.V., Greer, L.M. (2002) "Design of evapotranspirative (ET) covers at the Rocky Mountain Arsenal." *Proceedings: SWANA 6th Annual Landfill Symposium*.

Melchior, S. (1997). "In-situ studies of the performance of landfill caps (Compacted clay liners, geomembranes, geosynthetic clay liner, capillary barriers)." *Land Contamination and Reclamation*. 5(3), 209-216.

RVO. (1998). *Final RCRA-Equivalent Cover Demonstration Project, Comparative Analysis and Field Demonstration Design Scope of Work.*

Stormont, J.C., Hines, J.S., Pease, R.E., Kelsey, J.A., and O'Dowd, D. (2008). "The Effectiveness of a Geotextile as a Capillary Barrier." Proceedings of *GeoAmericas 2008*, First PanAmerican Geosynthetics Conference, Cancún, Mexico, pp. 225-231.

Tetra Tech EC, Inc. (TTECI) (2005). *RCRA-Equivalent Cover Post-Demonstration Geotechnical Evaluation, Final, Summary Report for Acceptance Zone Development and Density Requirements for RCRA-Equivalent Cover Soils.*

TTECI. (2007). *Integrated Cover System Design, Borrow Area Management Plan*. Rev. 1.

Tetra Tech FW, Inc. (TTFWI). 2005. *Final Capillary Break Test Report*.

U.S. Environmental Protection Agency (EPA). (1991) Seminar Publication. *Design and Construction of RCRA/CERCLA Final Covers*. EPA/625/4-91/02.

Williams, L., Hoyt, D., Hargreaves, G., Dwyer, S., and Zornberg, J.G. (2010). "Evaluation of a Capillary Barrier at the Rocky Mountain Arsenal." Proc. *Fifth International Conference on Unsaturated Soils,* UNSAT 2010, Barcelona, Spain, in press.

Zornberg, J.G., Bouazza, A., and McCartney, J.S. (2009). "Geosynthetic Capillary Barriers: Principles and Applications." Proceedings of the *First African Conference on Geosynthetics*, GeoAfrica 2009, Cape Town, South Africa (CD ROM).