

Evaluation of a capillary barrier at the Rocky Mountain Arsenal

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ABSTRACT: A monitoring program is currently being implemented to assess the performance of a capillary barrier constructed at the Rocky Mountain Arsenal, a high-profile hazardous waste site located northeast of Denver, Colorado, USA. Monitoring includes regulatory-required pan lysimeters to measure basal percolation as well as water content reflectometer probes to measure soil moisture profiles. The moisture content profiles allowed continued evaluation of the cover performance in response to natural precipitation and irrigation. The results to date indicate that the comparatively low density of the cover soils, selected to aid in vegetation establishment, appears to have been detrimental to the overall cover performance.

1 INTRODUCTION

Unsaturated soil covers [e.g. evapotranspirative (ET) covers] have been selected and constructed in multiple solid waste, mining, and hazardous waste containment facilities around the world. However, the selection of parameters governing the infiltration of moisture into ET cover systems is still controversial. Specifically, soil parameters that minimize the downward moisture infiltration are often compromised by soil parameters that maximize vegetation and upward moisture movement due to transpiration. Critical parameters that designers must balance include the soil type and its placement conditions, primarily the soil density (e.g. Zornberg *et al.* 2003). An increased soil density leads to a decreased hydraulic conductivity that slows infiltration. However, the increased soil density may also limit the type and quality of vegetation. In order to provide insight into the performance of unsaturated soil covers, this paper presents the results of a monitoring program implemented at the Rocky Mountain Arsenal (RMA), a high-profile hazardous waste site located northeast of Denver, Colorado, USA.

The RMA site, which is regulated under the US Environmental Protection Agency's (USEPA) Superfund program, was once considered to contain the "most contaminated square mile on earth" (Frumkin 2005). A primary remedy component at this site involves in-situ consolidation of contaminated soils to be covered with a total of six unsaturated soil covers. These six covers, which span over 160 ha of RMA, are deemed 'alternative' covers, as they were required to be 'equivalent' to a prescriptive RCRA-Subtitle C cover (FWENC 1996). Based on the site-specific conditions and studies available at the time (e.g. Melchior 1997), a quantitative threshold percolation of 1.3 mm/year was adopted in 1998 for the RMA alternative covers (RVO 1998).

The first RMA alternative cover consisting of a capillary barrier was constructed in 2007 over an 8.5 ha area in central RMA. Known as the Shell Cover, it includes a 1.22 m-thick soil layer underlain by a capillary break composed of a nonwoven geotextile placed over coarse gravel (chokestone layer). A comparatively low relative compaction (ranging from 75% to 85% of the maximum dry density from Standard Proctor tests) was specified for the cover soils in order to promote vegetation growth.

The post-construction monitoring program for the Shell Cover includes regulatory-required gravity lysimeters to measure basal percolation as well as water content reflectometers (WCRs) to measure moisture within the cover soils. Interpretation of the moisture content profiles within the Shell Cover is presented herein to evaluate the cover's performance in response to natural precipitation and irrigation.

2 BACKGROUND INFORMATION

2.1 Description of the capillary barrier system

The climate in Denver is semiarid, with an average annual precipitation of 396 mm and an average pan evaporation of 1,394 mm (as quantified for the 1948 to 1998 period). The wettest months of the year (April to October) are also the months with the highest pan evaporation, which makes the RMA site well suited for the use of ET cover systems. The RMA remedy required a field demonstration to prove equivalence of the alternative design with a prescriptive cover before design and construction of the final alternative covers.

The equivalence demonstration at RMA involved a field demonstration complemented with comparative numerical analyses (Kiel *et al.* 2002). Four ET test covers, approximately 9.14 m by 15.24 m, were constructed on a rolling plain at RMA in the summer of 1998. Data collected for these test plots included basal percolation, precipitation, moisture content and overland runoff. Basal percolation was collected in pan lysimeters, which involved a geocomposite drainage layer underlain by geomembrane. Precipitation was monitored using an all-season rain gauge. Surface water was collected in polyethylene geomembrane swales constructed around the cover perimeters. WCRs were used to measure volumetric moisture content profiles (RVO 1998).

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 criterion. (Kiel *et al.* 2002). With this approach, the lysimeter measurements for all test plots at RMA satisfied the quantitative percolation criterion over the demonstration period of 1998–2003. However, subsequent scrutiny of the WCR data clearly indicated that the design criterion had been achieved because a capillary break had developed within the constructed test plots due to the presence of a geocomposite drainage layer below the soil.

The final design for the Shell Cover involved a capillary barrier (Figure 1). As shown in the figure, the cover includes three components: a chokestone (gravel) layer, a geotextile, and a soil layer. A nominal 0.457-m thick biota barrier, consisting of crushed high-durability concrete obtained from runways at an adjacent airport demolition site, was

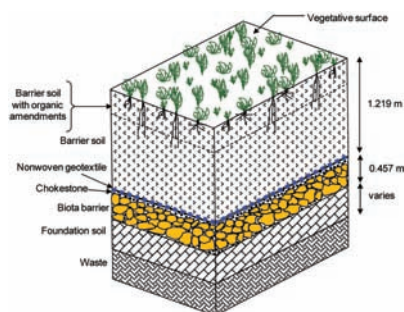


Figure 1. Capillary barrier at the Shell Cover at the RMA, Denver, Colorado, USA.

constructed over the contaminated soils and foundation soils. The biota barrier is designed to prevent burrowing animals from digging into the waste. The capillary break component of the cover, which was constructed directly over the biota barrier, includes a 2.54 cm-thick chokestone layer (coarse gravel with a maximum particle size of 19 mm). The capillary break component also includes a nonwoven geotextile that also helps minimize the migration of soil particles into the chokestone layer. The ET component of the cover involved a 1.22 m-thick soil layer, placed at a density ranging from 75% to 85% in relation to the maximum dry density according to Standard Proctor maximum tests. Soil amendment was added to the top 0.3 m of the soil layer to facilitate vegetation. The cover was revegetated with native grasses characteristic of a short-grass prairie and compatible with the habitat of the surrounding National Wildlife Refuge.

2.2 Description of the monitoring program

The Shell Cover was irrigated after seeding to promote initial establishment of the vegetation. The post-construction monitoring program included three gravity lysimeters to measure basal percolation. Each lysimeter included nests of WCR probes, installed to measure the real-time moisture profiles within the soil. The data evaluated in this paper includes soil moisture content, soil temperature, percolation, precipitation, and irrigation collected from July 9, 2007 to Dec. 31 2008.

Lysimeters 1, 2, and 3 are located within the Shell Cover at the northern downslope edge, upslope portion, and southern downslope edge, respectively (Figure 2). Each lysimeter includes a total of five nests with eight moisture sensors, as shown in Figure 3a. Nest 1 is located outside the lysimeter area (to the right of the lysimeter when facing downslope). Nests 2, 3, and 4 are located inside the lysimeter area, towards the downslope portion, central portion, and upslope portion of the lysimeter, respectively. Finally, Nest 5 is located

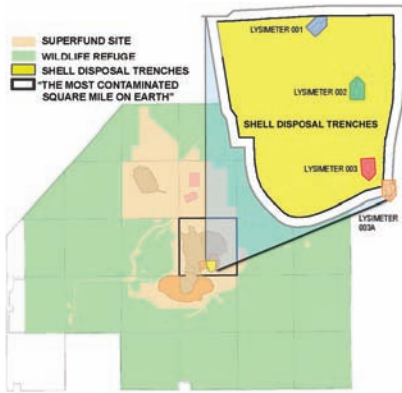


Figure 2. Lysimeter locations in Shell Cover.

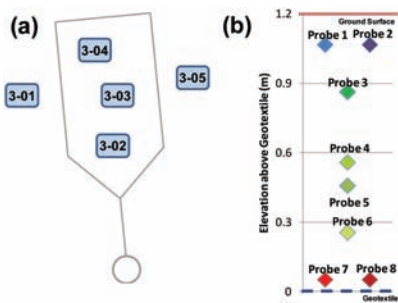


Figure 3. Distribution of nests: (a) Plan view of lysimeter 3, (b) Probes in lysimeter 3-03.

outside the lysimeter area (to the left of the lysimeter when facing downslope).

The location of the eight probes in each nest is illustrated in Figure 3b. Probes 1 and 2 (duplicates) are located 0.152 m below ground surface. Probe 3 is located 0.356 m below ground surface. On the other hand, Probes 4, 5, and 6 are located 0.66 m, 0.457 m, and 0.254 m above the geotextile. Finally, Probes 7 and 8 (duplicates) are located 0.051 m above the geotextile. In cases where the cover thickness exceeds 1.219 m (minimum cover thickness), the distance between Probes 4 and 5 was increased. Six temperature sensors were installed in the Shell Cover at depths corresponding to the locations of the moisture sensors.

3 ANALYSIS OF WEATHER DATA

3.1 Irrigation and precipitation

The Shell Cover was irrigated from July 2, 2007 to September 15, 2007 as shown in Figure 4. The average daily irrigation was 7 mm/day with a cumulative irrigation total of 379 mm. The irrigation rate

was uniform, as shown in the figure by an approximately linear cumulative irrigation.

The daily and cumulative precipitation recorded at the site for years 2007 and 2008 are also shown in Figure 4. A total cumulative precipitation of 359 mm was received at the site in 2007 (164 mm in the 3rd and 4th Quarters), while a total cumulative precipitation of only 211 mm was received in 2008. The steep portions of the cumulative precipitation curve correspond to rain or snow events, while the flat portions of the cumulative precipitation curve correspond to dry periods. It is of particular interest that the cumulative irrigation and precipitation on the Shell Cover in 2007 was 738 mm, nearly double the average annual precipitation for Denver (396 mm).

3.2 Temperature

Figure 5 shows the temperature data collected at the site from July 2007 to December 2008. This data is consistent with expectations as it shows that surficial sensor T1 registers the highest temperature among all probes during the summer, while showing the lowest temperature among all probes during the winter. As expected, the deepest sensor T6 has the lowest temperature among all probes during the summer, while it shows the highest temperature among all probes during the winter. Of particular relevance is the assessment of the sensors that record below freezing

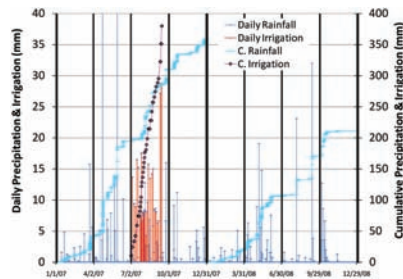


Figure 4. Daily and cumulative precipitation and irrigation.

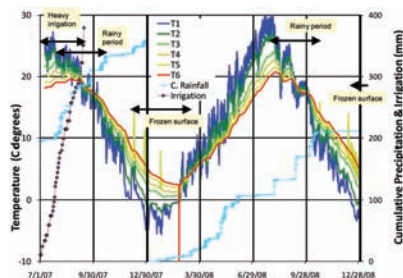


Figure 5. Precipitation, irrigation and temperature records.

temperatures (0°C). As shown in the figure, sensors T1 and T2 reach freezing temperatures in the first winter (December 19, 2007 to February 22, 2008) as well as during the second winter (since December 16, 2008). None of the deeper temperature sensors reached freezing temperature.

The multiple temperature probe depths are critical for interpreting the WCR data because freezing temperature in the cover soils affects moisture readings in at least three aspects, as follows:

- The dielectric constant of ice is significantly lower than the dielectric constant of liquid water. Consequently, the WCRs do not ‘detect’ water in ice form. The WCR readings drop significantly when the temperature falls below freezing in response to the change in water phase and not to a real moisture decrease.
- Freezing of the ground surface shuts down upward water migration from beneath the frozen depth. Consequently, moisture stored within the soil cover at the time of surface freezing can only migrate downwards or remain unchanged throughout the frozen ground period.
- Downward infiltration may take place once thawing (of either accumulated snow or of ice within the ground surface) begins.

3.3 Analysis of Overall Weather Conditions

Figure 5 also shows the combined precipitation, irrigation, and temperature records. This data shows a sequence of events over the 2007–2008 winter that likely contributed to a detrimental performance of the cover. Specifically, this information shows:

- An initial period of heavy irrigation just after construction, which contributed to the high moisture content throughout the cover;
- A subsequent period of rain and snow that may also have contributed to increased infiltration into the cover (or at least prevented its recovery); and
- A final period of frozen ground surface, which may have prevented evaporation (i.e. cover recovery) throughout the winter season, even if the 2007 winter was comparatively dry.

4 ANALYSIS OF MOISTURE DATA

Nest 3 of Lysimeter 3 (Nest 3–03), located at the center of Lysimeter 3 (Figure 3a), was selected as baseline for subsequent comparison and is the only one presented due to paper size constraints.

4.1 Evaluation of Time Series

The volumetric moisture content time series for Nest 3–03 is shown in Figure 6. All analyses were

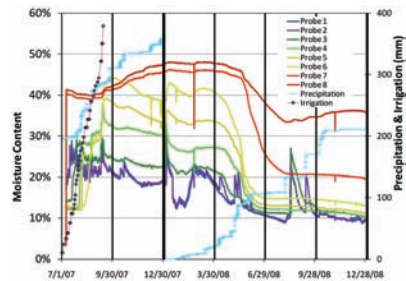


Figure 6. Volumetric moisture content time series.

conducted using the volumetric moisture content values corrected for temperature. The layout of the probes in Nest 3–03 and the color codes are shown in Figure 3b. Figure 6 also includes the cumulative precipitation and infiltration values as a reference.

Inspection of the data presented in Figure 6 reveals very good, essentially identical, agreement between the readings from duplicate Probes 1 and 2, as expected since they are located at the same depth. Also, Probes 1 and 2 show sharp moisture changes over short periods of time. These moisture fluctuations are expected of locations near the ground surface. Probes 1 and 2 show an increase in moisture in response to precipitation, which is particularly clear for the summer 2008 precipitation events.

The readings from duplicate Probes 7 and 8 also show good agreement, particularly before summer 2008. A discrepancy in the magnitude of these readings is observed after summer 2008 (approximately 15%). This discrepancy is attributed to local heterogeneities and to the high sensitivity of the calibration curves of WCR for high moisture content values. Readings from Probes 7 and 8 show smooth changes with time. This type of response is expected of locations towards the bottom of the cover. It should be noted that Probes 7 and 8 show continuously high values of moisture from July 2007 to mid-May 2008 (exceeding 40%). This response has important implications, as follows:

- Increasing moisture content at the bottom of the cover indicates that capillary action may be developing; particularly after mid-September 2007, when the bottom probes show increasing moisture content while the remaining probes show approximately constant values. It is speculated that the fluctuations are due to deficiencies in the temperature correction calibrations (note that the fluctuations are countercyclical with the yearly temperature fluctuations).
- The significant increase in moisture content at the bottom of the cover, detected soon after the initiation of the irrigation period, suggests a poor performance of the ET component of the cover. That is, the infiltration moisture fronts reach the bottom of the cover quickly, which is

- not desirable. A well-performing ET component would store and subsequently release moisture without triggering the development of the capillary barrier unless the season is exceptionally wet. It is acknowledged, though, that the Shell Cover was irrigated to encourage germination of grass seeds and vegetation was not expected to be fully-established during the initial monitoring period.
- A total percolation of 0.795 m³ was collected during the monitoring period in Lysimeter 3 (possibly soon after the irrigation period). This percolation is consistent with the fact that the moisture front reached the bottom of the cover. Even though breakthrough did occur, the potential development of the capillary break likely minimized the amount of percolation.

Probes 3, 4, 5, and 6 in Nest 3-03 are the intermediate probes from top to bottom within the nest. Moisture content data shows that the moisture content increases from the top to the bottom of the cover. These probes show marked increases in moisture in September 2007, becoming progressively smoother from the top probe to the bottom probe which is consistent with the expected response. This increase in moisture is attributed to the advancing moisture front induced by the heavy irrigation.

As shown in Figure 5, freezing temperatures reached the depth corresponding to Probe 3 (0.356 m below ground). Freezing of the ground surface can explain some of the trends observed in the data collected from early January 2008 to late February 2008. Specifically, the decrease in moisture content shown by Probes 1 to 3 during ground freezing occurs because WCRs do not account for the ice fraction of the volumetric moisture content. Also, the sudden increase in moisture in early January in most of the probes may be due to a downward moisture migration triggered by shutdown of ET after freezing of the ground surface.

The likely sequence of events that triggered moisture changes during June 2007 to July 2008 is:

- Breakthrough may have occurred in late September 2007. A sudden increase of moisture can be observed in Probes 4, 5, and 6 around this time, as well as a smooth increase in the moisture of Probes 7 and 8 (lower probes).

- Subsequent to the breakthrough, there is some indication from Probes 4, 5, and 6 that the soil may have started drying out towards the end of 2007.
- The recovery trend of Probes 4, 5, and 6 is halted when the ground surface becomes frozen in late December, with moisture readings remaining approximately constant until late March 2008 in spite of a comparatively dry winter.
- Once the ground surface temperature increased beyond freezing values in early March 2008, the anomalous drop in moisture in the surficial probes is no longer observed. Indeed, Probes 1 and 2 initiate a trend of decreasing moisture (from early March to July 2008). This trend is only altered by a moisture increase (late May 2008) that is triggered by precipitation events.
- Recovery of the cover initiated with decreasing moisture in Probes 1, 2 and 3 in early March, followed by Probes 4, 5, and 6 in mid-April 2008, and the lower Probes 7 and 8 in early June 2008. Recovery continued towards the end of 2008.

Probes 3, 4, 5, and 6 reached comparatively low moisture content by July 2008 (12 to 15%, which is consistent with the moisture content of the cover before irrigation in July 2007). This response indicates that the cover can recover after the dry summer season. A yearly cycle in which the bulk of the cover reaches comparatively low moisture content (e.g. 10 to 12%) is expected to provide evidence of the capability of the cover to recover from a wet season.

4.2 Evaluation of moisture profiles

The volumetric moisture content profiles for Nest 3-03 are shown in Figure 7. The moisture profiles shown in the figures correspond to the average moisture contents for time periods of approximately 2 days, 2 weeks, and 2 months, respectively.

The moisture profiles, averaged every 2 days during the initial 12 days, show an initial moisture profile of reasonably uniform moisture content of approximately 12% in the middle portion of the cover (Figure 7a). The initial moisture profile shows higher moisture content towards the surface (less than 20%), which is likely due to the cover irrigation. Also, the initial moisture profile shows comparatively

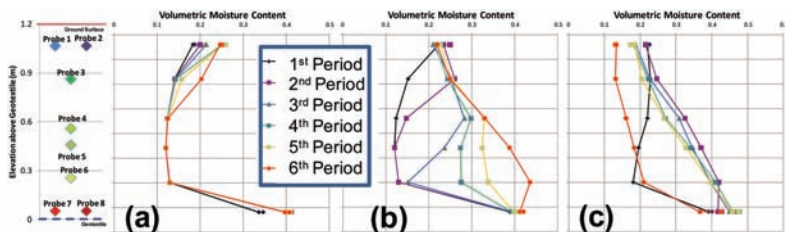


Figure 7. Average moisture content profiles during: (a) the initial 12 days; (b) the initial 12 weeks; (c) the initial year.

high moisture towards the base of the cover. It is possible that the moisture content at the base of the cover was already high when irrigation started, or that moisture at the base increased rapidly during irrigation due to preferential flow mechanisms. As shown in the figure, a moisture front is observed to advance from the ground surface into the cover.

The moisture profiles, averaged every 2 weeks during the initial 12 weeks, show the continued advance of the moisture front from the ground surface into the cover (Figure 7b); reaching the base of the cover approximately eight weeks after irrigation began. It is of concern that the moisture front reaches the base of the cover so quickly. While a low soil cover density was selected to promote vegetation growth, it is clear that the low soil density led to high hydraulic conductivity and, consequently, fast infiltration. Available soil hydraulic conductivity data indicates that a slightly higher relative compaction could have lowered hydraulic conductivity values by a factor of ten with a resulting ten-fold decrease in the moisture front velocity. The capillary break appears to develop when the moisture front reaches the base of the cover. This is shown by a continued increase of moisture, now reflected from the base of the cover upwards. That is, the moisture profile ‘bulges’ at the cover base once it is reached by the moisture front.

The moisture profiles, averaged every 2 months during the initial 12 months, indicate the further development of the capillary break (Figure 7c). It should be noted that the initial moisture profile (July-September 2007) corresponds to the average of the profiles shown in Figure 7a. The four moisture profiles ranging from September 2007 to July 2008 show a significant increase in moisture throughout the entire profile. The moisture content increases with depth, with particularly high moisture values at the bottom of the cover. After breakthrough, the profiles remain unchanged at a high moisture value and without showing signs of cover recovery for approximately 8 months. The last moisture profile shows that the cover has begun to recover, as indicated by a comparatively low moisture content throughout the cover system, with the sole exception of the bottom probes (Probes 7 and 8).

5 CONCLUSIONS

The moisture content profiles provided key information for evaluating important aspects of the Shell Cover performance at RMA. The following moisture migration mechanisms were identified using moisture data collected during 18 months of monitoring:

- A front of increasing moisture content advancing from the top of the cover towards the bottom was observed. The speed of the advancing moisture

front, potential development of a capillary break, and potential recovery of the unsaturated soil barrier are evident in the moisture content profiles.

- A capillary barrier effect may have been triggered once the moisture front reached the bottom of the cover. While this indicates potentially good performance of the capillary barrier component of the system, it also indicates a poor performance of the ET component. While the specified low soil cover density was intended to aid vegetation growth, it also led to a fast infiltration into the cover. The fast infiltration (only 8 weeks to reach the base of the cover) is significantly shorter than the approximately 6 month-long dry seasons in the Denver area.
- Ground freezing delayed recovery of the cover, despite a comparatively dry winter season. The additional, temporary infiltration barrier induced by ground freezing affected the cover performance detrimentally by preventing ET.

Overall, it is recommended that the design density of the covers soils be selected to ensure that the soil layer prevents a moisture front from reaching the cover base before the time period between dry seasons. Also, alternative covers proposed for areas where seasonal temperatures drop below freezing should acknowledge the significant decrease in evaporation that takes place during ground freezing.

Despite the potential difficulties triggered by the low soil cover density and by conducting irrigation immediately before winter, moisture profiles appear to indicate that the Shell Cover has begun to recover, and is expected to continue.

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