Covering It All

Landfill covers that will permanently contain the residuals of chemical warfare agents and pesticides at the Rocky Mountain Arsenal Superfund site, in Colorado, were designed to perform many functions, including providing a barrier to water infiltration, soil and wind erosion, and intrusion by wildlife. Designed as alternatives to the types of covers normally used at hazardous waste sites, the covers had to be validated beyond a shadow of a doubt before full-scale construction could begin.

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Located 10 mi northeast of Denver, the Rocky Mountain Arsenal, *inset,* originally encompassed 27 sq mi. The site was used by the army to manufacture chemical warfare agents and incendiary munitions for use in World War II and by the Shell Oil Company to manufacture pesticides. To minimize the amount of fill needed to achieve an overall slope of 3 percent for the integrated cover system that would encase the contaminated soils, a "broken back" design was conceived. This involved long, low-slope drainages that cut through the large cover areas.

EPA FIELD OVERSIGHT PHOTOGRAPHY, *LEFT*

WHEN DESIGNING COVERS for contaminated soils, engineers generally follow the procedures outlined by the U.S. Environmental Protection Agency (EPA) and rely on such guidelines as the EPA's 1991 report *Design and Construction of RCRA/CERCLA Final Covers.* (The acronym "RCRA" denotes the Resource Conservation and Recovery Act; "CERCLA" denotes the Comprehensive Environmental Response, Compensation and Liability Act, which led to the federal funding source for the remediation of hazardous waste sites referred to as the Superfund.) The prescriptive design called for in that publication relies on the use of such materials as geomembranes when designing a cover that comes into intimate contact with compacted clay that has a low saturated hydraulic conductivity (for example, 10^{-9} m/s or less). Such materials limit the infiltration of water into the waste. But these designs do not accommodate every situation, and sometimes alternatives must be envisioned. The regulations do allow for such alternative designs but often require a demonstration to prove that the performance of the proposed alternative cover is "equivalent" to that of the prescriptive design. Such alternative unsaturated soil covers are referred to as RCRA-equivalent covers.

Unsaturated soil covers are an alternative approach that has been deployed at a number of sites worldwide. (See "Alternative Landfill Covers Pass the Test," by Stephen F. Dwyer, *Civil Engineering,* September 1998, pages 50–52, and "Finding a Better Cover," by Stephen F. Dwyer, *Civil Engineering,* January 2001, pages 58–63.) Such an equivalent design was recently created for the defunct Rocky Mountain Arsenal (RMA), in Colorado. The site is a hazardous waste facility regulated under the Superfund and was once considered by the U.S. Army Corps of Engineers to contain the most contaminated square mile on earth. A primary element in the remediation of the site is the consolidation of contaminated soils beneath six soil covers. These covers were required to have a performance equivalent to that of a cover prescribed in title C of the RCRA, meaning that they had to have an assumed performance of zero percolation. In addition to controlling storm-water infiltration, the RMA covers were required to fulfill two additional functions: prevent biointrusion and control erosion. Other objectives and conditions at the site that imposed additional requirements on the design and construction efforts included the large expanse that was to be covered, the use of on-site borrow soil, and ensuring that the final cover slopes and vegetation would be compatible with such adjacent areas as the Rocky Mountain Arsenal National Wildlife Refuge.

Ultimately, an alternative cover system design utilizing unsaturated soil covers that met these multiple criteria was developed and constructed by the U.S. Army; Shell Oil Company, of Houston; and the latter's prime contractor, Tetra Tech EC, Inc., a subsidiary of Tetra Tech, of Pasadena, California. The design of these unsaturated soil covers includes four main components—a biointrusion layer, a capillary barrier, an unsaturated soil layer, and vegetation—and it took approximately 11 years to demonstrate the validity of the covers and gain approval for their use. These negotiations involved, on the one hand, the army and Shell Oil as the owners and operators of the RMA and, on the other, the EPA, the Colorado Department of Public Health and Environment, and the Tri-County Health Department as respectively the federal, state, and local regulatory oversight entities. The EPA's oversight of the RMA cover projects was conducted by both staff and consulting engineers and included a review of the design submittals and construction activities to ensure that they would protect public health and the environment, comply with the selected cleanup remedy, and satisfy the performance criteria.

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When active, the RMA site comprised 27 sq mi. It is located 10 mi northeast of Denver. Denver's climate is semiarid, with an average annual precipitation of 15 in., average temperatures ranging from 15°F to 88°F, and a ground freezing depth of up to 4 ft. In 1942 the army established the RMA site on undeveloped ranchland and farmland and used it to manufacture chemical warfare agents and incendiary munitions for use in World War II. Beginning in 1946, some facilities were leased to private companies, including Shell Oil, which manufactured pesticides there from 1952 to 1982. The weapons and pesticide manufacturing created large amounts of waste. Numerous leaks and spills, together with stack emissions, contaminated both the RMA itself and areas to the north and northwest. Prior to 1956, liquid waste products were pumped into various unlined evaporation ponds in the center of the RMA, where there were natural depressions, according to the army. This disposal practice resulted in contamination of the soil, structures, surface water, and groundwater at concentration levels that posed unacceptable risks to human health and the environment. As a result, the RMA was added to the EPA's Superfund National Priorities List in 1987, and a remedy to address the on-site contamination was selected in 1996. The selection formally established the remediation approach and specified the actions to be implemented for approximately 3,000 acres of contaminated soil, more than 750 structures, and 15 groundwater plumes.

A key element of the remedy was to interrupt the exposure pathways by placing the most contaminated soil and structure demolition debris in two landfills constructed on-site in accordance with subtitle C of the RCRA and by consolidating soil and debris that were less contaminated under RCRA-equivalent covers constructed over six preexisting, highly contaminated areas considered too risky for excavation. These consolidation areas do not have a liner system or leachate collection capabilities. The design, construction, and monitoring of the 453 acres of RCRA-equivalent covers at the RMA are the focus of this article. The map opposite shows the location of the covers as well as the hazardous waste landfills.

THE FIRST OF THE SIX RCRA-equivalent cover systems constructed at the RMA was completed in June 2007 over the Shell disposal trenches. Referred to as the Shell cover, it encompasses approximately 21 acres. The remaining RCRA-equivalent cover areas were completed in September 2010 and include the basin F cover, which extends over approximately 103 acres, and four consolidation projects adjacent to the Shell cover encompassing 304 acres and referred to collectively as the integrated cover system (ICS). (See map.) The ICS consists of basin A (approximately 148 acres), complex (army) trenches (approximately 91 acres), lime basins (approximately 13 acres), and a former shell-processing area known as the South Plants (approximately 53 acres). The figure on page 68 depicts the cross section of the cover system, and the figure on page 69 shows the exposed layers through an almost vertical cut through the section of the Shell cover that extends beyond the containment perimeter.

Before construction of the covers, up to 20 ft of clean fill 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 evapotranspiration and capillary barrier methods to control infiltration, the material used to construct the capillary barrier was changed after the Shell cover was constructed.

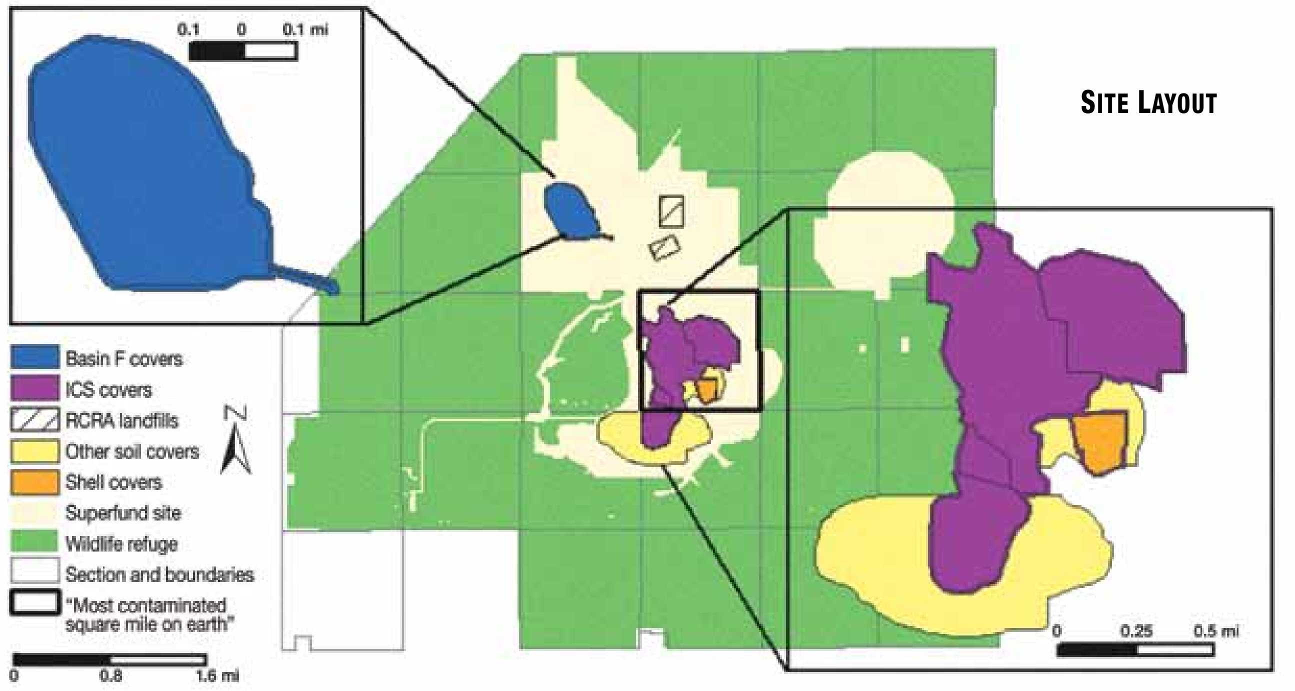
As shown in the figures on pages 68 and 69, the RCRA-equivalent cover systems include the following components, from bottom to top:

- Biointrusion component: Designed to prevent biota from accessing underlying contaminated soil, this component was to be constructed of concrete cobbles (at least 16 in. thick) overlain by a layer of aggregate ("choke stone") that would provide a uniform surface for placement of the subsequent capillary barrier material.
- Capillary barrier component: This took the form of a nonwoven geotextile for the Shell cover and a layer of well-graded, washed pea gravel 1 to 3 in. thick for the others.
- Unsaturated soil component: This 48 in. thick layer of soil with certain geotechnical and agronomic characteristics was excavated from approved borrow areas on-site. An additional 6 in. of soil was added to this layer to address potential soil loss from erosion. The top 12 inches of the total 48 in. thick soil layer was amended to facilitate vegetation growth.
- Vegetation component: Included here are native grasses compatible with the short-grass prairie habitat of the surrounding wildlife refuge.

The biota control function of the covers is achieved by the biointrusion and vegetation components. The infiltration control function is achieved by the integrated response of the capillary barrier, unsaturated soil, and vegetation components. Finally, the erosion control function is achieved by the unsaturated soil and vegetation components, along with the grading and drainage control features of the cover system.

The biota control function was required because of the presence of burrowing wildlife in the surrounding wildlife refuge. The primary design criteria for the biointrusion layer were established for the predominant burrowing animal species present at the RMA: badgers and prairie dogs. A gradation with at least 33 percent of the cobble diameters ranging from 6 to 12 in. was specified. This gradation resulted from a study that defined the size of particles that would be large enough to prevent a badger from pushing them to the surface but that would also produce voids small enough to prevent access to such small rodents as prairie dogs and pocket gophers. A thickness of 16 to 18 in. for the biota barrier material (BBM) layer was selected. To further prevent biointrusion, the design required that the BBM be extended, or "run out," 50 ft beyond the cover perimeter. This increased the areal extent of the ICS by approximately 25 acres.

Because the covers must isolate the waste left in place in perpetuity, it was of paramount importance that the BBM be made of a highly durable material. Thus, in addition to the specified gradation, the cobbles used to construct the BBM layer, according to the final bid package issued for construction, had to be resistant to animals, freeze-thaw action, chemical breakdown from the overlying cover soils, and moisture-induced degradation (for example, aggressive water attack, acidic aqueous solutions, and sulfates). The BBM was placed beneath the 48 in. thick soil layer to address the freeze-thaw concerns. Placing the BBM under the infiltration control components also provided additional resistance to chemical degradation because the primary function of the overlying soil was to minimize water infiltration into the underlying waste and therefore into the BBM.



Site Layout

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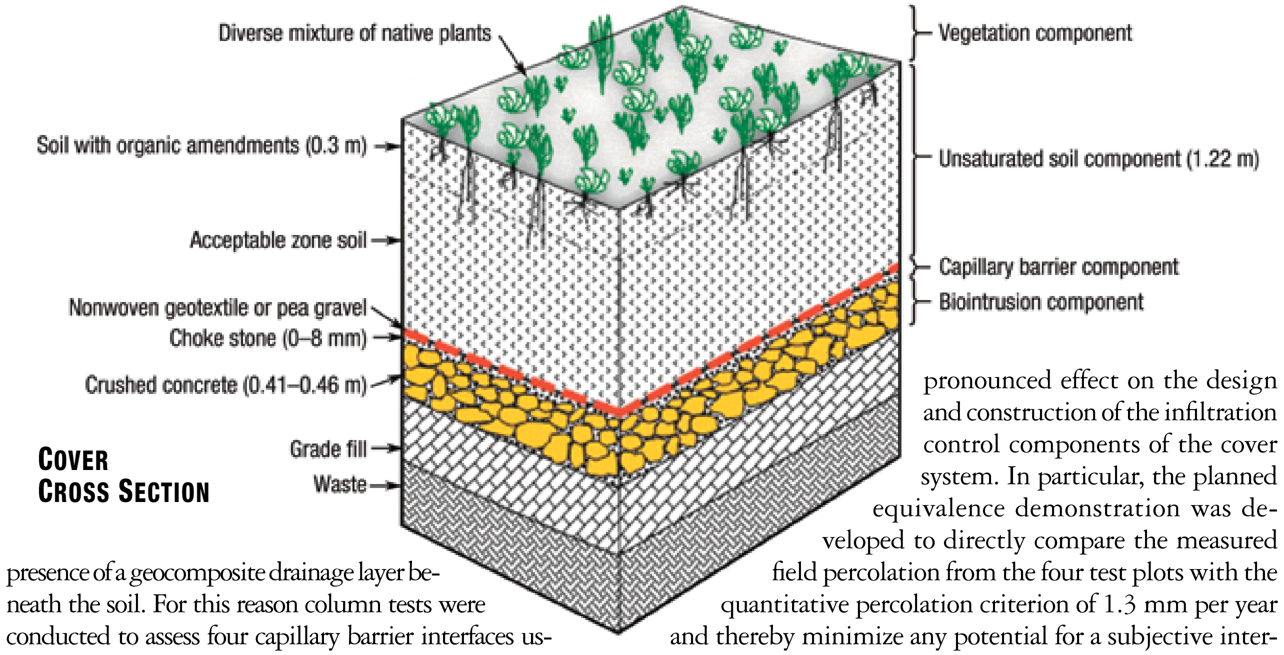
While such natural materials as crushed granite were an option for the BBM, an opportunity arose to recycle high-strength concrete from the adjacent and recently decommissioned Stapleton International Airport. The acceptability criteria as stipulated in the construction documents for this recycled concrete option required a minimum compressive strength of 2,000 psi and a unit weight of more than 130 lb/cu ft. Laboratory testing of the Stapleton runways and aprons indicated that the concrete was acceptable because of its density, durability, and hardness and because it exhibited only limited aggregate segregation or surface deterioration. In addition to meeting the design criteria, the airport concrete was cost effective, eliminated a great deal of truck traffic through the adjacent communities, and promoted the EPA's mission to protect human health and the environment through the reduction, reuse, or recycling of materials.

The specifications for the BBM placement were performance based, which enabled the contractors to be innovative in developing expeditious construction techniques. Relatively tight thickness tolerances were enforced to avoid overbuilding the BBM so that the quantity of materials available would be sufficient to construct the 453 acres of the six RCRA-equivalent covers as well as the two RCRA covers. Though challenging, placement of the BBM within the relatively tight thickness tolerances was adequately controlled by bulldozers using a Global Positioning System (GPS) grade control system. During construction of the Shell cover, trucks dumped stockpiles of the BBM onto the prepared subgrade, and bulldozers pushed the material into a lift thickness of approximately 16 to 18 in. The resulting BBM surface was irregular, and a significant amount of choke stone with a particle size of $^3/_8$ in. was required to level the surface undulations and fill in voids to achieve an adequately smooth surface for placing the overlying capillary barrier geotextile. Importing sufficient amounts of choke stone was costly and time consuming.

As mentioned above, the lessons learned in constructing the Shell cover led to a modification of the BBM placement process for the ICS and basin F covers. In particular, the BBM was dumped on an already constructed BBM area and then pushed out onto the prepared subgrade. This made it possible for fines from the bottom of the haul truck to be dropped onto the BBM surface, thereby leveling the surface. This change in construction technique reduced the amount of choke stone needed for the ICS and basin F covers. So while the Shell cover required a nominal 3 in. of choke stone over an irregular 18 in. thick layer of BBM to smooth the surface, the basin F and ICS covers used 0 to 3 in. of choke stone as a result of the improved BBM placement approach.

Capillary barriers develop by placing a fine-grained soil over a coarse-grained soil or a geotextile. Differences in pore size distribution between two adjacent layers create a contrast in unsaturated hydraulic conductivity values that leads to the retention of water in the fine-grained soil layer. The matric suction at the interface must approach small values (in other words, almost saturated conditions) before any appreciable flow occurs into the lower coarse-grained layer or geotextile. Therefore, the fine-grained soil layer exhibits significantly greater moisture content than does the lower layer at the same level of matric suction. This leads to increased moisture storage in the fine-grained unsaturated soil layer.

AN EVALUATION conducted by Tetra Tech of the data collected during a cover equivalence demonstration indicated that a capillary barrier had developed within the lysimeters of the constructed test plots because of the



COVER CROSS SECTION

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presence of a geocomposite drainage layer beneath the soil. For this reason column tests were conducted to assess four capillary barrier interfaces using a fine-grained soil layer placed over a geocomposite drainage layer similar to that used in the equivalence demonstration, a geotextile with choke stone beneath it, a layer of choke stone, and a layer of gravel. The columns were irrigated until breakthrough in each profile was recorded. At breakthrough, similar suction values were measured within the upper, fine-grained soil layer for each of the proposed profiles. On the basis of these results, it was concluded that all of the tested interfaces should promote the development of a capillary barrier.

The Shell cover utilizes a nonwoven geotextile as capillary barrier material underlying the fine-grained, unsaturated soil layer. The geotextile layer also acts as a filter, minimizing the migration of soil particles into the underlying choke stone. The selected geotextile was bright orange to serve as a deterrent to accidental excavations into the underlying contaminated soils. Given the cost of the geotextile and the difficulty involved in constructing the overlying soil component at the specified low densities without damaging the geotextile, the ICS and basin F cover designs were modified. In particular, a 1 to 3 in. thick layer of well-graded, washed pea gravel with a particle size less than $^{3}/_{8}$ in. was used as capillary barrier material in these covers.

The unsaturated soil component serves both infiltration and erosion control functions. Evapotranspiration and moisture storage are components that significantly influence the performance of unsaturated soil cover systems. The innovation of this approach is that basal percolation control is partly achieved through the storage of moisture that infiltrates the unsaturated soil layer during precipitation events until it is released back to the atmosphere through evapotranspiration.

On the basis of the conditions and hazards of the site and the limited number of studies available at the time (for example, S. Melchior, "In Situ Studies of the Performance of Landfill Caps [Compacted Clay Liners, Geomembranes, Geosynthetic Clay Liners, Capillary Barriers]," *Land Contamination & Remediation* 5, number 3 [1997]: 209–21), a quantitative percolation criterion of 1.3 mm per year was adopted for the RMA alternative covers, according to the construction documents. The use of this criterion had a pronounced effect on the design and construction of the infiltration control components of the cover system. In particular, the planned equivalence demonstration was developed to directly compare the measured field percolation from the four test plots with the quantitative percolation criterion of 1.3 mm per year and thereby minimize any potential for a subjective interpretation of the results.

Four roughly 30 by 50 ft test plots separate from those described above and consisting of unsaturated soil layers were designed and constructed using on-site soils but without biointrusion or capillary barrier components. The test plots were created with three soil thicknesses: 42, 48, and 60 in. Data for each test plot were monitored between 1998 and 2003 for basal percolation, precipitation, moisture content, and overland runoff (according to R.E. Kiel, D.G. Chadwick, J. Lowrey, C. Mackey, and L. Greer, "Design of Evapotranspirative [ET] Covers at the Rocky Mountain Arsenal," in *Proceedings of the 7th Annual SWANA Landfill Symposium* [Silver Spring, Maryland: Solid Waste Association of North America, 2002]). Basal percolation was collected in pan lysimeters, which included a geocomposite drainage layer underlain by a geomembrane. A comparison of the lysimeter data with the 1.3 mm per year criterion indicated that all of the test plots satisfied that criterion. However, subsequent scrutiny of the moisture content data indicated that the design criterion had been achieved because a capillary barrier had developed within the constructed test plots at the interface between the soil layer and the underlying geocomposite drainage layer.

The requirement to duplicate the successful infiltration control achieved in the test plots in full-scale construction imposed additional performance criteria on the cover design process. In addition to adopting a 48 in. thick soil layer and incorporating an underlying geotextile to create a capillary barrier as in the test plots, the cover design required quantification of the soil properties and imposed particular soil placement conditions and agronomic characteristics. An important criterion for selection of the on-site soils to be used in cover construction was that their texture be within a designated acceptable zone. Furthermore, to promote vegetative growth, the amount of calcium carbonate in the soil had to be less than 15 percent by weight.

The acceptable zone for soil texture was based on the field demonstration, hydraulic property testing, and percolation modeling of the successful test plot soils. It was determined using the U.S. Department of Agriculture textural triangle, a tool commonly used to determine soil textures. The triangle determined the percentages of silt, sand, and clay. Another requirement imposed on the RCRA-equivalent covers was that the unsaturated soil layer be lightly compacted during placement to enhance the early development of the vegetation layer, according to a report by Tetra Tech. During construction, areas that were considered to have been excessively compacted were reworked. On the Shell cover, the required density was achieved by first using side dump trucks that could place most of the 48 in. thick layer of soil in one lift; then a bulldozer pushed the soil up to its final thickness. On the ICS and basin F covers, heavy-duty, end-dump mining trucks placed a lift just over the 48 in. target thickness, and a relatively low ground-pressure bulldozer struck off the lift at the required grade level. Both techniques achieved the low-density requirements.

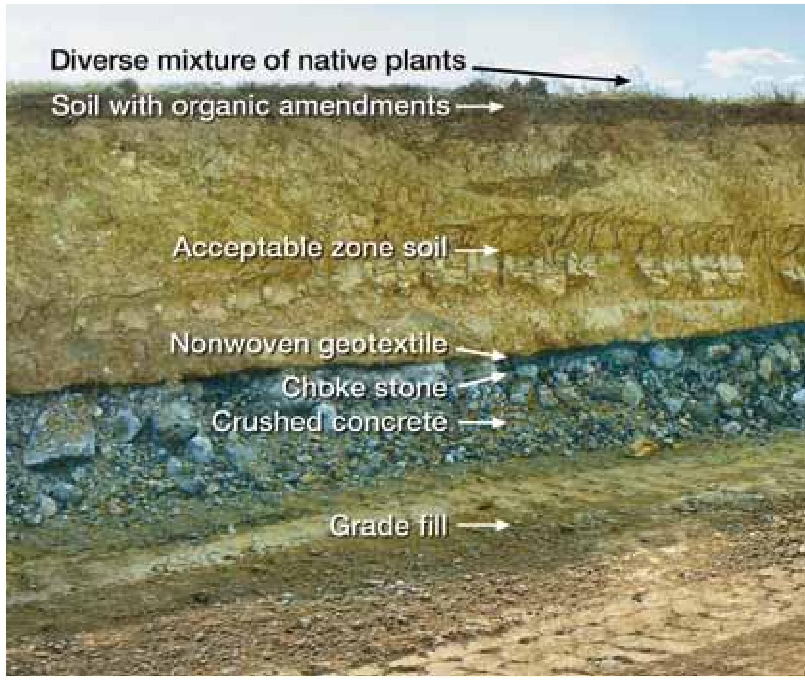
The remedy objectives for the RCRA-equivalent covers included minimizing erosion by wind and water, maximizing runoff, and minimizing ponding. Long-term soil loss from storm-water and wind erosion was calculated to be less than 0.4 in. over a 100-year period. As a result, an additional 6 in. of soil was added to the minimum cover thickness (42 in.) needed to meet the percolation criteria for a total cover thickness of 48 in.

For the RCRA-equivalent cover demonstration project, it was important that the slope of the test plots be the same as in the full-scale covers. The slope selected for the covers was 3 percent, which is consistent with the minimum values set forth in EPA guidelines. The original topography of the contaminated areas consisted of former disposal basins and relatively flat land, so low slopes were selected to minimize the amount of grade fill required. Accordingly, placement of grade fill in a mounded or domed fashion would have required significant amounts of fill and recontouring. While large volumes of on-site borrow soil were available, its excavation and placement would have involved substantial construction costs. Furthermore, overland flow lengths were limited to 500 ft to minimize rill and gully formation. Therefore, to minimize the amount of grade fill needed to achieve the overall 3 percent slopes, a "broken back" design was adopted that consisted of long, low-slope drainages that cut through the large cover areas (see the photo on page 64). This minimized the overall cover height by establishing multiple drainage channels to direct the flow of storm water. The final design for all the RMA RCRA-equivalent covers includes approximately 2.5 mi of drainage channels ranging in length from 150 to 2,246 ft at grades of from 0.3 to 1 percent.

These low-drainage slopes concentrated storm-water flow in the drainages and led to the use of a full-cover approach as outlined in subtitle C of the RCRA under these drainage channels. The subtitle C cover included a geosynthetic clay liner, a 60 mil thick linear low-density polyethylene geomembrane, a geocomposite drainage layer, and a drainage gravel and slotted pipe down the flow line. Because of the low grades of the drainage channels, the channel surfaces were also lined with concrete to reduce variability in the final drainage surface and promote storm-water flow from the cover.

Construction of the low-slope drainage channels proved to be difficult. While the grades were closely controlled for layers underlying the concrete liners, the final grades for some drainage channels resulted in reverse flow, which had to be reworked. The channel construction was successfully completed by using slip form concrete placement equipment to control the final, top-of-concrete channel grades.

Vegetation, an important component of the covers, is necessary to achieve the various functions of the cover system. In particular, roots help minimize soil loss (an erosion control function), the entire plant aids in removing water through enhanced transpiration (the infiltration control function), and the aboveground portion of the plant provides some control of animal species at the site (the biota control function). For this project, a diverse mixture of native plants was



The alternative covers consisted of various layers designed to serve different functions. A layer of cobbles and "choke stones" was designed to prevent biota from accessing underlying contaminated soil. Above this, a capillary barrier was created; in the case of the Shell covers, this was a nonwoven geotextile. Above this was a layer of unsaturated soil with particular geotechnical and agronomic characteristics; this soil had been excavated from an acceptable zone on-site. This layer was topped with 12 in. of soil that included organic amendments to facilitate the growth of vegetation, including native grasses that are compatible with the short grasses of a nearby wildlife refuge.

EPA FIELD OVERSIGHT PHOTOGRAPH

chosen during design that would maximize water removal, be in keeping with the surrounding wildlife refuge, and remain resilient to possible changes in the environment caused by pathogen and pest outbreaks, such physical disturbances as overgrazing or fire, and climatic fluctuations.

The development of the seed mix for the cover vegetation involved considerations of the following types of plants:

- Those that intercept some of the rain before it impacts the ground surface, thereby reducing the potential for erosion;
- Those that help dissipate wind energy, reducing eolian erosion;
- Those with a shallow root system that would enhance the soil surface's resistance to water and wind erosion;
- Those with a complementary deep root system that would help increase evapotranspiration;
- Those that would thrive in both cool and warm seasons to extend evapotranspiration throughout the year;
- Tall grass species that would help deter invasion by prairie dogs.

Forbs were excluded so that herbicides could be used to control weeds in maintaining the covers.

Because the on-site borrow selected for cover construction involved subsurface soil, it did not have the nutrients needed to promote the growth of vegetation. Therefore, the specifications required that an amendment with organic matter be incorporated—mixed with native topsoil to provide additional micronutrients—into the top 12 in. of the soil layer. Moreover, the clay content of the cover soils was limited to 40 percent because clay can retard plant growth.

Several of the vegetation criteria also affected the design of the soil component of the cover. In particular, cover soils were required to have less than 15 percent calcium carbonate by weight to minimize salinity levels that can adversely affect vegetation. As previously mentioned, to enhance vegetation growth the 48 in. thick soil layer was placed at a relatively low density, ranging from 75 to 85 percent of the standard maximum dry density as determined by a Proctor compaction test, a commonly used measurement.

After construction, the covers were seeded and irrigated. Seeding was generally conducted during the summer months, requiring irrigation (often to a level twice that of the annual precipitation amount) to facilitate plant germination and early growth. Based on the soil moisture data from the Shell cover, the covers appear to have been irrigated to saturation. This excessive watering resulted in significant flux through the cover systems as measured in the pan lysimeters. We recommended an irrigation approach that would limit the infiltration of irrigated water into the upper portion of the soil layer to a depth of 6 to 12 in.

BOTH ENGINEERING AND institutional controls were established to protect the integrity of the covers and, as a result, aid in ensuring the long-term protection of human health and the environment from the waste contained beneath the covers. The engineering controls include obelisks, a fence, warning signs, and survey monuments at the perimeter of the waste containment area that clearly demarcate the region as well as the cover boundaries. The obelisks, made of concrete with steel and porcelain enamel plates, show a plan view of the covers. They are 4 ft high and are spaced along the cover perimeter approximately within the line of sight of each other. The fence is 6 ft tall and includes a 1 ft opening at the bottom to allow the passage of wildlife (including coyotes). Signs are placed on the fence every 500 ft to clearly identify the area as one of hazardous waste containment and to prohibit unauthorized access. Survey monuments are placed around the cover boundary, and a survey plat is on file with the local county.

The decision in 1996 on the remedy to be used in addressing the contamination at the RMA also involved institutional controls that apply to the covers. These prohibit residential development, agricultural activities, the use of groundwater and surface water as a source of potable water, and the consumption of all fish and game. Moreover, the army is responsible for maintaining the integrity of the remedy. In particular, institutional controls for the covers prevent contact with the hazardous substances that are contained beneath them and maintain the integrity of the engineered structures that are part of the containment remedy. Activities that may damage or impair the proper functioning of the covers are prohibited, according to the construction documents; these include excavation, drilling, tilling, grading, and construction of any sort, unless these activities are required as a response action.

Until the vegetation is fully established, the performance of the RCRA-equivalent cover system is being rigorously monitored to assess its functionality. Generally, monitoring of the covers includes visual observations for damage (for example, from erosion, vandalism, or burrowing animals), inspection of the vegetation, and percolation monitoring using lysimeters. The Shell cover has also been instrumented with water content reflectometers to measure moisture within the cover soil. Visual inspections and percolation monitoring are conducted monthly, qualitative vegetation inspections are conducted semiannually, and quantitative vegetation inspections are performed annually. Soil moisture content, soil temperature, percolation, precipitation, and irrigation data also are collected. Annual reports that document the inspection findings, percolation monitoring data, vegetation assessment data, and maintenance activities are issued by Tetra Tech in November of each year. So far two such reports have been issued: the *Annual Covers Report 2008* and the *Annual Covers Report 2009.* These studies provide inspection and performance data from October 2007 through September 2009.

The monitoring of the vegetation evaluates distress, overgrazing, the presence of weeds or bare areas, and the establishment of the seeded species. It is expected that it will take approximately five to eight years for the vegetation to fully develop. According to the Tetra Tech reports, the performance criteria for the long-term success of the established vegetation after the fifth growing season are as follows:

- Total live vegetation cover in any single year will be equal to or greater than 25 percent.
- The two-year running average value for the total ground cover will not be less than 50 percent.
- The three-year running average for total ground cover will not be less than 67 percent.

The unsaturated soil component of the cover is monitored by measuring basal percolation through each of the RCRA-equivalent covers using 21 pan lysimeters located beneath the cover systems at designated locations. Each of the three lysimeters on the Shell cover includes a total of five nests with eight moisture sensors. The moisture sensors will be operated for the first seven seasons after construction and will provide data to aid in determining whether the cover is operational and functional. This monitoring may be discontinued by the army at the end of the seventh full spring season following the cover construction unless the army, Shell, and the regulatory agencies agree that additional moisture content data are warranted.

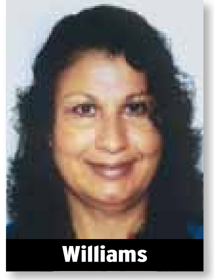
Nest 1 is located outside the lysimeter area (to the right of the lysimeter when facing downslope). Nests 2, 3, and 4 are located inside the lysimeter area toward respectively the downslope portion, the central portion, and the upslope portion of the lysimeter. Nest 5 is located outside the lysimeter area (to the left of the lysimeter when facing downslope).

Probes 1 and 2 (which are duplicates) are located approximately 6 in. below the ground surface. Probe 3 is located approximately 14 in. below the ground surface. In contrast, probes 4, 5, and 6 are located respectively 26, 18, and 10 in. above the geotextile. Finally, probes 7 and 8 (also duplicates) are located 2 in. above the geotextile. In cases where the cover thickness exceeds 48 in., the distance between probes 4 and 5 was increased. Six temperature sensors were also installed in the Shell cover at depths corresponding to the locations of the moisture sensors.

The placement of the moisture probe nests makes it possible to observe the moisture profiles within the covers. This includes assessing the effect of a capillary barrier within the cover profile as well as determining whether the lysimeters affect the cover water balance.

Long-term monitoring of the biointrusion component cannot be conducted, primarily because those components are located beneath the 48 in. thick soil layer. However, any breach in this component can be observed during monthly inspections conducted for burrowing animals through the soil component of the cover. Since prairie dogs will be removed as soon as they are discovered, it is expected that badgers will be kept away as well, since the former are among the chief prey of the latter. Settlement monuments were installed to monitor for soil loss or settlement of the entire soil cover. The monuments take the form of a pipe and a base plate that are situated atop the BBM layer and extend to the soil surface. These settlement monuments are monitored as part of the cover inspections, which are conducted to find defects caused by rills, gullies, excessive sheet erosion, settlement, ponding, or a breach in the overall integrity of the cover drainages.

The design, construction, and initial monitoring of the unsaturated soil covers at the RMA illustrate the challenges that can be expected in designing and constructing a cover system that must satisfy a range of interdependent criteria. The design and construction of an RCRA-equivalent cover for containment of highly contaminated waste are especially challenging because of the biota, infiltration, and erosion control functions that must be performed by the cover system. Here, the design and construction of these components required the integration of multiple criteria pertaining to the site established through negotiations between regulatory agencies and the responsible parties to achieve a system design that would be in keeping with its surroundings. The interaction of such a large cover system with the surrounding land use dictated such critical design aspects as slopes, drainage design, details to prevent biota intrusion, and vegetation choices. As monitoring data become available, the functionality and long-term performance of the cover systems will be regularly evaluated. **CE**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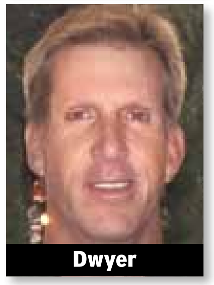
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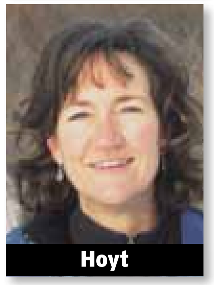
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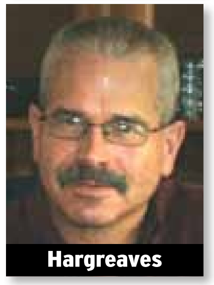
Hargreaves

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PROJECT CREDITS **Owner**: U.S. Army and Shell Oil Company, Houston **Engineer of record and construction manager:** Tetra Tech EC, Inc., a subsidiary of Tetra Tech, Pasadena, California **Regulatory oversight:** U.S. Environmental Protection Agency, Denver; Colorado Department of Public Health and Environment; and Tri-County Health Department, Greenwood Village, Colorado **Technical expertise to the Environmental Protection Agency:** Dwyer Engineering, LLC, Albuquerque, New Mexico; Pacific Western Technologies, Ltd., Wheat Ridge, Colorado; and Jorge G. Zornberg, Ph.D., P.E., M.ASCE, University of Texas at Austin