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FIELD TEST OF POTENTIAL RCRA-EQUIVALENT COVERS AT THE ROCKY MOUNTAIN ARSENAL, COLORADO

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ABSTRACT

As part of the cleanup of the Rocky Mountain Arsenal (near Denver, Colorado), almost 200 acres of RCRA-Equivalent covers must be built over areas where contaminated materials will be left in place. These covers must be either traditional Subtitle C covers, or alternative covers having equivalent performance. Before implementation of any alternative covers, equivalent percolation performance must be demonstrated by both comparative analyses and by a field demonstration. Based upon numerical modeling of cover percolation performance, four potential alternatives to prescriptive RCRA Subtitle C covers were selected for a field demonstration. Full-scale construction using any of these designs at the Arsenal could save tens of millions of dollars compared to the cost of traditional Subtitle C covers, and long-term sustainability of the covers seems assured due to their similarity to natural prairie systems. Construction of the four test covers began in April 1998. Each cover consists of a single vegetated soil layer, but each design varies in soil thickness and/or soil properties. The vegetation design consists of a mixture of native cool and warm season grasses and forbs selected for a variety of factors such as transpiration characteristics, persistence, longevity, drought tolerance, and soil type. Each of the four test covers were constructed over a 30 ft by 50 ft percolation collection system, and were instrumented to provide soil moisture, surface runoff, precipitation, and percolation data. An irrigation system was installed for testing under abnormally wet conditions and to aid in vegetation establishment. Data from the first several months of operation have been collected. Initial establishment of the native vegetation is excellent, and even though the vegetation is in the early stages of development, soil moisture and deep percolation monitoring data are encouraging.

INTRODUCTION

The Rocky Mountain Arsenal (RMA) occupies almost 27 square miles of mostly open land adjacent to Denver, Colorado, about 10 miles northeast of downtown Denver (see Figure 1). The RMA was established in 1942 by the U.S. Army to manufacture chemical weapons for use in World War II. Private industry was encouraged to lease facilities at RMA after the war to foster economic growth in the area, offset operational costs, and maintain the facilities for national security. Under the lease program, various private companies manufactured agricultural chemicals from 1946 to 1982. Common industrial and waste disposal practices used during those years resulted in contamination of significant portions of RMA. In 1996 a Record of Decision (ROD) was issued outlining a comprehensive plan for remediating RMA. When cleanup of the site is finished the site will be managed by the U.S. Fish and Wildlife Service as a wildlife refuge in accordance with the Rocky Mountain Arsenal National Wildlife Refuge Act of 1992.

The selected remedy outlined in the ROD for the Rocky Mountain Arsenal includes construction of RCRA or RCRA-equivalent covers over three former waste disposal sites (former Basin F, the Army Disposal Trenches, and the Shell Disposal Trenches) occupying a total area of almost 200 acres. To construct RCRA-equivalent covers, the ROD specifies that it is necessary to demonstrate performance equivalent to a RCRA landfill cover according to an EPA- and State-approved demonstration that includes comparative analyses and a field demonstration. Accordingly, a working group was formed of representatives of the U.S. Environmental Protection Agency, Colorado Department of Public Health and Environment, U.S. Fish and Wildlife Service, U.S. Army, and Shell Oil/Morrison Knudsen Corporation to design and demonstrate a RCRA-equivalent cover that could be supported by the parties. To date, comparative analyses of some alternative designs have been

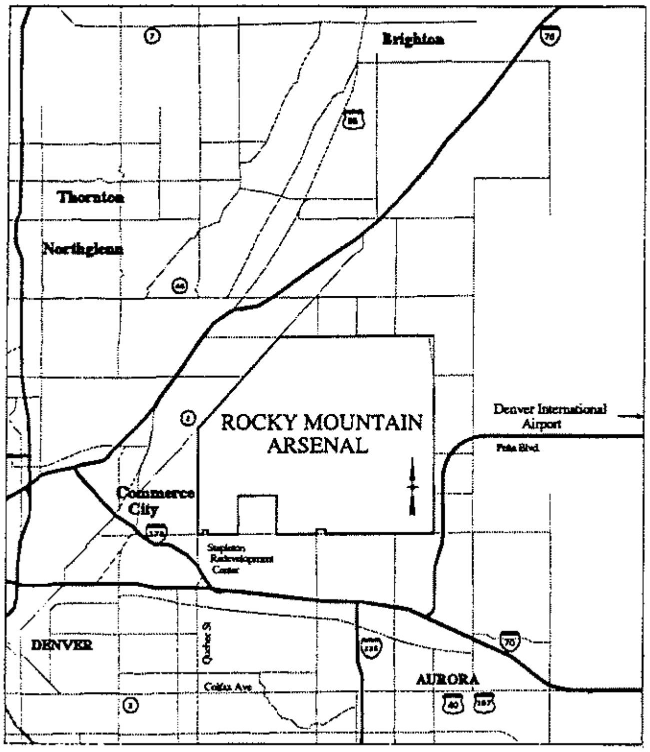

Figure 1. Regional location map

completed, and a field demonstration based on the designs is currently in process.

This paper describes the basis for, and design of, the potential RCRA-equivalent covers and contains results from the first several months of a large-scale field demonstration of those alternative cover designs.

BACKGROUND

Traditional landfill cover designs presently in use for RCRA Subtitle C regulated facilities as recommended by the EPA are used across the United States with minimal regard for regional conditions. These RCRA covers employ a resistive barrier type design that utilizes a barrier layer having a combination of a geomembrane and a low saturated hydraulic conductivity soil layer to provide resistance to downward flow. Experience in arid and semiarid areas has shown these resistive designs to be vulnerable to desiccation and cracking during and after installation. If the geomembranes are damaged, desiccation becomes an important failure mode for compacted soil hydraulic barriers, especially in arid environments (Suter et al. 1993). The basic soil cover used with Subtitle D covers also has a barrier layer that is subject to desiccation cracking and deterioration due to freeze/thaw cycles, among other problems.

In these traditional resistive cover designs, the consulting and regulatory communities generally take a prescriptive rather than performance approach to cover evaluation. Ecological processes are often ignored when considering cover effectiveness. Thus, long-term evaluation of prescriptive cover performance in a given ecosystem is often ignored.

In contrast to resistive designs, capacitive designs rely on the ability of the cover to store water until evaporation or transpiration can remove the water. The capacity to store water under a variety of environmental conditions becomes the key issue. Capacitive designs are best suited for arid and semiarid climates, as they would be unlikely to perform acceptably in locations where precipitation exceeds evapotranspiration. Given the active interaction of the cover with climate and vegetation, the evaluation process must be performance oriented.

Depending upon the level of effort required to gain approval for use of non-prescriptive covers, design costs associated with capacitive covers may be increased compared to those for prescriptive resistive covers where the evaluation philosophy is based primarily on passive flux control using low permeability materials. Capacitive systems are relatively simple to construct and are not plagued by maintenance considerations. Since such systems can be constructed of a relatively broad range of soils, the materials used for a capacitive water storage cover generally come from a nearby borrow area. Therefore, when considering both design and construction costs, these systems may be much more economical to implement than covers utilizing resistive barrier layers (Ankeny et al. 1997).

The semiarid climate, thick loamy soils, and indigenous vegetation at RMA made the site suitable for consideration of a capacitive cover design. As measured at the former Stapleton Airport adjacent to RMA, average annual precipitation averaged 15.58 inches (396 millimeters [mm]) for the 1948-1998 period, with an average of 75 percent of the precipitation falling during the April through October period. Annual potential evapotranspiration is much greater than annual precipitation in the Denver area. This is readily apparent in Figure 2 which shows monthly precipitation averages at Stapleton and monthly pan evaporation averages at Cherry Creek Reservoir (with winter evaporation values being estimated). The 54.9 inches (1394 mm) of average pan evaporation are almost four times greater than average annual precipitation at Stapleton. Figure 2 also shows that the wettest months are typically those when the potential for evapotranspiration is greatest (as indicated by high pan evaporation). Such climatological patterns are desirable for the effective performance of a cover based upon the capacitive design concept.

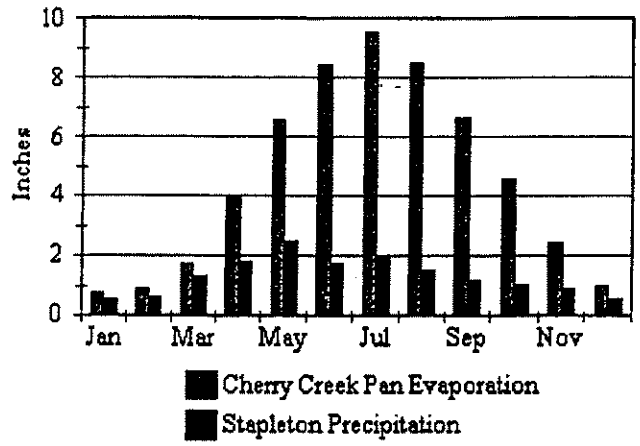

Figure 2 Average monthly precipitation and pan evaporation in the Denver area.

At and near RMA there appears to be considerable evidence that, at least with some soils, deep percolation from the direct infiltration of precipitation into and through the soils is very low or nonexistent. For example, in 1971 a 10-ft diameter weighing lysimeter was constructed at the Pawnee National Grasslands on the plains of northeastern Colorado. The lysimeter was built to contain a 4-ft thickness of Ascalon series soils, a soil series that is also abundant at RMA. Although average annual precipitation at the Pawnee site is probably lower than at RMA (just under 13 inches per year at the Pawnee National Grasslands versus just over 15 inches per year at the former Stapleton Airport adjacent to RMA), after 27 years of data collection there has been no observed drainage water from the base of the lysimeter soil column even though the vegetation was once killed for a bare soil experiment (Lauenroth, 1998).

Another indication of little or no deep percolation from some types of soils on RMA is that numerous test pits and borings have shown a pronounced buildup of dissolved salts at a depth of roughly 3-6 feet (approximately 1-2 meters [m]), indicating there is little or no downward movement of soil water beyond that depth.

Before settlement, the RMA area existed as a shortgrass prairie. The lack of deep-rooted vegetation (e.g., trees and shrubs) over the loamy soils on RMA is indicative of a system that does not have much deep soil water available for plant use. This is substantiated by soil moisture data collected from some soil borings in the loamy soils of RMA showing the soil moisture content more than a few feet below the ground surface to be very low (with soil water tension typically in the range of 15-25 atmospheres).

Indirect evidence such as that enumerated above provides a basis for expecting that a cover similar to the vegetative soil cover that naturally exists over much of RMA might perform equivalently to a traditional RCRA cover with regard to minimizing percolation through the cover. It also seems reasonable to expect that such a cover would have a very long life, since such natural prairie systems have persisted for thousands of years in the soils and climate at RMA. Besides the possible technical benefits of covers that are designed to mimic natural prairie systems, the construction costs associated with such a simple vegetated soil cover would be much less than for the traditional RCRA Subtitle C designs. For all these reasons an attempt to develop alternatives that could provide the desired evidence of RCRA-equivalency was initiated at RMA.

The field demonstration and testing program outlined herein for the alternative test covers were developed by the working group referred to above. After three summers allowed for vegetation establishment, an official test year will commence on September 1, 2000. To ensure that the test measures performance during an abnormally wet year, natural precipitation will be supplemented with irrigation, when necessary, to meet preestablished precipitation goals. During the test year, natural precipitation plus irrigation will be at least 21.08 inches (535 mm). Any of the test covers that produce no more than an equivalent of 0.051 inches (1.3 mm) of water over the area of the cover during the test year will be deemed to meet the RMA test for RCRA-equivalency with regard to percolation, and the test cover design may be used as the basis for the design of the RCRA-equivalent covers at RMA.

DEVELOPMENT OF ALTERNATIVE COVER DESIGNS

Development of the alternative covers for testing was a multidisciplinary effort utilizing expertise in agronomy, soil science, hydrology, wildlife, engineering, and construction. Results of ongoing vegetation studies were utilized, and computer modeling was performed to aid in designing the test covers and to fulfill the ROD requirement for comparative analyses of any alternative covers.

Vegetation Studies

The RCRA-equivalent cover project benefitted from several years of ongoing vegetation studies at RMA. Vegetation mapping of the entire RMA site had been previously performed and an inventory of plant species on some relatively undisturbed RMA sites containing plant species representative of pre-settlement conditions had been conducted. Another program had mapped RMA soils. Technical literature and experts were consulted to determine

appropriate plant species for each soil type. Separate seed mixes for five various RMA soil types were initially developed and tested in seeding trials. Results of these trials provided site specific information regarding ease of establishment, persistence, and competitiveness of the various species. The initial seed mixes were modified based upon these initial tests, and the modified mixes were also field tested. The results were used to once again modify the seed mixes to produce some desirable baseline seed mixes.

For the proposed RCRA-equivalent covers, specific project requirements and objectives formed the basis for some final modifications to the baseline seed mixes mentioned above. These factors included drought tolerance, soil texture, vegetation height (to deter prairie dog invasion), transpiration characteristics (utilizing both cool season and warm season species to provide transpiration throughout as much of the year as possible, and utilizing species with high leaf area indices to promote transpiration), and seed availability. Because the future land use for the site is as a shortgrass prairie national wildlife refuge, only native species were considered.

Computer Modeling

The comparative analyses required in the ROD were performed by simulating unsaturated flow through sections of various alternative covers. After considering a number of possible numerical modeling codes, the working group selected UNSAT-H for performing the analyses. UNSAT-H is a highly mechanistic, one-dimensional finite-difference code developed by Fayer and Jones (1990) that simulates the soil water balance. UNSAT-H simulates infiltration, drainage, moisture redistribution, surface evaporation, and plant-water uptake from soil. It uses hourly precipitation data and daily meteorologic data to model surface moisture fluxes and plant interactions in the hydrologic processes.

A simple modification was made to the UNSAT-H algorithm used to calculate potential transpiration to more realistically estimate potential transpiration when leaf area indices are low. Otherwise, the model unrealistically allowed no transpiration when leaf area indices are low as they are each spring and fall at RMA. Transpiration in UNSAT-H is calculated after first partitioning potential evapotranspiration (PET) into potential transpiration (PT) and potential evaporation (PE). Except for a model option developed specifically for simulating cheatgrass transpiration at the Hanford Site in the State of Washington, Version 2.0 of UNSAT-H calculates PT from the leaf area index (i.e., the leaf area per unit area of soil surface, or LAI) as follows:

$$PT = PET(0.7\sqrt{LAI} - 0.21) \quad \text{if } 0.1 \le LAI \le 2.7 \qquad \text{Eqn 1}$$

$$\text{if } LAI > 2.7 \text{ then } PT = PET \qquad \text{Eqn 2}$$

$$\text{if } LAI < 0.1 \text{ then } PT = 0 \qquad \text{Eqn 3}$$

An examination of the original Ritchie and Burnett (1971) paper proposing the above set of equations showed that they produce a fairly poor fit to the original data, and also produce a poor match to a hand-drawn curve in the original paper. Based on the original data, it appears that use of Equations 1, 2, and 3 would result in underestimating transpiration when LAIs are low. To improve estimations of transpiration, the Ritchie and Burnett (1971) data were fit with the following equation:

$$PT = (PET)(0.52\sqrt{LAI}) \quad (\text{r-squared} > 0.99) \qquad \text{Eqn 4}$$

Figure 3 contains a plot of the original Ritchie and Burnett data, a curve described by Equations 1, 2, and 3, and a curve described by Equation 4. The UNSAT-H code modification used in this study was simply to replace Equations 1and 3 with Equation 4. This change is expected to eliminate a source of bias in the model that would otherwise result in underestimating potential transpiration (thereby underestimating actual transpiration and evapotranspiration).

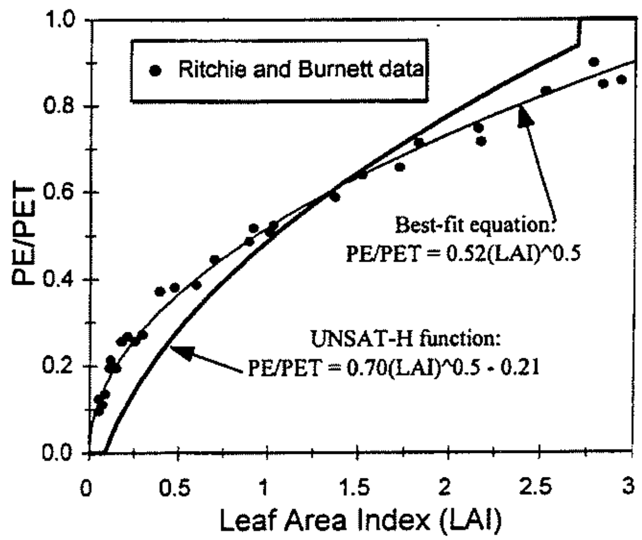

Figure 3. Relationship between LAI and PE/PET

Among the more important inputs required in the modeling are meteorologic data and parameters used to characterize the vegetation and soils, described briefly below.

Meteorologic Inputs: RMA is adjacent to the former Stapleton Airport, where meteorological data have been collected since the late 1940s. Individual precipitation events vary between the two sites, but the long-term trends and averages at RMA are expected to be similar to those at Stapleton. Therefore, Stapleton meteorological data were used as input for UNSAT-H modeling of the alternative test covers.

Hourly precipitation records from the Stapleton weather station were used to develop the precipitation portion of the input files. Precipitation data were first preprocessed to account for snow and snowmelt. On days when snow was recorded, all precipitation was assumed to be snow and was stored for subsequent melting. Until it melted, the snow was assumed to not provide a precipitation input to the soil column. Snowmelt was predicted using the Restricted Degree-Day Radiation Balance Approach outlined by Kustas and others (1994). On days with melting snow, snowmelt was added to the rain (if any) to produce the precipitation portion of the input files.

The working group decided to simulate the historic periods most likely to produce deep percolation through soil covers. Two simulation time periods were selected based on a review of the precipitation record at Stapleton. The wettest winter/early spring period ever recorded at Stapleton was in 1982-1983, and the wettest 1-year, 3-year, and 5-year periods were all within the 1965-1969 time period. It was expected that the historical period most likely to produce deep percolation from a vegetative cover would be during one of these two periods, so both periods were simulated.

Vegetation Inputs: UNSAT-H requires the input of various parameters for use in predicting the amount of transpiration from the soil profile. One important set of vegetative parameters describes the LAI distribution throughout the year. Estimates of seasonally distributed LAIs were provided by Redente (1997) based on literature and local field experience with the proposed vegetation species. The estimated LAIs varied from a minimum of zero during the winter to a high of one during the summer. Parameters relating to the vertical distribution of roots were estimated from information presented by Liang et al. (1989). Parameters relating to the limiting effect of low soil moisture levels on transpiration were based on information presented by Gardner (1983).

Soil Inputs: Soil investigations were conducted to characterize, sample, and test typical soils available at RMA for possible use in constructing the full-scale covers. Nineteen test pits were excavated to depths of up to 21 feet in preferred borrow areas. A number of representative soil samples were tested for unsaturated hydraulic characteristics for use in the modeling.

If the computer modeling indicated some of the RMA soils could be successfully used in RCRA-equivalent covers at RMA, it would be necessary to develop a soil specification that could be practically applied in a large-scale construction project. Use of unsaturated hydraulic characteristics of the soils for this purpose seemed unrealistic, but it was hoped that some relationships could be observed between soils that worked well in the modeling and more common soil tests. Consequently, numerous soil samples were also analyzed for common parameters such as grain-size distributions, Atterberg limits, and soil classification using the Unified Soil Classification System (USCS).

Modeling Results: The results of simulations using soil samples selected as being representative of most soil available in the preferred borrow areas were very encouraging. For each soil type, the 1982-1983 precipitation data (with the unusually wet winter/spring period) controlled the minimum thickness of vegetated soil cover required to meet the performance requirements established by the working group. The high summer evapotranspiration rates appeared to more than compensate for the fact that summer precipitation in portions of the 1965-1969 period was greater than the winter/spring precipitation in the 1982-1983 period.

Simulation results indicated that the cover thickness required to achieve the deep percolation criterion varied from 1.5 to 2.5 feet (considered in 6-inch increments) for seven of the eight soil samples selected to represent most of the soils in preferred borrow areas. Simulations using the eighth soil showed a required thickness of about 3.5 feet. This latter soil had significantly less clay than any of the other samples, and Atterberg limit testing indicated it to be nonplastic. Consequently, the soil specification used for construction of the test covers (discussed below) was written to exclude use of nonplastic soils.

Selected Designs for Testing

At the conclusion of the modeling effort described above, four conceptual designs were chosen for the field demonstration. Each of the four test covers are simple soil-vegetative covers, having a specified soil layer thickness and gradation. Each test plot was constructed over a 30 ft by 50 ft collection pan consisting of a 60-mil VFPE flexible membrane liner to collect any percolation through the covers. The liner was placed on a compacted soil subgrade constructed on a uniform 3 percent grade. A geocomposite drainage layer consisting of a polyethylene geonet

sandwiched between nonwoven geotextiles separates the VFPE liner from the soil layer. Drainage from each test cover is conveyed to an HDPE vault where it is measured in a tipping bucket rain gage and stored for measurement verification. A schematic drawing of a typical test cover is shown in Figure 4. A minimum 8-ft vegetated soil cover buffer extends beyond the perimeter of each collection pan to minimize edge effects. Surface runoff from each plot is collected and measured. A sprinkler system provides the capability to test under unusually wet conditions and to aid in establishing the vegetation. A schematic drawing showing the overall layout of the test covers and the instrumentation systems is shown in Figure 5.

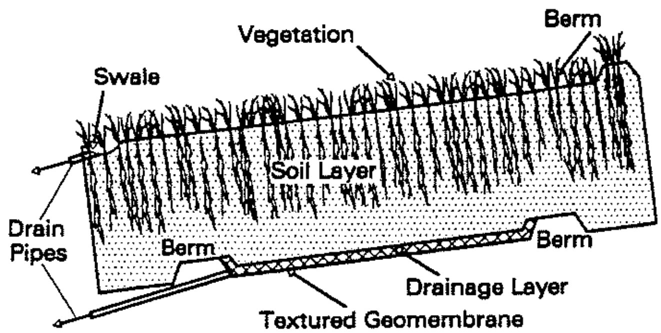

Figure 4. Typical RMA test cover schematic

The geonet drainage layer has minimal water storage capacity and a high saturated hydraulic conductivity. For full-scale implementation, the ROD specifies that a biota barrier must be included over areas where RCRA-equivalent covers can be considered. For full-scale implementation it is expected that the biota barrier will be an 18-inch-thick layer of cobbles or concrete rubble having far more water storage capacity than would the geocomposite drainage layer in the test covers. Consequently, the biota barrier would probably tend to reduce percolation more than does the geonet used beneath the test covers and test results should be conservatively high relative to full-scale conditions.

Soil Layer: Test cover thicknesses of 42 inches, 48 inches, and 60 inches (1.07 m, 1.22 m, and 1.52 m, respectively) were selected for testing. As mentioned above, modeling results indicated that thinner test cover sections would meet the percolation criterion established for the field demonstration, but a decision had been made to bury RMA biota barrier layers at least 42 inches (1.07 m) to protect them from freezing. At those depths, modeling results indicated that most of the RMA soils tested would be acceptable. A decision was made to utilize the finer-grained soils (mostly loam or clay loam soils) in three covers having soil layer thicknesses of 42, 48, and 60 inches. To see if the coarser-grained material is also suitable, a fourth test cover tests a 42-inch layer of coarser-grained soil (mostly sandy loam or sandy clay loam).

Since the alternative covers do not rely on a resistive barrier layer to minimize percolation, the soil specification did not include a hydraulic conductivity requirement. The saturated hydraulic conductivities of the acceptable soils would seem very high relative to the hydraulic conductivity desired in the compacted clay layers used in typical RCRA covers. The criteria for determining whether the soils were acceptable for use in the covers utilized particle-size gradations, Atterberg limits, and moisture content when placed, three commonly utilized measurements in construction projects. To look for correlations between particle-size gradation and model-predicted performance, the soils used for model simulations were plotted on a standard soil textural triangle as shown on Figure 6. In that figure the cover thicknesses required in the modeling to limit percolation to acceptable levels in the worst-case year are posted next to each data point. The division between sand and silt used in the textural triangle of Figure 6 is based on the U.S. Department of Agriculture (USDA) soil classifications which use a particle size approximately corresponding to a No. 270 sieve as dividing sand from silt. To help determine a practical construction specification, the particle-size gradation data were replotted on a modified soil texture triangle using the No. 200 sieve size, commonly used in construction projects, to divide sand from silt. The results are shown on Figure 7.

The three finer-grained test covers have at least 50 percent of each soil sample passing the No. 200 sieve (i.e., based on the USCS at least 50 percent of soil samples must be silt or clay). For the coarser-grained soil cover, soils having between 35 and 50 percent of the material passing the No. 200 sieve (i.e., between 35 and 50 percent silt or clay) were used. Additionally, on all four covers design specifications stipulated that soils have less than 10 percent gravel (based on the No. 4 sieve), the liquid limit be less than 40 percent, and the plasticity index be between 7 and 30 percent. The maximum liquid and plastic limits were set to prevent the use of soils having the greatest tendency to desiccate and crack. The minimum plastic limit was included to reflect the modeling results showing that the nonplastic soil (the sample showing a 3.5 ft cover as being needed in Figure 7) required use of a thicker soil layer to eliminate percolation. The large majority of RMA soils encountered in the test pit investigations would satisfy the soil specifications for at least one of the test covers.

Vegetation: The vegetation selected for seeding on the test covers includes a mix of 10 grass and 8 forb species. Grasses compose about 95 percent of the total seed mixture

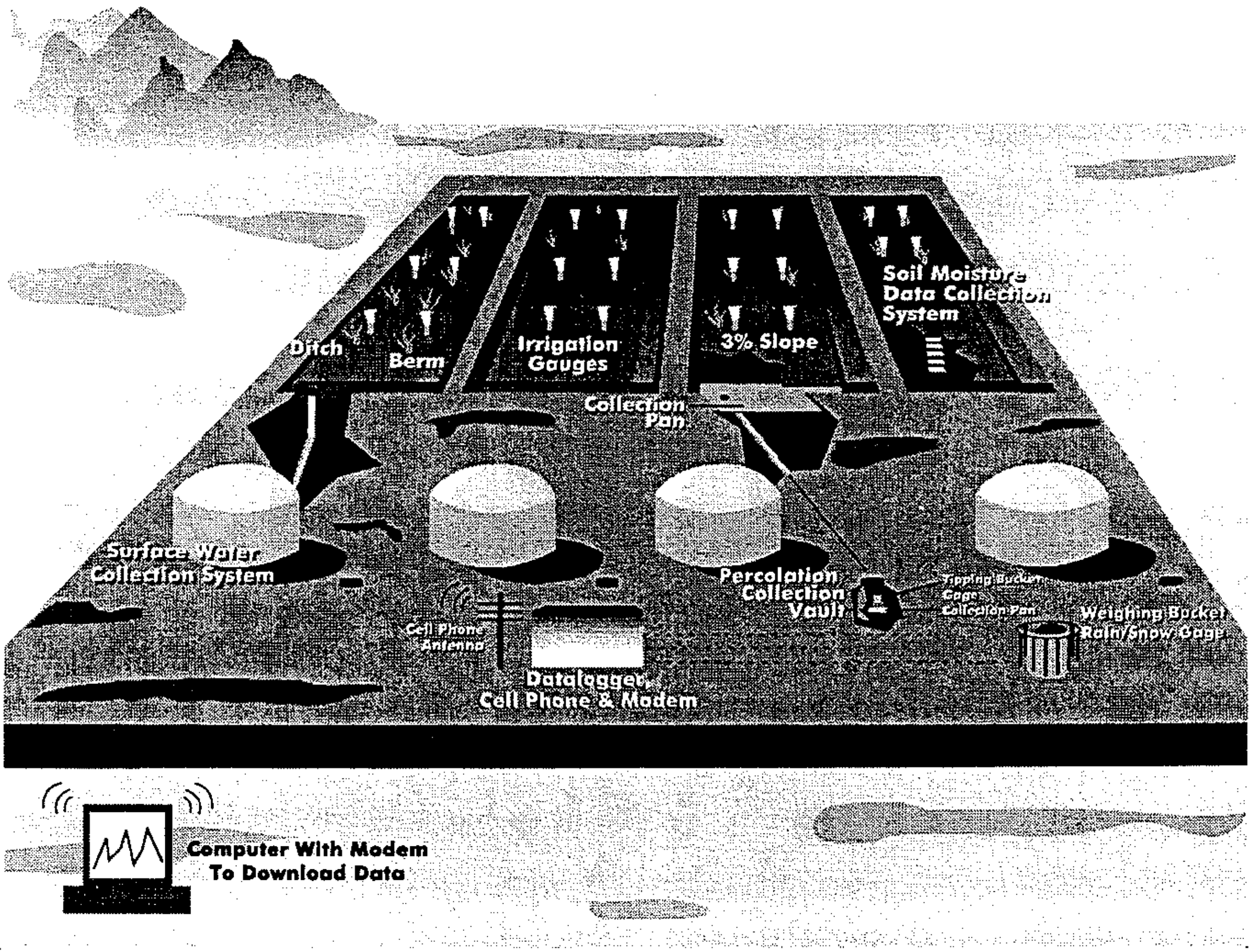

Figure 5. RCRA-equivalent cover demonstration project monitoring instrumentation (drawn by Kathy O'Neill)

and include such species as Buffalo grass, Blue grama, Switchgrass, Western Wheatgrass, and others. Forbs were included to increase the biodiversity on the covers and to promote transpiration over a wider range of conditions, thus potentially improving cover performance.

Due to the size of soil covers to be constructed at RMA (thousands of acres, including covers of all kinds), using natural topsoil for the cover surfaces would be problematic. Acceptable topsoil can be developed if suitable amendments are incorporated into the subsoil material that is available for use. Consequently, no topsoil was used in constructing the test covers, but organic amendments consisting of composted biosolids were incorporated into the top several inches of the covers at a rate of 40 tons per acre.

<u>Data Collection System:</u> A data collection system was incorporated into the field demonstration to provide readily accessible water balance information including drainage from the base of the test covers, soil moisture levels, precipitation, irrigation, and surface runoff. Drainage from the liner beneath each test cover is conveyed to a watertight HDPE vault where it is measured by a tipping bucket rain gage, and stored for measurement verification. Soil moisture profiles are monitored with time domain reflectometry (TDR) at six locations over the four covers. TDR probes are installed at six depths through the soil profile at each of the soil moisture monitoring sites. Natural precipitation adjacent to the covers is measured in a universal rain gage equipped with a wind shield. Irrigation is measured in six precipitation gages distributed over each test cover. Surface runoff from each plot is collected in lined swales and conveyed into 1800-gallon storage tanks where

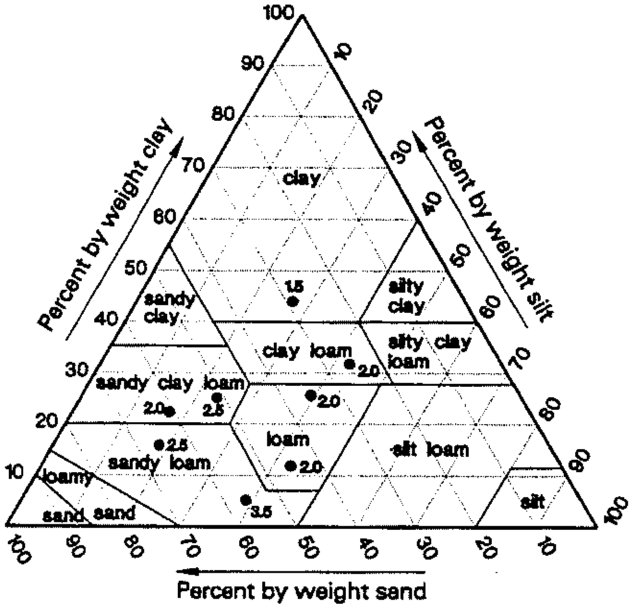

Figure 6. Model-based required cover thickness related to soil texture for various RMA soils.

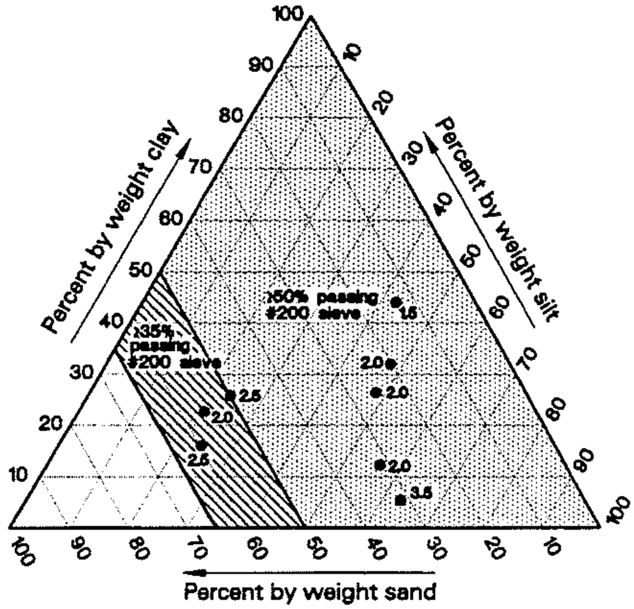

Figure 7. Model-based required cover thickness using a modified soil textural classification system.

accumulations are measured at least weekly. Electronic data from the percolation collection system, precipitation gage, and TDR probes are transmitted to a datalogger from which data can be remotely accessed by modem.

TEST COVER CONSTRUCTION

The four test covers were constructed in the northern part of RMA during the spring and summer of 1998. Cover construction began April 6. The test cover size was in part based upon the working group's desire that the test covers be constructed with large-scale equipment, similar in size to equipment that might be used to construct full-scale covers for the remediation projects. Accordingly, the covers were constructed using construction equipment, construction methods, and soil specifications chosen to be as similar as feasible to those that might actually be used for full-scale cover construction.

Unlike traditional covers, the concept upon which the test covers are expected to work is not dependent upon a soil layer having a low saturated hydraulic conductivity. Heavily compacting the soil in the proposed alternative covers, as is common in the resistive barrier layer of traditional RCRA covers, would inhibit development of healthy, drought-resistant vegetation, and would reduce the water-holding capacity of the soil layer. The performance and/or durability of the alternative covers are expected to be best if the soil densities are similar to those that would exist under natural conditions. Consequently, the test cover soils were placed so as to minimize construction-related compaction, recognizing that if the constructed soil densities are initially too low, natural settling would cause the soil covers to approach naturally occurring densities. For this reason the test cover soils were placed in thick lifts, allowing placement only when the soil moisture content did not exceed 10 percent by weight. To protect the VFPE liner, the first 2 feet of soil was placed with an excavator reaching in from beyond the perimeter of the test covers. The remaining soil was placed in a single lift by pushing soil over the covers with a dozer. This construction method kept all equipment off of the covers until the full depth of soil had been placed. The cover surfaces were then cut to finished grade. After the covers had been constructed to grade they were ripped deeply to negate the effects of any compaction that had occurred during placement.

For the soils being used to construct the finer-grained test covers, soil testing prior to placement was kept to a minimum in an attempt to more realistically reflect the level of testing that might occur in a full-scale project. After placement, several soil samples were collected from each of the three covers for documentation purposes. A summary of those test results is contained in Table 1. Numerous soil samples were taken within the borrow area in order to identify the appropriate materials for constructing the coarser-grained test cover. This was done to provide reasonable assurance that the soil used in the test cover would not be better (i.e., finer-grained) than desired. Testing results from the samples

Table 1. Results from Documentation Soil Sampling

	Coarse-grained Cover		Fine-grained Covers			
	Specification	Test Cover A	Specification	Test Cover B	Test Cover C	Test Cover D
Thickness (before ripping)		42 inches		48 inches	60 inches	42 inches
Percent Passing #200 Sieve	35-50 %	Ave 43.4 Range 37-47	>50 %	Ave 60.2 Range 56-63	Ave 59.2 Range 53-67	Ave 61.5 Range 59-63
Plastic Limit	7-40	Ave 9.0 Range 7-11	7-40	Ave 12.8 Range 11-16	Ave 11.7 Range 10-16	Ave 12.0 Range 11-13
Liquid Limit	30	Ave 24.4 Range 24-25	30	Ave 27.6 Range 26-30	Ave 26.7 Range 25-30	Ave 26.8 Range 26-28

that passed the specification requirements for the coarse-grained cover are also listed on Table 1.

After ripping, the organic amendments were spread over the cover surfaces and incorporated into the top several inches of the covers with a chisel plow. Commercial fertilizers were not used on the test covers. After repeated passes with the chiseling equipment to smooth out the undulations caused by ripping, the covers were harrowed, and on May 13, 1998 the covers were seeded. Seedlings were somewhat slow to emerge due to lack of natural precipitation and delays in construction of the irrigation system. Seedling emergence began about June 19 and irrigation was initiated on June 26. Several light irrigations were applied during the summer to aid vegetation establishment. It is anticipated that irrigation will be phased out by the end of the second growing season (except to augment precipitation during the test year to test performance under abnormally wet conditions).

The TDR soil moisture monitoring system became operational on July 10. Measurements of natural precipitation using the recording precipitation gage and measurements of surface runoff began September 1. Prior to that date, precipitation was manually measured in the irrigation gages on the test covers.

INITIAL RESULTS FROM TEST COVER FIELD DEMONSTRATION

Although the true test of the performance will come later as the vegetation improves and the covers are tested under abnormally wet conditions, initial test results from the field demonstration of the test covers are encouraging,

Vegetation

Despite the delayed start of growth, all seeded species were established in suitable densities and cover for the initial growing season. The only reseeding that took place was on areas that were redisturbed through installation of monitoring instrumentation. By the end of the growing season there were no large remaining bare areas on the covers. Cover by weedy species was negligible.

Vegetation cover data were collected in early October when plants had achieved maximum growth for the season and were becoming dormant. Total cover by live vegetation averaged 26 percent on the four test covers. Of the total cover, 97 percent was provided by seeded species. There was essentially no cover from litter since there had been no previous vegetation on the area and mulch was not applied after seeding. Consequently, the remaining 74 percent of the site was bare soil. Although this total vegetation cover is somewhat low compared to established stands, it is high for an establishment year. The plants are robust. It is expected that vegetation cover at the site will increase to values comparable to mature plant communities during the next two growing seasons and litter will build up on the ground surface. Bare soil values will decrease accordingly.

Deep Percolation

Although the official testing period will not begin until September 1, 2000 after the vegetation has become established, the percolation results are encouraging. To date, there has been little or no percolation from the base of the test covers. Any drainage water would fall into a tipping bucket rain gage for recording, then into a large plastic pan. Overflow, if any, from the pan would be stored in the bottom of the watertight vault. During the first few months of

operation, vapor condensation around the vault cover also dripped through the rain gage, so actual test cover drainage water would be some amount less than the amount falling into the rain gage. On January 21, 1999 plastic covers were placed over the rain gages to prevent the condensation on the vault walls from falling into the gages. Since then, no drainage has been recorded from any of the test covers. Prior to elimination of the condensation problem, the total water recorded by all four rain gages at the four covers was just under a gallon, with about two-thirds of the total being measured in the gage at Test Cover D (i.e., the 42-inch-thick test cover of finer-grained soils).

Although the field demonstration is considered as being in the vegetation establishment phase prior to when the effectiveness of the test covers will be determined, some interesting observations can be made. The amount of water applied to the covers since July 1998 (when precipitation measurements began) has been abnormally high. Precipitation/irrigation totals for the July 1998 through March 1999 period ranged from 14.44 to 14.85 inches (367 to 377 mm) on the four covers. In the 52-year precipitation record at the former Stapleton Airport, only two years have had greater total precipitation during similar 9-month time periods.

Of more relevance than total precipitation over an extended period is the temporal pattern of the precipitation. The months having the greatest precipitation at Stapleton have historically been during the high evapotranspiration season of May through August. Performance of the covers during individual months of high precipitation is promising based on the July 1998 results when the combined amount of precipitation/irrigation ranged from 6.10 to 6.35 inches (155 to 161 mm) on the four covers. At Stapleton, only three months have ever recorded greater precipitation, with the maximum monthly precipitation being 7.31 inches (186 mm). As indicated by the percolation data mentioned previously, even though the vegetation was just getting started during July 1998, percolation (if any) during the month was negligible.

As mentioned previously, computer modeling results indicated that the most critical period for preventing deep percolation is probably during the winter and early spring. Precipitation during the 1998-1999 winter was lower than normal, although with approximately 2 inches of irrigation applied late in March, the November through March totals were slightly greater than the average Stapleton precipitation totals for similar periods. However, soil moisture data indicate the covers could have performed well had the amount of applied water been significantly greater during the November-March period.

Soil Moisture Trends

Figure 8 contains a graph showing how the daily soil moisture content changes over time at various depths in Test Cover D. Soil moisture trends and patterns apparent at that location are fairly representative of those on the other covers. The figure also shows daily values of precipitation and irrigation.

The relationship between water potential and moisture content varies with soil texture. Since the soils within the test covers are not completely homogeneous, conclusions based on differences (especially small differences) in moisture content between different probes could be misleading. However, much can be learned from the moisture content changes over time at each probe. Particularly near the cover surface, spacings of the TDR probes are probably inadequate to allow an accurate calculation of the amount of water contained in the soil profile.

One of the more important observations regarding soil moisture profiles is that the soil moisture levels have been consistently low in the bottom portion of the test cover. The soil at the lowest two positions always remained fairly dry (below 10 percent moisture content, by volume), although the barely perceptible soil moisture increase at a depth of 33.8 inches may have been in response to the gradual migration of the wetting front from the heavy July precipitation/irrigation. At a minimum, the wet July caused a wetting front to slowly reach a depth of at least 26.1 inches.

As expected, except when moisture contents were near their maximums, water movement within the covers was gradual. The wetting front attenuates and slows as it moves downward. Soil moisture levels were high at the 3- and 10.7-inch depths at the end of the first day of TDR monitoring from the heavy rain that occurred earlier in the day, but a significant increase in soil moisture at the 18.4-inch depth did not begin until two days later, and even then the soil moisture increase at that depth was slower than it had been at shallower depths. Even with significant amounts of precipitation/irrigation throughout the rest of July, soil moisture levels did not begin to increase at the 26.1-inch depth until early August after soil moisture levels at the shallower probes had already begun declining from their summer highs. Soil moisture levels at the 26.1-inch depth never reached the high values the shallower probes had reached, although such comparisons may be influenced by soil texture differences in the soil profile.

Apparent from Figure 8 is the fact that soil moisture levels fluctuate quickly and frequently in the shallowest probes, but with greater depth the fluctuations subsided, until in the

deeper probes the data fluctuations were extremely mild, and slow. Any significant water application on the cover resulted in an increase in soil moisture at the 3-inch depth, and the soils at that depth quickly began to dry between precipitation/irrigation events. A careful evaluation of the data shows that when the shallow soils are fairly dry, it takes about 0.3 inches of precipitation/irrigation to cause an increase in soil moisture content at the 3-inch depth. As can be seen from the results in late March, application of the approximately 2 inches of water in a three-day period on relatively dry test covers resulted in water movement to at least the 26.1-inch depth (although this is the only one of the six soil moisture profiles with data indicating the soil moisture reached that depth).

It is of interest to note that the test covers dried out significantly after the summer of 1998, even though vegetation was just beginning to get established and root systems would have been relatively sparse and shallow. In the future, a more mature vegetative community should provide more rapid drying of the test covers between precipitation events.

Surface Runoff

The vegetated soil surface on the test covers is similar to those constructed over traditional RCRA covers, so measurement of surface runoff is not being conducted to determine whether the test covers are RCRA-equivalent. Rather, the data are being collected for general information purposes. Surface runoff on the test covers comes from natural precipitation, as the irrigation system applies water at a rate that produces essentially no runoff except from the impermeable swales. Estimates of actual surface runoff are made by adjusting the collected runoff by the estimated amount of runoff from the swales.

Because of construction difficulties, surface water runoff measurements did not begin until September 1, 1998. Prior to that, runoff had been significant during the heavier summer storms. From September 1998 through March 1999, runoff-producing events were uncommon, as is typical of the fall and winter at RMA. From the 3.67 inches of natural precipitation falling during that period, surface runoff is estimated to be 0.21 inches from Test Cover A (the coarser-grained cover), and is estimated to range from 0.19 to 0.25 inches over the three finer-grained covers. The tendency for precipitation to cause surface runoff should decrease substantially as the vegetative cover increases.

CONCLUSION

Initial results from the RCRA-equivalent cover field demonstration seem consistent with indirect evidence obtained from local deep percolation studies, numerical modeling, and lysimeter data from the Pawnee National Grasslands, all indicating that a simple vegetated soil cover may be as effective as the traditional prescriptive RCRA Subtitle C covers in eliminating deep percolation. During the first several months of the field demonstration, deep percolation from the test covers has been essentially nonexistent, in spite of the fact that vegetation was immature during the entire period. Soil moisture data indicate little or no water penetrated below depths of about 26 to 33 inches (0.66 to 0.86 m) in the test covers, even though more than 6 inches of precipitation and irrigation were applied to the covers in a single month (July 1998). The limited data collected to date do not show a significant difference in the depth to which the infiltrating precipitation reaches in the various covers, despite the textural differences between the coarse-grained and fine-grained covers. During the fall and winter the soils in the test covers dried substantially.

More will be learned about the effectiveness of the covers in preventing deep percolation as the vegetation development progresses and the test covers are monitored during a test year having abnormally heavy precipitation. At this point in the field demonstration the alternative test covers appear to be working as expected, and there seems to be justification for optimism that the performance of the vegetative covers will be equivalent to that of a RCRA Subtitle C cover. Given the potential for tens of millions of dollars in cost savings provided by these alternative covers and their proven long-term sustainability, it appears that soil-vegetative covers could provide a valuable alternative to traditional RCRA Subtitle C covers at RMA and other sites where the climatic conditions are favorable.

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