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SAND2000-2428
Unlimited Release
Printed October 2000

Construction Overview of Six Landfill Cover Designs

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Prepared by
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Construction Overview of Six Landfill Cover Designs

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Abstract

This paper provides an insight into the construction of six different landfill cover designs. The covers are part of a large-scale field demonstration comparing and contrasting final landfill closure designs. Four alternative and two conventional cover designs (a RCRA Subtitle 'D' Soil Cover and a RCRA Subtitle 'C' Compacted Clay Cover) were constructed of uniform size, side-by-side. The demonstration is intended to evaluate the various cover designs based on their respective water balance performance, ease and reliability of construction, and cost.

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Background

The US Department of Energy (DOE) is in the midst of a major clean-up effort of their facilities that is expected to cost billions of dollars. These cost estimates however are based on cleanup technologies currently used by DOE. Research has shown that many of these technologies have proven to be inadequate (Mulder and Haven 1995). Consequently, work has begun on the development and improvement of environmental restoration and management technologies. One particular area being researched is landfill covers. As part of their ongoing environmental restoration activities, the DOE has many radioactive, hazardous, mixed waste, and sanitary landfills to be closed in the near future (Hakonson et al., 1994). These sites, as well as mine and mill tailings piles and surface impoundments, all require either remediation to a 'clean site' status or capping with an engineered cover upon closure. Additionally, engineered covers are being considered as an interim measure to be placed on contaminated sites until they can be remediated.

The Alternative Landfill Cover Demonstration (ALCD) is a large-scale field test at Sandia National Laboratories located on Kirtland Air Force Base in Albuquerque, New Mexico (Figure 1). Its intent is to compare and document the performance of alternative landfill cover technologies of various costs and complexities for interim stabilization and/or final closure of landfills in arid and semi-arid environments. The test covers are constructed side-by-side for comparison based on their performance, cost, and ease of construction. The ALCD is not intended to showcase any one particular cover system. The focus of this project is to provide the necessary tools; i.e., cost, construction and performance data, to the public and regulatory agencies so that design engineers will have less expensive, regulatory acceptable alternatives to the conventional cover designs.

Introduction

The covers were independently designed. The designs were packaged into a set of construction bid documents that included drawings and specifications for each test cover. The covers were divided into two separate bid packages known as Phase I and Phase II. The Phase I covers built in FY95 include a conventional RCRA Subtitle 'D' Soil Cover, a conventional RCRA Subtitle 'C' Compacted Clay Cover, and the first alternative cover - a Geosynthetic Clay Liner (GCL) Cover. The RCRA Soil and Compacted Clay Covers were constructed to serve as baselines for comparison against the alternative cover designs. The Phase II covers built in FY96 are alternative covers that include the Capillary Barrier, Anisotropic Barrier, and Evapotranspiration (ET) Cover. Each phase of construction was competitively bid with the low bidder receiving a firm fixed price contract.

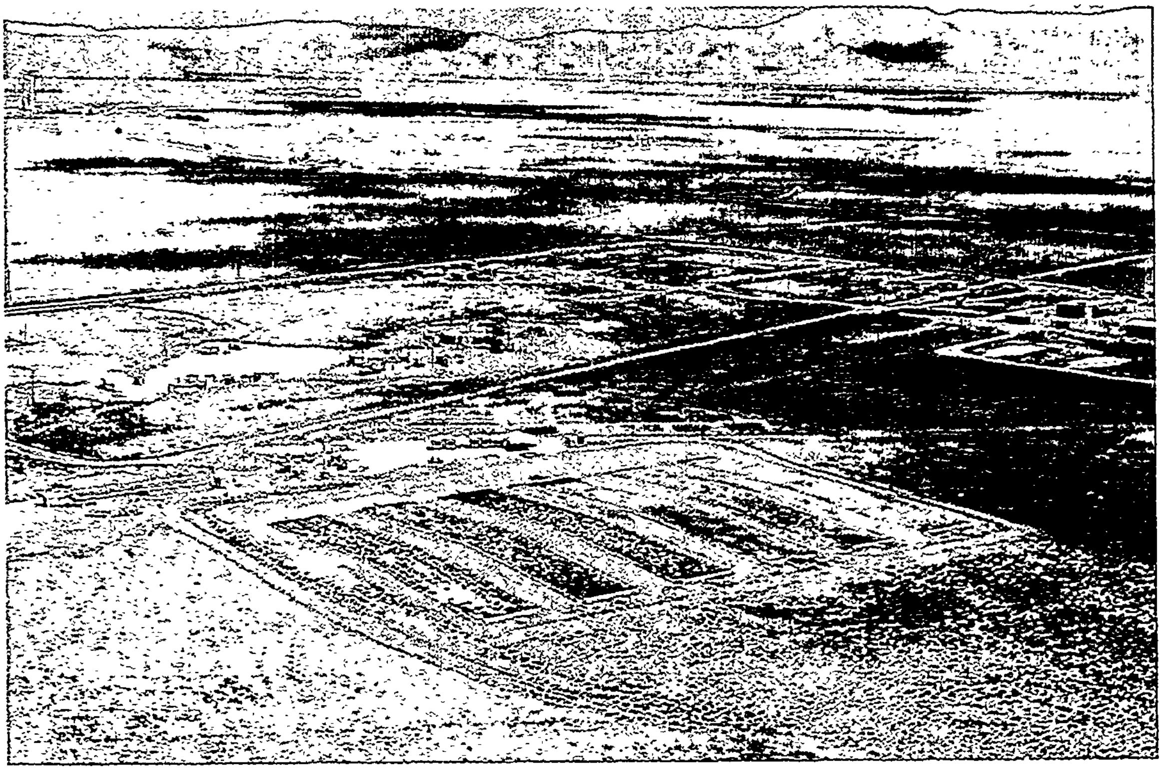


Figure 1. Aerial View of Alternative Landfill Cover Demonstration

The test covers are each 13 m wide by 100 m long. The 100 m dimension was chosen because it is representative of hazardous and mixed waste landfills found throughout the DOE complex (approximately 2 acres in surface area). All covers were constructed with a 5% slope in all layers. The slope lengths are 50 m each (100 m length crowned at the middle with half of the length, 50 m, sloping to the east and the other 50 m sloping toward the west). The western slope is monitored under ambient conditions (passive monitoring). A sprinkler system was installed in the eastern slope of each cover to facilitate stress testing (active monitoring) of the covers (Figure 2).

Continuous water balance and meteorological data is currently being obtained. It will be actively collected for a minimum five-year post construction period. In addition, periodic measurements of vegetation cover, biomass, leaf area index, and species composition are being taken.

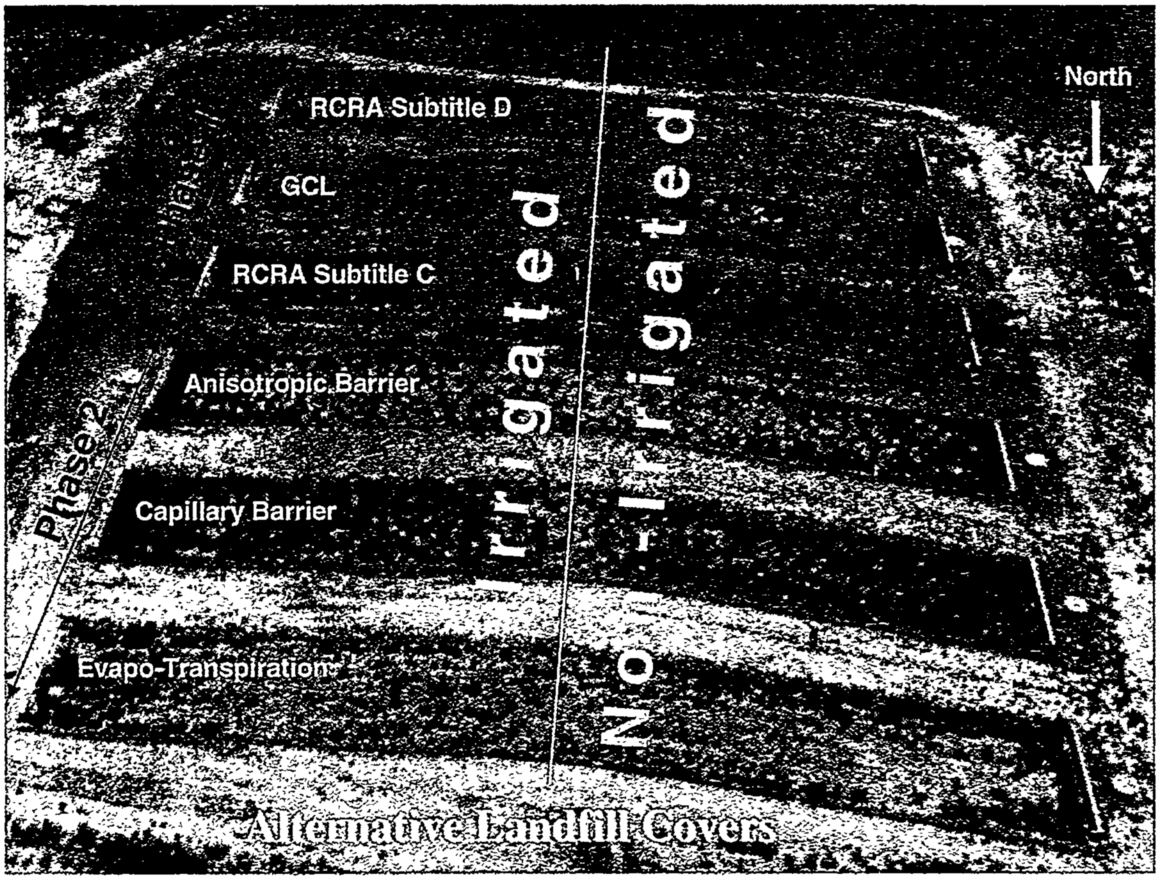


Figure 2. Test Cover Layout

Baseline Test Covers

Baseline Test Cover 1 (Plot 1) is a basic Soil Cover installed to meet minimum requirements for RCRA Subtitle 'D' governed landfills per 40CFR258. These requirements apply to municipal solid waste landfills (MSWL) to be closed using engineered covers and are designed with intent to meet the following performance objectives:

1. cover permeability less than or equal to the permeability of the bottom liner/subsoil or no greater than 10^{-5} cm/sec;
2. minimize infiltration using no less than 45 cm of soil; and
3. minimize erosion using no less than 15 cm of soil for plant growth.

The installed test cover is 60 cm thick (Figure 3). It is constructed of essentially two layers. The bottom layer is a 45 cm thick compacted soil barrier layer. The top vegetation layer is 15 cm of loosely laid topsoil.

RCRA Subtitle 'D' Soil Cover

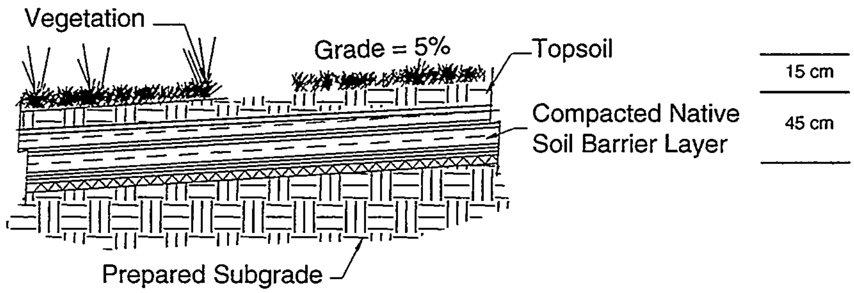


Figure 3. Profile of Baseline Test Cover 1 (Soil Cover)

The barrier layer's primary purpose is to minimize the infiltration of water into the underlying waste. The fill soil used in constructing the test covers was taken from on-site cut excavations. Similarly, all topsoil used in the demonstration was topsoil cut from the site, stockpiled separately from the fill soil, and later reused as topsoil on the test covers. Quality Assurance (QA) similar to that recommended by the EPA (EPA 1991) was employed throughout the construction of the test covers.

QA on the barrier layer was of particular importance. The QA on the soil barrier layer ensured the accomplishment of three objectives:

- layer materials were suitable;
- layer materials were properly placed;
- and completed layer was properly protected.

The primary objective in placing the barrier layer was to construct a uniform layer that has minimal hydraulic conductivity. In order to achieve this, adequate soil must be used: the soil must possess a minimum percentage of fines (passing no. 200 sieve) with a maximum percentage of gravel (percentage passing no. 4 sieve); and no clods or stones larger than the maximum size allowed. Refer to Table 1 for QA specifics for the Soil Cover.

TABLE 1. Tests/Observations for Material in Soil Cover (Plot 1)

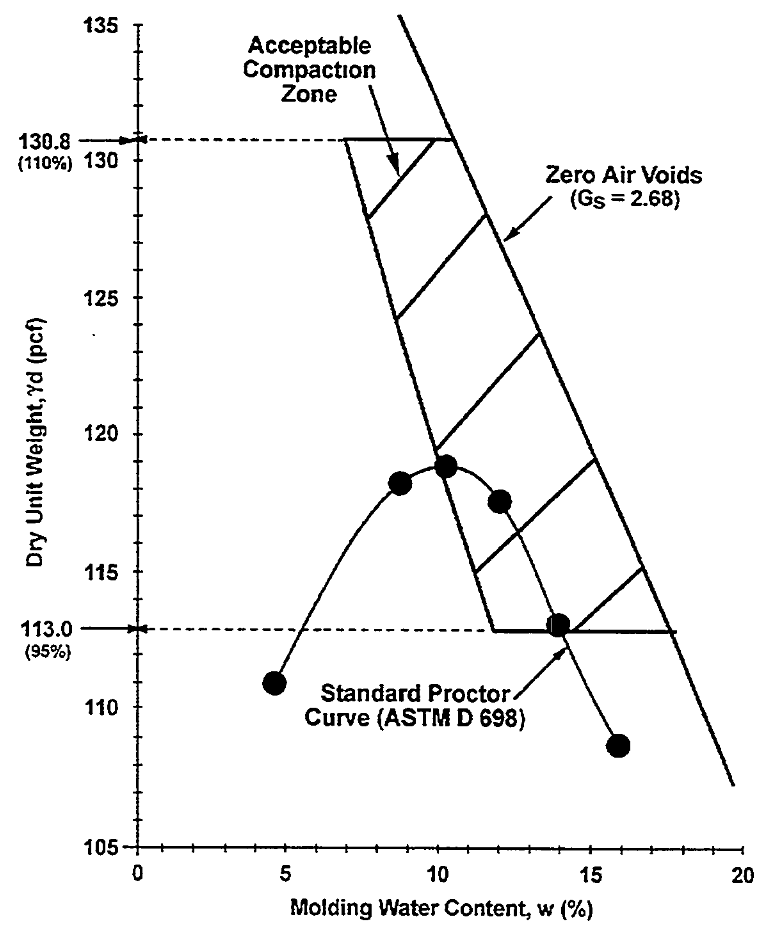
Parameter	Method	Min. Frequency	Limiting Criteria
percent of fines (200 sieve)	ASTM D422/D1140	2/lift/cover	20% minimum
Percent gravel (4 sieve)	ASTM D422	2/lift/cover	10% maximum
Max. Size Clod/Stone	observation	continuous	5 cm dia. max.
Bentonite Content	observation	continuous	6% min. by weight
Water Content	ASTM D2216	1/lift cover	wet of optimum(1)
Water Content	ASTM D3017	5/lift/cover(4)	wet of optimum(1)
Compaction	ASTM D698	1	95% min. to 110% of MDD(6)
Compaction	ASTM D1556	1/lift/cover	95% min. to 110% of MDD(6)
Compaction	ASTM D2922	5/lift/cover(4)	95% min. to 110% of MDD(6)
Compactor Weight	observation	record actual weight	13,600 kg min.(2)
Compaction Passes	observation	(3)TBD	(3)TBD
Lift Thickness	observation	(3)TBD	23 cm max. (loose)
PI	ASTM D4318	1/lift/cover	0 to 35%
In-Situ Hydraulic Conductivity	ASTM D5093	1/cover(5)	1 X 10^{-5} cm/sec max.

(1) Must be within acceptable range within standard proctor curve, Figure 4.
(2) Recommended minimum weight. To coincide with use of standard proctor curve.
(3) To be determined in the field.
(4) If an outlier is found, 2 more tests must be taken.
(5) Test pad constructed adjacent to test cover. Profile replicated barrier layer in test cover.
(6) MDD = maximum dry density per soil's standard proctor curve, Figure 4.

The maximum size clods and rocks allowed in the barrier layer soil is important. Large objects are more of a problem with dry hard soils than with moist soils. If these large objects remain, higher hydraulic conductivities will result. During placement of each lift in the barrier layer, laborers discarded all foreign objects greater than 5 cm in diameter. This process was continued during placement and was verified by visual observation.

Water content is key when compacting soil layers for several reasons. The soil must be within a moisture range to enable compaction of the layer to be within an acceptable density range. The optimum moisture content allows for the maximum dry density

(MDD) to be achieved during compaction. The EPA recommends soil barrier layers be compacted 'wet of optimum' yet still within the acceptable range, in an effort to minimize the saturated hydraulic conductivity of the soil layer. The higher water content is recommended to enable the soil to be remolded while being compacted. Based on a Standard Proctor Curve (ASTM D698) from soil obtained in the field and tested in the laboratory, optimum gravimetric moisture content was 11.3% while the MDD was 118.9 pcf. The acceptable compaction zone (Figure 4) was determined with this curve. A minimum compaction level of 95% of MDD was determined in the lab to yield an acceptable low hydraulic conductivity. This high compaction, along with the moisture in the soil, allows the voids in the soil to be greatly minimized and thus gives the lift a lower hydraulic conductivity. Clods can easily be remolded when wet. A potential problem when the soil is compacted 'wet of optimum' is that the soil is subject to desiccation cracking (Suter 1993).



Acceptable Compaction Zone - "Wet Side"
Plot 1 - Barrier Soil Layer

Figure 4. Acceptable Compaction Zone - Baseline Test Cover 1

The barrier layer was constructed in three 15-cm thick compacted lifts. A large front end loader was used to place the loose lifts. A grader and bulldozer were then used to smooth the lifts to uniform thickness. A smooth-rolled vibratory compactor was used to compact each lift. This was typical for all compacted soil layers in all test covers. Whenever a lift was placed above and in contact with a smooth-rolled lift, the top of the smooth-rolled lift was scarified to a depth of two to four cm to allow the lifts to bond together better thus eliminating an interface joint. Refer to Table 1 for Quality Control measures taken to ensure the barrier layer was installed as specified.

The top vegetation layer consisted of uncompacted topsoil placed immediately on top of the barrier layer. The vegetation soil layer provided a medium allowing plant growth. This plant growth reduces the harmful effects of surface erosion due to both runoff and wind. Generally, topsoil should be composed of an adequate supply of nutrients to encourage nonwoody indigenous plants. A medium-textured soil such as a loam generally fits these requirements. Quality assurance during placement of this layer ensured adequate and uniform depth for the entire layer. Debris and stones exceeding allowable maximum size were discarded.

Baseline Test Cover 2 (Plot 3) is a Compacted Clay Cover designed and constructed in accordance with minimum regulatory requirements for closure of hazardous and mixed waste landfills found in 40 CFR Parts 264 and 265, Subpart N. Under these regulations, owners/operators of landfills are required to perform landfill closures. The primary closure requirements of 264.310 and 265.310 specify the owners/operators to design and construct a low-permeability cover over the landfill to minimize migration of liquids into the waste and to provide 30 years of post-closure monitoring and maintenance in order to prevent waste migration into the environment. The cover design provides the following:

1. minimizes liquid migration,
2. promotes drainage while controlling erosion,
3. minimizes maintenance,
4. has a permeability equal to or less than the permeability of the natural subsoil,
5. accounting for freeze/thaw effects,
6. accommodates settling and subsidence so that the cover's integrity is maintained.

The recommended EPA RCRA Subtitle 'C' final cover design (EPA 1991) from bottom to top consists of:

1. A composite barrier layer consisting of a minimum 60-cm thick layer of compacted natural or amended soil with a maximum saturated hydraulic conductivity of 1×10^{-7} cm/sec in intimate contact with a minimum 40-mil geomembrane overlying this soil layer;
2. A drainage layer consisting of a minimum 30-cm thick sand layer having a minimum saturated hydraulic conductivity of 1×10^{-2} cm/sec, or a layer of geosynthetic material having the same characteristics;

3. A top vegetation/soil layer consisting of a minimum 60-cm of soil graded at a slope between 3 and 5 percent with vegetation or an armored top surface.

The Compacted Clay Cover was designed and constructed with the following features. It is 1.5 m thick. The profile for this cover consists of three layers (Figure 5). The bottom layer is a 60 cm thick compacted soil layer. This layer's primary purpose is as a barrier layer to prevent the downward migration of water into the underlying waste. Similar to Baseline Test Cover 1, the soil material selected had to meet specified requirements.

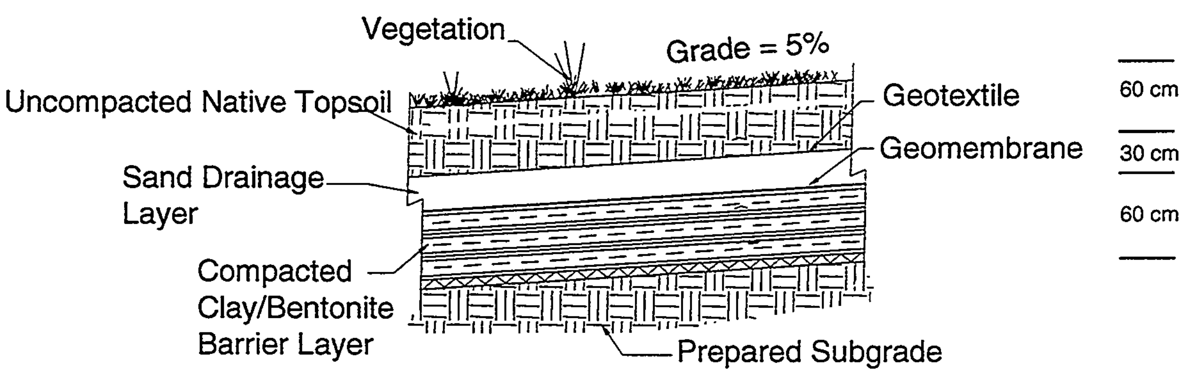


Figure 5. Profile of Baseline Test Cover 2 (Compacted Clay Cover)

Specified soil material requirements include the PI to be within an acceptable range, a minimum percentage of fines, a maximum percentage of gravel, a maximum clod/stone size, water content and density acceptable ranges. Laboratory tests revealed that the native soil required amendment to meet the saturated hydraulic conductivity requirement (maximum of 1×10^{-7} cm/sec). The goal of the laboratory testing was to find a combination of native soil and soil amendment. In this case sodium bentonite was used as an amendment to yield a maximum saturated hydraulic conductivity of 1×10^{-8} cm/sec. Past experience has shown that laboratory testing of hydraulic conductivity yields results at least an order of magnitude better than in-situ soil measurements. Through laboratory testing using a rigid-wall permeameter (Boyton and Daniels 1985), it was determined that a mixture of 6% by weight of sodium bentonite with the native soil compacted 'wet of optimum' to a minimum of 98% of maximum dry density per ASTM D698 would be adequate. All permeameter tests in the 'wet of optimum' range yielded results between 10^{-8} to 10^{-9} cm/sec range. The bentonite was purchased in two ton bags trucked in from Wyoming. The volumetric ratio of soil to bentonite was calculated to fulfill the 6% by weight requirement. The soil was mixed according to this ratio using a front end loader bucket as the measurement instrument for the soil. The soils were laid out adjacent to the test bed according to the determined soil mixture. They were mixed together using a grader by adjusting the blade so that as the grader passed over the soil it would cause it to roll over itself. This was performed until a thorough mixture was achieved. Based on the weights of the two soils at the determined rate, a soil mixture unit weight was calculated. Field samples were taken of the mixed soil and weighed to determine compliance with the calculated weight. The soil was then wetted, placed and compacted.

Figure 6. Bentonite and Soil Layout Prior to Mixing

The barrier layer was constructed in four 15-cm thick compacted lifts. It was compacted 'wet of optimum' as recommended by the EPA (EPA 1991) to lower the saturated hydraulic conductivity. Based on a Standard Proctor Curve (ASTM D698) from samples of the amended soil tested in the laboratory, the optimum moisture content was determined to be 11.8%. The acceptable compaction zone was determined similar to that seen in Figure 4. The allowable gravimetric water content was 11.8 to 16% while the allowable density requirement was between 98% to 110% of the MDD.

A maximum percentage of gravel was upheld as well. Gravel uniformly mixed and totally surrounded by clay does not usually pose a problem. The problem comes when the mixture is not uniform and there is a high percentage of gravel that can lead to gravel pockets being formed resulting in higher hydraulic conductivities.

Each lift's surface was scarified after compaction prior to placement of the next lift of soil to eliminate interface joints. However, the upper lift was not scarified to allow for intimate contact with the overlying geomembrane to create a composite barrier layer. All objects larger than a centimeter were removed from the top lift's surface in an effort to minimize the potential for damage to the geomembrane.

A 40 mil linear low density polyethylene (LLDPE) geomembrane was placed directly on the soil barrier layer. The objectives of the installed geomembrane were to prevent the downward percolation of liquids and to withstand construction traffic as the test covers were installed. The geomembrane was trucked to the site along with the other geosynthetics used in the demonstration. Each panel was rolled out into place using a tractor with a spreader bar attachment (Figure 7). As the tractor backed-up the roll of geomembrane was supported on the spreader bar and laid in place. As the geomembrane unrolled, laborers guided it into place. This was done for each panel. The panels were then welded together using a self-propelled hot air welder that provided a double seam (Figure 8). The QA requirements specified for the material acceptance and installation of the geomembrane were very detailed and lengthy. In general, it required that the membrane be installed with no defects. The seams were tested for continuity and strength. Any defects found were patched with a piece of LLDPE using an extrusion weld and vacuum tested for complete adhesion.

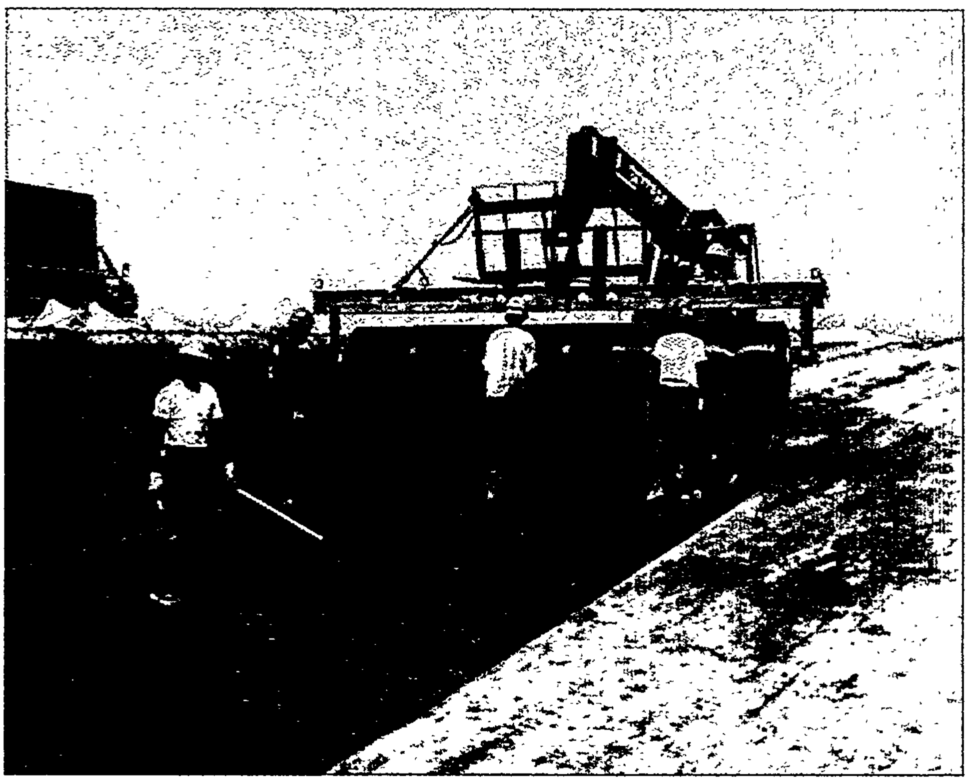


Figure 7. Geomembrane Placement with Spreader Bar Attachment

Figure 8. Welding Seams of Geomembrane Panels

The middle layer is a 30 cm thick drainage layer. The purpose of the drainage layer is to minimize the time any infiltrated water is in contact with the underlying barrier layer by quickly routing water that has passed through the vegetation layer laterally to collection drains located at the perimeter of the landfill. This layer was constructed of sand placed directly on the geomembrane. Quality assurance for the sand drainage layer ensured that the layer materials were suitable and that they were properly placed. The sand used was a common material referred to as "washed concrete sand." The sand was chosen because its percent fines content was very low and its saturated hydraulic conductivity exceeded the minimum 1 x 10^{-2} cm/sec requirement. The sand was not to have fines passing the no. 200 sieve greater than 5% to minimize the risk of future clogging of the drainage layer. The sand was placed in one uncompacted lift. A nonwoven polyester needle-punched geotextile was placed directly on top of the sand drainage layer to serve as a filter between the drainage layer material (sand) and topsoil layer. The geotextiles were then rolled into place with a minimum panel overlap of 15 cm. There was no physical seaming performed. The objectives of the geotextile installed was to provide a filter fabric to prevent the upper soil from mixing with the underlying medium while allowing free flowing drainage. In addition, the geotextile provided medium to withstand construction traffic during the installation of the test covers. Quality assurance required the geotextile panels have adequate overlapping of seams, and be continuos and undamaged across the entire plan of the cover.

The top layer is a 60 cm thick vegetation layer comprised of uncompacted soil. This layer's primary purpose is to provide for vegetation growth, erosion protection, and protect the underlying layers from freeze/thaw cycles. The vegetative layer allows for storage of infiltrated water that can later be evaporated and/or transpired through vegetation growth. As built, it consists of 45 cm of native soil covered by 15 cm of topsoil. This vegetation layer was placed in two lifts. The first 45 cm of native soil was spread into place and left uncompacted. The 15 cm of topsoil was then spread in place on top of the native soil. The two soil types were kept in separate stockpiles. The QA for this layer was relatively simple. It ensured that large objects were discarded and that the depth of soil was consistent and uncompacted.

TABLE 2. Tests/Observations for Material in Subtitle 'C' -Compacted Clay Cover (Plot 2)

Parameter	Method	Min. Frequency	Limiting Criteria Vegetation Layer	Limiting Criteria Sand Drainage Layer	Limiting Criteria Soil Barrier Layer
Percent Fines (200 sieve)	ASTM D422 or ASTM D1140	2/lift/cover [(4)]	20% min.	5% maximum	20% min.
Percent Gravel (4 sieve)	ASTM D422	2/lift/cover	10% max.		10% max.
Max. Size Clod/Stone	observation	continuous	5 cm dia. max.		5 cm dia. max.
Bentonite Content	observation - SNL present during mixing	[(3)]			6% by weight, min.
Water Content	ASTM D2216	1/lift cover			wet of optimum
Water Content	ASTM D3017[(1)]	5/lift/cover[(4)]			wet of optimum
Compaction	ASTM D698[(2)]	1	Loose	Loose	98% min.
Compaction	ASTM D1556	1/lift/cover	Loose	Loose	98% min.
Compaction	ASTM D2922	5/lift/cover[(4)]	Loose	Loose	98% min.
Compactor Weight	observation	record actual weight			13,600 kg[(5)]
Compaction Passes	observation	[(3)]	[(3)]		
Lift Thickness	observation	[(3)]			23 cm, max. (loose)
PI	ASTM D4318	1/lift/cover[(4)]			10 to 35%
Hydraulic Conductivity	ASTM D5093	1 test plot per cover, plots 1 & 3		0.01 cm/sec, min.	1 X 10^{-7} cm/sec, max.[(6)]

(1) Must be calibrated using microwave oven technique
(2) Must be calibrated using sand cone
(3) To be determined in the field
(4) If an outlier is found, 2 more tests must be taken
(5) Recommended weight
(6) Test pad constructed adjacent to test cover. Profile replicated barrier layer in test cover

Alternative Test Covers

Design criteria for the alternative cover designs was very basic. The covers were to be (1) less expensive to construct than Baseline Test Cover 2; (2) more effective than the baseline covers at preventing percolation; and (3) easier and more reliable to construct. All soil used in the construction of the alternative test covers came from on-site cut excavations. Other materials to be purchased off-site such as sand and gravel used must be common and readily available (i.e., no exotic grain-size distributions, etc.).

Any and all compaction of soil required by design in the alternative covers was compacted 'dry of optimum' rather than 'wet of optimum' as currently recommended by the EPA with the baseline covers. Dry-side compaction should result in a compacted barrier soil that is less susceptible to desiccation cracking. Dry-side compaction also made construction easier and therefore, less expensive and should provide more soil water storage capability than wet-side storage due to the lower initial degree of saturation.

The determination to compact this soil 'dry of optimum' for all the alternative covers was confirmed by laboratory testing that showed the saturated hydraulic conductivity of the soil is relatively insensitive to the molding water content. The hydraulic conductivity's of three soil test specimens were determined. One of the specimens was compacted 'wet of optimum', one was compacted at the optimum water content, while the third was compacted 'dry of optimum'. The three specimens' hydraulic conductivity varied by less than an order of magnitude in gravimetric water content ranges of $w_{opt-4.1\%} < w < w_{opt+4.5\%}$, thus revealing the relative insensitivity of the hydraulic conductivity to water content.

Alternative Test Cover 1 (Plot 2) is a Geosynthetic Clay Liner (GCL) Cover (Figure 9) identical to the traditional Compacted Clay Cover with the exception that the problematic clay barrier layer was replaced with a manufactured sheet installed in its place known as a GCL. All other aspects of the cover were identical to Baseline Test Cover 2. The overall thickness of this cover as-built was 90 cm. From bottom to top is the barrier layer (the GCL membrane covered with a geomembrane that comprises the composite barrier layer), 30 cm sand drainage layer, geotextile filter fabric, and 60 cm vegetation soil layer, respectively.

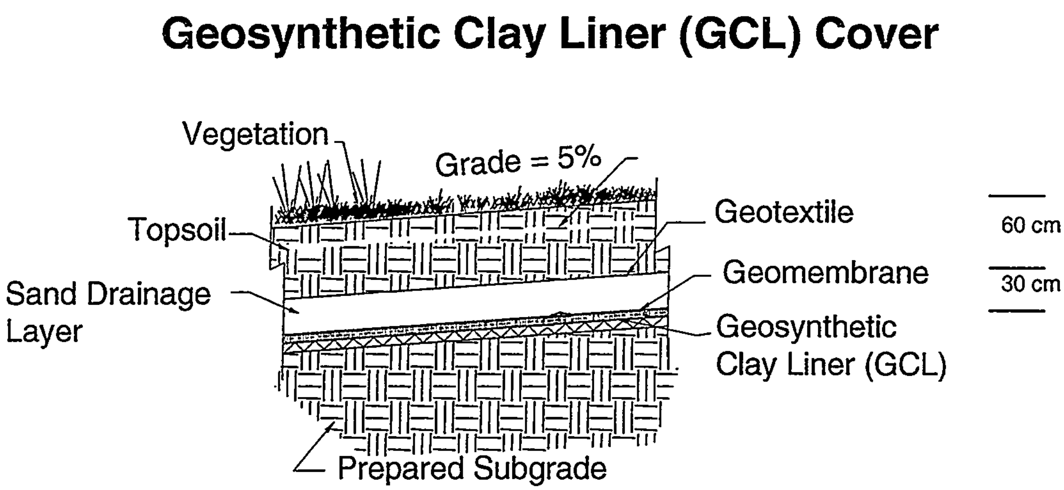


Figure 9. Profile of Alternative Test Cover 1 (GCL Cover)

The objectives of the GCL were to prevent the downward percolation of liquids and to withstand construction traffic as the test covers are installed. The GCL installed is a product manufactured by Claymax. It consists of two nonwoven fabrics sandwiching a thin layer of bentonite. The GCL was relatively easily installed. The rolls of GCL were placed on the cover and rolled out into place (Figure 10). Panels were overlapped a minimum of 15 cm with no physical seaming. The replacement of the clay barrier layer with a GCL reduced the construction time and cost for this cover versus the Compacted Clay Cover by more than 50% (Dwyer 1997). Extra care was required to ensure keeping the GCL dry and protected from moisture particularly during inclement weather. The QA for the installation of the GCL required the panels be continuos and undamaged across the entire plan of the cover and that seams be adequately overlapped. The delivered-saturated hydraulic conductivity of the GCL per the manufacturer (Claymax 1995) was 5 x 10^{-9} cm/sec.

Figure 10. GCL Installation

TABLE 3. Tests/Observations for Material in GCL Cover (Plot 2)

Parameter	Method	Min. Frequency	Limiting Criteria Vegetation Layer	Limiting Criteria Sand Drainage Layer
% of fines (200 sieve)	ASTM D422 or D1140	2/lift/cover	20% minimum	5% maximum
% of gravel (4 sieve)	ASTM D422	2/lift/cover	10% maximum	-
Compaction	observation	continuous	loose, uniform	loose
Max. size clod/stone	observation	continuous	5 cm max.	-
Saturated Hydraulic Conductivity	ASTM D5084	1/cover - supplier's submittal	-	1 X 10^{-2} cm/sec (min.)

Alternative Test Cover 2 (Plot 4) is a Capillary Barrier. This cover system consists of four primary layers from bottom to top: (1) a lower drainage layer; (2) a barrier soil layer; (3) an upper drainage layer; and (4) a surface or topsoil layer (Figure 11). The barrier soil layer and lower drainage layer comprise the capillary barrier. The lower drainage layer is composed of 30 cm of washed concrete sand and was installed in one uncompacted lift. Quality assurance for this cover involved making certain the layer thickness was uniform and was a minimum of 30 cm thick. The material had to fall within the allowable particle size distribution (PSD) shown in Figure 12. This PSD ensured that the hydraulic conductivity and filtration requirements were met. The filtration requirements were necessary to ensure that two different and adjoining soil layers did not mix because there was no geotextile placed between them.

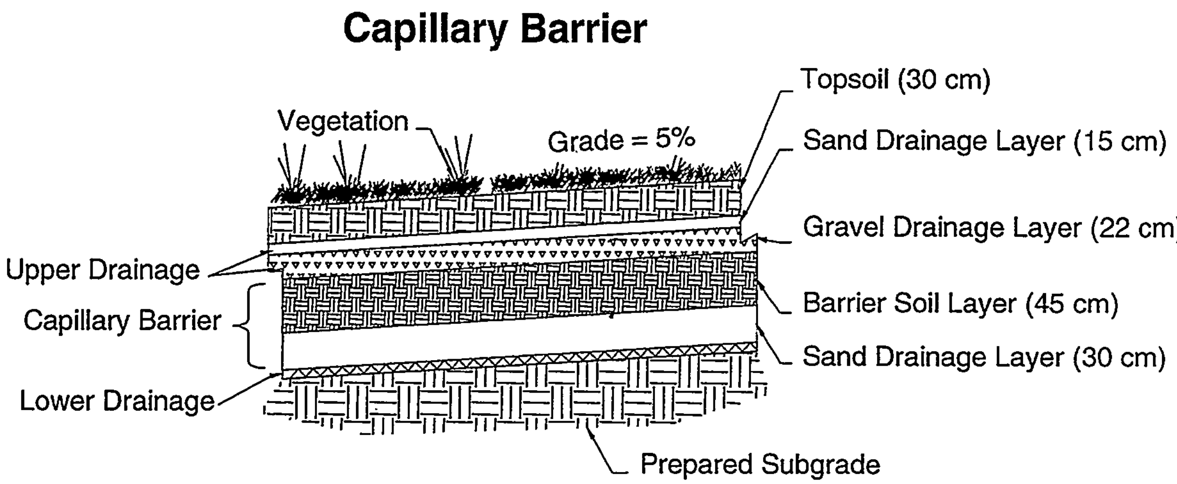


Figure 11. Profile of Alternative Test Cover 2 (Capillary Barrier)

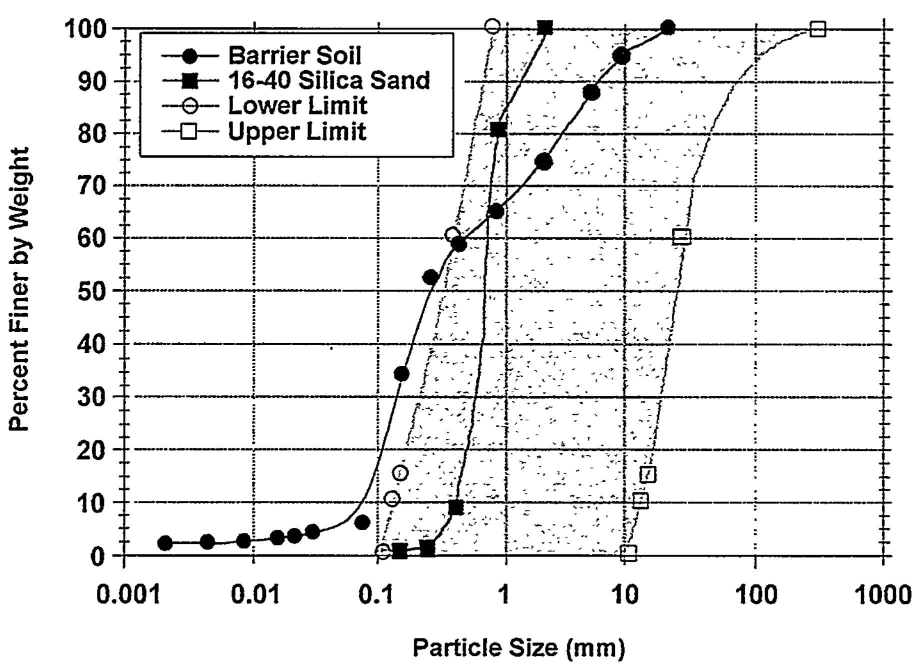


Figure 12. Allowable Particle Size Distribution - Capillary Barrier Lower Drainage Layer

Figure 13. Capillary Barrier Installation

The 45 cm barrier soil layer was installed directly on the sand (Figure 13). The soil was installed in three equal 15 cm thick compacted lifts. Special care was required for installation of the first lift of soil. The key to the capillary barrier, besides the soil types, was providing a smooth, straight interface between the two layer materials. The sand was installed so that the surface was smooth with a consistent slope. The barrier soil was placed onto the sand and pushed into place. When the soil was being worked into place on top of the sand a small steel track bulldozer was used. This helped reduce the point load and spread the weight of the equipment over as much surface area as possible. The bulldozer remained on the upper lift while spreading the material, thus not disturbing the smooth transition between the soil and sand. After the uncompacted lift had been spread into place, a smooth-rolled vibratory compactor was used to compact the lift. This compactor type was chosen rather than kneading compaction so as not to disturb the smooth interface between materials. For the first lift, the contractor was not allowed to turn on the vibrator while compacting. This was because of the uncertainty that the vibration could cause mixing of the two materials. Compaction was performed with the soil 'dry of optimum'. See Figure 14 for the acceptable compaction zone. Compaction was relatively easily achieved.

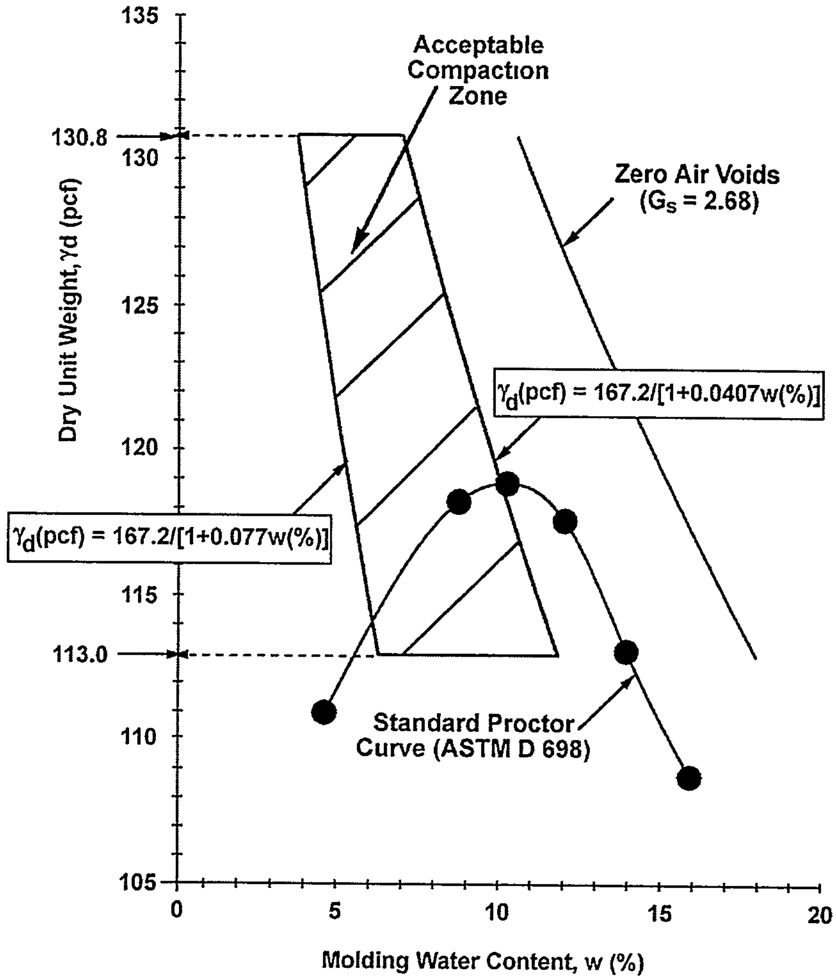


Figure 14. Acceptable Compaction Zone - Capillary Barrier Soil Layer

The upper drainage layers were placed on the barrier soil layer. This upper drainage layer is comprised of two materials consisting of 22 cm of clean pea gravel and 15 cm of washed concrete sand. The pea gravel serving as the drainage layer, was placed in one uncompacted lift directly on the soil barrier layer. Quality assurance verified that the lift was of uniform thickness, a minimum of 22 cm deep, and fell within the allowable PSD shown in Figure 15. The sand was then placed on the gravel. Special care was taken not to mix the sand and gravel. The procedure used earlier on the first lift of the barrier soil layer was utilized. Quality assurance also ensured the sand layer was of uniform depth and fell within the acceptable PSD as shown in Figure 15. By design, the depth was to have been a minimum of 8 cm, but this proved to be impractical. The minimum practical depth to ensure a uniformly thick layer was 15 cm, which is what was placed over the upper drainage layer. This sand layer was placed in one uncompacted lift again using special care not to mix the dissimilar materials. The sand served as a filter medium between the soil in the vegetation layer and the pea gravel in the upper drainage layer. Finally, a 30 cm thick layer of topsoil was placed on the sand. This was installed in one uncompacted lift using special care not to mix the materials thus ensuring a clean interface between the two materials.

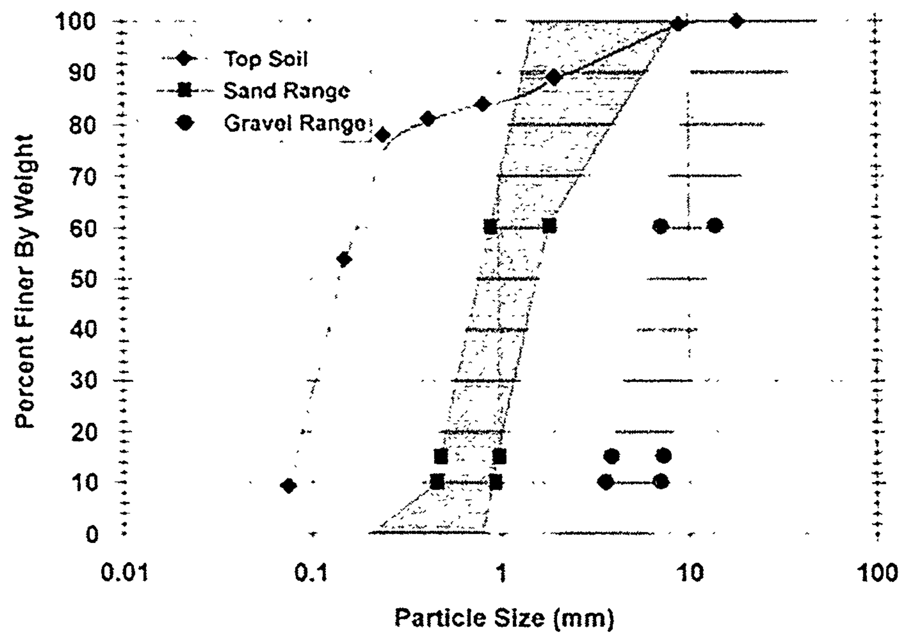


Figure 15. Allowable Particle Size Distribution for Sand/Gravel Layers in Capillary Barrier (Upper Drainage Layers) and Anisotropic Barrier

TABLE 4. Tests/Observations for Material in the Capillary Barrier (Plot 4)

Parameter	Method	Minimum Frequency	Limiting Criteria Vegetation Layer	Limiting Criteria Sand Layer	Limiting Criteria Gravel Layer	Limiting Criteria Barrier Soil
Max. Size Stone/Clod	observation	continuous	5 cm dia.	(1)	(2)	2 cm
Compaction	ASTM D1556	1/lift/cover	loose	loose	loose	95-110%
Compaction	ASTM D2922	5/lift/cover	loose	loose	loose	95-110%
PI	ASTM D4318	1/cover	-	-	-	10-35
Particle Size Distribution	ASTM D422	1/cover	-	(1)	(2)	-
% fines	ASTM D1140	1/cover	20% min.	5% max.	5% max.	20% min.
Moisture Content	ASTM D2216	1/lift/cover	-	-	-	dry of optimum (3)
Moisture Content	ASTM D3017	5/lift/cover	-	-	-	dry of optimum (3)
Lift Thickness	observation	continuous	-	-	-	15 cm compacted
Compactor Weight	observation	record actual weight.	-	-	-	13,600 kg min.
Percent Gravel	ASTM D422	1/cover	10% max.	-	-	10% max.
Hydraulic Conductivity	ASTM D5084	1/cover	-	0.01 cm/sec	0.1 cm/sec	-

(1) see PSD, Figures 12 & 15
(2) see PSD, Figures 12 & 15
(3) see proctor curve, Figure 14

Alternative Test Cover 3 (Plot 5) referred to as the Anisotropic Barrier attempts to limit downward movement of water while encouraging lateral movement of water. This cover is composed of a layering of capillary barriers.

This cover system consists of 4 layers: (1) a top vegetation layer; (2) a cover soil layer; (3) an interface layer; and (4) a sublayer (Figure 16). The vegetation layer is 15 cm thick.

It is comprised of a mixture of local topsoil and pea-gravel. The gravel to soil mixture by weight was 25%. The gravel was added to assist in minimizing surface erosion due to surface runoff. This layer encourages evapotranspiration, allows for vegetation growth, and reduced surface erosion. The cover native soil layer is 60 cm of native soil. Its function is to allow for water storage and eventual evapotranspiration and to serve as a rooting medium. The interface layer is 15 cm of fine sand that serves as a filter between the overlying soil and the underlying gravel. It also serves as a drainage layer to laterally divert water that has percolated through the cover soil. The sublayer is 15 cm of pea-gravel. The soil over sand layers create one capillary barrier while the sand over gravel creates a second capillary break. The interface layer and sublayer combined also serve a dual purpose as bio-barriers to reduce the penetration or intrusion of roots and burrowing animals into the underlying waste.

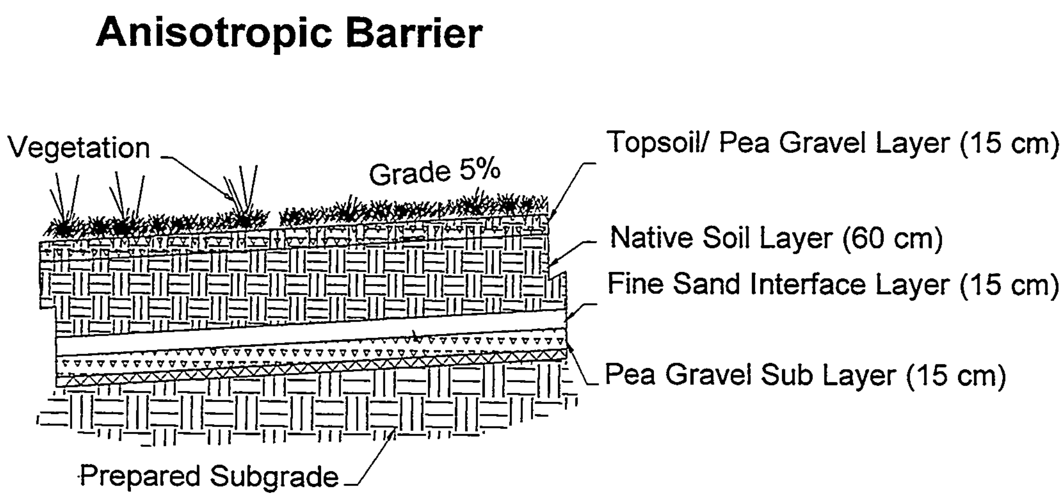


Figure 16. Profile of Alternative Test Cover 3 (Anisotropic Barrier)

The sublayer is composed of clean pea gravel that was installed in one uncompacted lift. Quality assurance ensured its thickness was uniform and met the minimum depth requirement and that the material fell within an acceptable PSD (Figure 15). The fine sand interface layer consisted of washed concrete sand and was installed on top of the pea gravel sublayer. This sand was installed in one uncompacted lift. Special care similar to that utilized on the Capillary Barrier was used to maintain a clean interface between the sand and pea gravel. Quality assurance was used to ensure the interface remained smooth, the layer thickness was adequate and uniform, and the material fell within an acceptable PSD (Figure 15). Immediately on top of the sand interface layer, the cover native soil layer was placed. This layer was installed in two equal lifts. Special care was taken during placement of the first lift to again maintain a clean interface between the sand and soil (Figure 17). The soil by design was to be placed within the acceptable compaction zone shown in Figure 18. Traditional compaction equipment was not used. The density range was achieved through normal construction activities such as placing and spreading the lifts into place. Quality assurance ensured that the equipment uniformly drove over the entire lift. The surface of the second lift was scarified prior to placement of the vegetation layer to eliminate an interface joint.

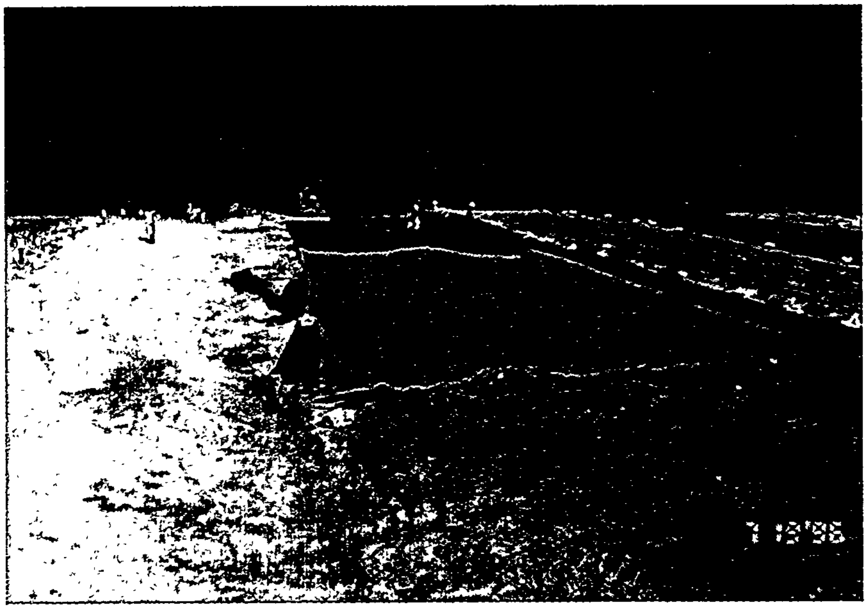
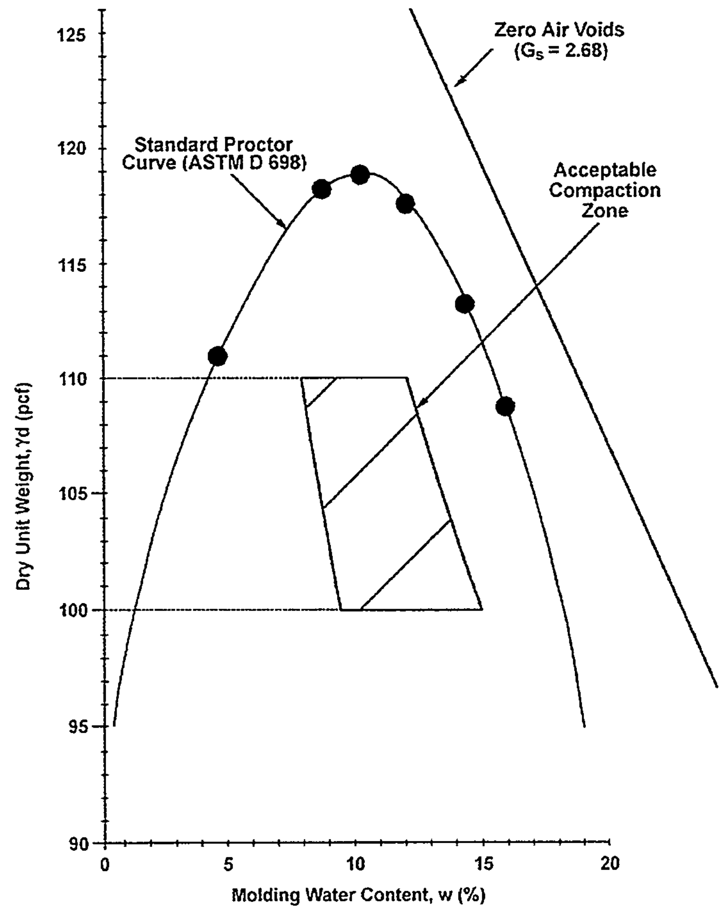


Figure 17. Anisotropic Barrier Installation



Acceptable Compaction Zone - "Dry Side"
Plot 5 - Soil Layer

Figure 18. Acceptable Compaction Zone - Anisotropic Barrier Soil Layer

A volume ratio was calculated based on a mixture of 25% pea gravel to soil by weight. The bucket of a front end loader was used as the measurement device. The correct volume ratios were placed in a line adjacent to each other and mixed with a grader. The grader passed back and forth over the line of soil mixture until a uniform mixture was achieved. The soil/gravel mixture was then placed in one uncompacted lift.

TABLE 5. Tests/Observations for Material in Anisotropic Barrier (Plot 5)

Parameter	Method	Minimum Frequency	Limiting Criteria Vegetation Layer	Limiting Criteria Sand Layer	Limiting Criteria Gravel Layer	Limiting Criteria Compacted Soil Layer
Max. Size Stone/Clod	observation	continuous	5 cm dia.	(1)	(2)	5 cm dia.
Compaction	ASTM D1556	1/lift/cover	loose	loose	loose	85% to 93% of MDD
Compaction	ASTM D2922	5/lift/cover	loose	loose	loose	85% to 93% of MDD
PI	ASTM D4318	1/cover	-	-	-	0-35
Particle Size Distribution	ASTM D422	1/cover	-	(1)	(2)	-
Percent Fines	ASTM D1140	1/cover	20% min.	5% max.	5% max.	20% min.
Moisture Content	ASTM D2216	1/lift/cover	-	-	-	dry of optimum (3)
Moisture Content	ASTM D3017	5/lift/cover	-	-	-	dry of optimum (3)
Lift Thickness	observation	continuous	-	-	-	15 cm compacted
Compactor Weight	observation	record actual weight	-	-	-	13,600 kg, min.
Percent gravel	ASTM D422	1/cover	-	-	-	10% max.
Percent gravel	observation	continuous	25% by weight	-	-	-
Hydraulic Conductivity	ASTM D5084	1/cover	-	0.01 cm/sec	0.1 cm/sec	-

(1) see PSD, Figure 15
(2) see PSD, Figure 15
(3) see proctor curve, Figure 18

Alternative Test Cover 4 (Plot 6) is referred to as an Evapotranspiration (ET) Cover (Figure 19). The ET Cover consists of a single, vegetated soil layer constructed to represent an optimum mix of soil texture, soil thickness, and vegetation cover.

The installed test cover is a 105 cm thick monolithic soil cover. The bottom 90 cm of native soil was compacted while the top 15 cm of topsoil was loosely placed. The soil allows for water storage, which combined with the vegetation, will increase evapotranspiration.

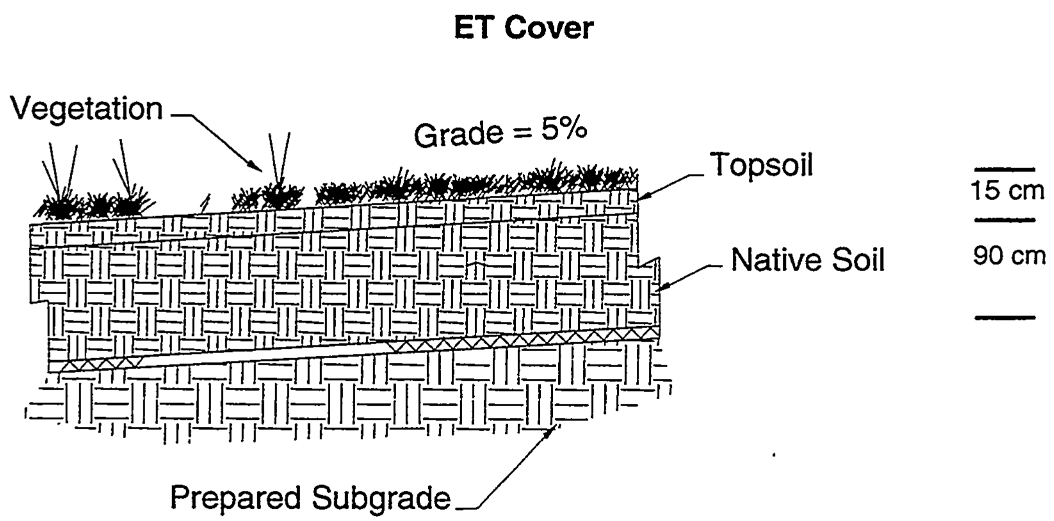


Figure 19. Profile of Alternative Cover 4 (ET Cover)

The native soil layer was placed in six equal lifts. The soil was installed similar to that for the barrier layer in Baseline Test Cover 1. The exception being that the soil was compacted 'dry of optimum' (Figure 14). The topsoil layer was taken from the topsoil stockpile and placed in one uncompacted lift. A thin gravel veneer was placed on the surface after the cover was seeded. The gravel veneer was simply pushed into place at a minimum depth (2 to 4 cm) to ensure complete coverage of the topsoil. The gravel veneer was placed to assist with vegetation establishment and minimizing erosion.

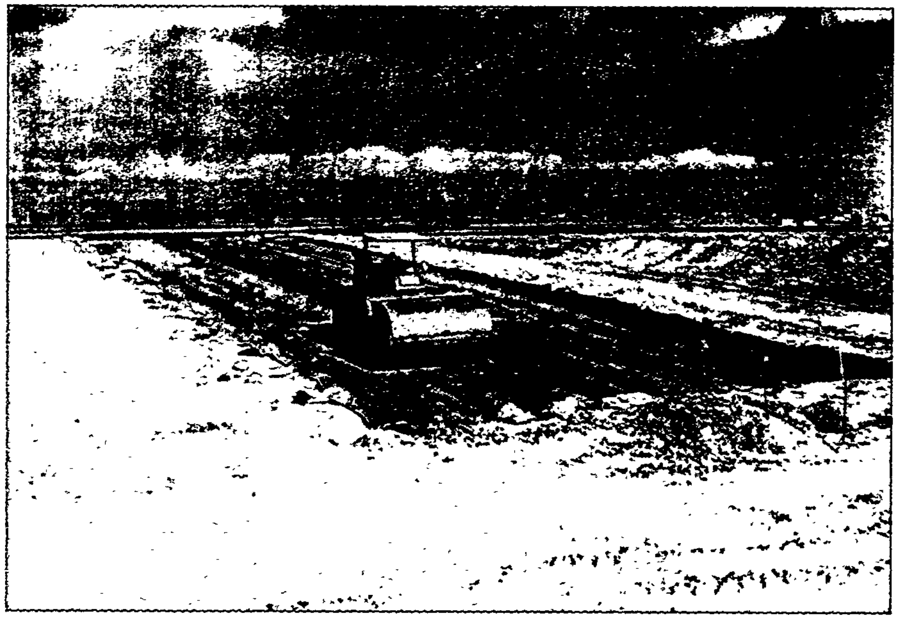


Figure 20. Compacting Soil in ET Cover

TABLE 6. Tests/Observations for Material in ET Cover (Plot 6)

Parameter	Method	Min. Frequency	Limiting Criteria Topsoil	Limiting Criteria Compacted Soil
Percent Fines (200 sieve)	ASTM D422 or D1140	2/lift/cover	20% min.	20% min.
Percent Gravel (4 sieve)	ASTM D422	2/lift/cover	10% max.	10% max.
Max. Size Clod/Stone	observation	continuous	5 cm dia. max.	5 cm dia. max.
Surface Gravel Veneer	observation	continuos	5 cm dia.; 2 to 4 cm depth	-
Water Content	ASTM D2216	1/lift cover	-	dry of optimum(1)
Water Content	ASTM D3017	5/lift/cover(4)	-	dry of optimum(1)
Compaction	ASTM D698	1	-	95% to 110% of MDD (1)
Compaction	ASTM D1556	1/lift/cover	-	95% to 110% of MDD (1)
Compaction	ASTM D2922	5/lift/cover(4)	-	95% to 110% of MDD (1)
Compactor Weight	observation	record actual weight	-	13,600 kg min.(2)
Lift Thickness	observation	(3)	-	15 cm max. (compacted)
PI	ASTM D4318	1/lift/cover	-	0 to 35%

(1) Must be within acceptable range within standard proctor curve (Figure 14)
(2) Recommended min. weight. To coincide with use of standard proctor curve
(3) To be determined in the field
(4) If an outlier was found, 2 additional tests were taken

Table 7. Allowable Outliers for Material Tests

Parameter	Maximum Overall Allowable Percent of Outliers (if applicable)
Percent Fines	5, no more than 1 per lift
Percent Gravel	5, no more than 1 per lift
Max. Size Clod	10, reduce as much as practical
Bentonite Content	5
Water Content	5
Compaction	5
Lift Thickness	5
PI	5, no more than 1 per lift

After the covers were constructed, they were drill seeded. A botanist with expertise in arid revegetation from the U.S. Forest Service provided an optimal seed mix for the site (Table 8). The mix was chosen based on an acceptable native vegetation that would provide an adequate coverage in both warm and cool growing seasons.

Table 8. Seed Mix for Test Covers

Mixture(2)	Desired Establishment(1) (% of total vegetation)	Quantity in (lbs./acre)
Warm Season Grasses:		
Bouteloua gracillis (Blue Grama)	20	1.0
Hilaria jamesii (Galleta)	10	3.0
Sporabolis cyptandrus (Sand Dropseed)	50	0.5
Cool Season Grasses:		
Oryzopsis hymenoides (Indian Ricegrass)	10	3.0
Stipa comata (Needle & Thread)	10	4.0

(1) Approximate percentage of total species present in number of plants per given area.

(2) Note that differences in weight among the various species can result in large differences in the mass ratio (lbs./acre) of seed required in the seed mixture.

Construction Quality Assurance

One of the most important factors that determines the quality of a constructed product is the key personnel involved in this process. There were minimum personnel qualifications standards set that were strictly enforced for key individuals throughout the construction of the test covers. The key individuals involved in Materials Quality Assurance

(MQA)/Construction Quality Assurance (CQA) during the construction of the test covers and their minimum recommended qualifications are listed below in Table 9.

Table 9. Minimum Personnel Qualifications (EPA, 1994)

Individual	Minimum Qualifications
Design Engineer	Registered professional engineer. Prior landfill cover design experience required.
SNL Designated Representative	The specific individual designated by SNL with knowledge of the project, its plans, specifications, and Quality Control (QC)/Quality Assurance (QA) documents.
Manufacturer/Fabricator	Experience in manufacturing, or fabricating, at least 1,000,000 ft^2 of similar geosynthetic materials.
MQC Personnel	Manufacturer, or fabricator trained personnel in charge of quality control of the geosynthetic materials to be used in the specific waste containment facility.
MQC Officer	The individual specifically designated by a manufacturer or fabricator in charge of geosynthetic material quality control.
Geosynthetic Installer's Representative	Experience installing at least 100,000 ft^2 of similar geosynthetic materials. Must have an on-site foremen that is NICET trained.
CQC Personnel	Employed by the general contractor, installation contractor, or earthwork contractor involved in waste containment facilities; appropriately trained.
CQA Personnel	Appropriately trained for applicable QA testing.
MQA/CQA Engineer	Registered professional engineer employed separately from the contractor.
MQA/CQA Certifying Engineer	Registered professional engineer with the State of New Mexico.

A complete MQA/CQA plan that included a detailed description of all MQA/CQA activities used during materials inspection and construction to manage the installed quality of the facility was prepared prior to the start of construction activities. This MQA/CQA plan was tailored to this specific project and integrated into the project plans and specifications.

A copy of the site-specific plans and specifications, MQA/CQA plan, and the MQA/CQA engineer retained MQA/CQA documentation reports at the facility. The plans, specifications, and MQA/CQA documents were the chief means for the facility owner/operator to demonstrate to the interested stakeholder(s) that MQA/CQA objectives for this project were met. Because of the fact that there is widespread interest by regulators throughout the country in the results of this project, this was of particular importance.

Routine daily reporting and documentation procedures were required. The MQA/CQA engineer prepared daily written inspection reports that were included in the final MQA/CQA document. The daily reports included information about work that was accomplished, tests and observations that were made, and descriptions of the adequacy of the work that was performed.

The MQA/CQA engineer prepared a daily written summary report. This report provided a chronological framework for identifying and recording all other reports and aids in tracking what was done and by whom. At a minimum, the daily summary reports contained the following:

- Date, project name (ALCD), location, waste containment unit under construction, personnel involved in major activities, and other relevant identification information
- Description of weather conditions, including temperature, cloud cover, and precipitation
- Summaries of any meetings held and actions recommended or taken
- Specific work units and locations of construction under way during that particular day
- Equipment and personnel being utilized in each work task, including subcontractors
- Identification of areas or units of work being inspected
- Unique identifying sheet number of geomembranes for cross-referencing and document control
- Description of off-site materials received, including any quality control data provided by the supplier
- Calibrations or recalibrations of test equipment, including actions taken as a result of recalibration
- Decisions made regarding approval of units of material or of work and/or corrective actions to be taken in instances of substandard or suspect quality
- Unique identifying sheet numbers of inspection data sheets and/or problem reporting and corrective measures used to substantiate any MQA/CQA decisions described in the previous item
- Signature of the MQA/CQA engineer

All observations, results of field tests, and results of laboratory tests performed on- or off-site were recorded on a data sheet. Recorded observations took the form of notes, charts, sketches, photographs, or a combination of these. At a minimum, the inspection data sheets included the following information:

- Description or title of the inspection activity
- Location of the inspection activity or location from which the sample was obtained
- Type of inspection activity and procedure used (reference to standard method when appropriate or specific method described in MQA/CQA plan)
- Unique identifying geomembrane sheet number for cross-referencing and document control
- Recorded observation or test data
- Results of the inspection activity (e.g., pass/fail); comparison with specification requirements
- Personnel involved in the inspection including the individual preparing the data sheet
- Signature of the MQA/CQA inspector and review signature by the MQA/CQA engineer

When a problem was defined as material or workmanship that did not meet the requirements of the plans, specifications, or MQA/CQA plan for a project or any obvious defect in material or workmanship, - a problem identification and corrective measures report was prepared. At a minimum, these problem identification and corrective measure reports contained the following information:

- Location of the problem
- Description of the problem in sufficient detail and with supporting sketches or photographic information where appropriate to adequately describe the problem
- Unique identifying geomembrane sheet number for cross-referencing and document control
- Probable cause
- How and when the problem was located (referenced to inspection data sheet or daily summary report by inspector)
- Where relevant, estimation of how long the problem existed
- Any disagreement noted by the inspector between the inspector and contractor about whether or not a problem exists or the cause of the problem
- Suggested corrective measure(s)

- Documentation of correction if corrective action was taken and completed prior to finalization of the problem and corrective measures report (referenced to inspection data sheet, where applicable)
- Where applicable, suggested methods to prevent similar problems
- Signature of the MQA/CQA inspector and review signature of MQA/CQA engineer

Drawings of record, or "as-built" drawings, were prepared to document the actual lines, grades and conditions of each component of the demonstration. For soil components, the record drawings included survey data that show bottom and top elevations of a particular component, the plan dimensions of the component, and locations of all destructive test samples. For geosynthetic components, the "as-built" drawings show the dimensions of all geomembrane field panels, the location of each panel, identification of all seams and panels with appropriate identification numbering or lettering, location of all patches and repairs, and location of all destructive test samples. Separate drawings show record cross sections and special features.

At the completion of the project, the MQA/CQA engineer prepared a final report. This report includes all daily inspection reports, daily MQA/CQA engineer's summary reports, inspection data sheets, problem identification and corrective measures reports, and other documentation such as quality control data provided by manufacturers or fabricators. In addition the final report includes laboratory test results, photographs, as-built drawings, internal MQA/CQA memoranda or reports with data interpretation or analyses, and design changes made by the design engineer during construction. The document was certified to be correct by the MQA/CQA certifying engineer. The final documentation emphasized that areas of responsibility and lines of authority were clearly defined, understood, and accepted by all parties involved in the project.

The MQA/CQA documents were maintained under a document control procedure. Any modifications to the documents were reported to and agreed upon by all parties involved. An indexing procedure was developed for convenient replacement of pages in the MQA/CQA plan when modifications became necessary, with revision status indicated on appropriate pages.

During construction, the MQA/CQA engineer was responsible for all MQA/CQA documents including copies of the design criteria, plans, specifications, and MQA/CQA plan, and originals of all data sheets and reports. Duplicate records were kept at a separate location to avoid loss of information if the originals were destroyed.

Designated meetings included a pre-bid meeting held prior to bidding of the contract. Also, a pre-construction meeting was held in conjunction with a resolution meeting after the contract had been awarded but prior to the start of construction activities.

The pre-bid meeting was used to discuss the MQA/CQA plan and to resolve differences of opinion before the project was let for bidding. This meeting was held before construction bids were prepared so that the companies bidding on the construction could better understand the level of MQA/CQA to be employed on the project. Also, if the bidders identified problems with the MQA/CQA plan, SNL had the opportunity to rectify those problems early in the process.

The objectives of the resolution meeting were to establish lines of communication, review construction plans and specifications, emphasize the critical aspects of a project necessary to ensure proper quality, begin planning and coordination of tasks, and anticipate any problems that might cause difficulties or delays in construction. The meeting was attended by the design engineer, representatives of the general contractor and/or major subcontractors, the MQA/CQA engineer, and the MQA/CQA certifying engineer. The resolution meeting covered the following activities:

- An individual was assigned to take minutes (a representative of SNL)
- Individuals were introduced to one another and their responsibilities (or potential responsibilities) were identified
- Copies of the project plans and specifications were made available for discussion
- The MQA/CQA plan was distributed
- Copies of any special permit restrictions that are relevant to construction or MQA/CQA were distributed
- The plans and specifications were described. Unique design features were discussed (so the contractors will understand the rationale behind the general design), potential construction problems were identified and discussed, and questions from any of the parties concerning the construction were discussed
- The MQA/CQA plan was reviewed and discussed, with the MQA/CQA engineer and MQA/CQA certifying engineer identifying their expectations and identifying the most critical components
- Procedures for MQC/CQC proposed by installers and contractors were reviewed and discussed
- Corrective actions to resolve potential construction problems were discussed
- Procedures for documentation and distribution of documents were discussed
- Each organization's responsibility, authority, and lines of communication were discussed
- Suggested modifications to the MQA/CQA plan that would improve quality management on the project were solicited
- Construction variables (e.g., precipitation, wind, temperature) and schedule were discussed

It was of particular importance that all parties knew the procedures for inspection and testing during the construction phase. The criteria for pass/fail decisions were clearly defined including resolution of test data outliers and key problems that the MQA/CQA personnel identified were clearly noted. Each individual's responsibilities and authority were understood and procedures regarding resolution of problems were defined and followed.

The pre-construction meeting was held in conjunction with the resolution meeting, which was scheduled after the general construction contracts had been awarded and the major subcontractors and material suppliers were established. The purpose of this meeting was to review the details of the MQA/CQA plan, make sure that the responsibility and authority of each individual was clearly understood, agree on procedures to resolve construction problems, and to establish a foundation of cooperation in quality management. The pre-construction meeting was attended by the design engineer, representatives of the general contractor and major subcontractors, the MQA/CQA engineer, and the MQA/CQA certifying engineer. The pre-construction meeting included the following activities:

- Assign an individual (SNL representative) to take minutes
- Introduce parties and identify their responsibility and authority
- Distribute the MQA/CQA plan, identify any revisions made after the resolution meeting, and answer any questions about the MQA/CQA plan, procedures, or documentation
- Discuss responsibilities and lines of communication
- Discuss reporting procedures, distribution of documents, the schedule for any regular meetings, and resolution of construction problems
- Review site requirements and logistics, including safety procedures
- Review the design, discuss the most critical aspects of the construction, and discuss scheduling and sequencing issues
- Discuss MQC procedures that the geosynthetics manufacturer(s) will employ
- Discuss CQC procedures that the installer or contractor will employ, for example, establish and agree on geomembrane repair procedures
- Make a list of action items that require resolution and assign responsibilities for these items

Weekly progress meetings were held at the job site. At times these were held more often at the discretion of the CQA engineer. These meetings were helpful in maintaining lines of communication, resolving problems, identifying action items, and improving overall quality management. Persons who attended these meetings were those involved in the specific issues being discussed. At all times, the MQA/CQA engineer or his/her designated representative was present.

All samples were identified in the manner described in the MQA/CQA plan. Whenever a sample was taken, a chain of custody record was made for that sample. If the sample was transferred to another individual or laboratory, records were kept of the transfer so that chain of custody could be traced. The purpose of keeping a record of sample custody was to assist in tracing the cause of anomalous test results or other testing problems, and to help prevent accidental loss of test samples. Soil samples were discarded after testing. Destructive testing samples of geosynthetic materials were taken in triplicate, with one sample tested by CQC personnel, one tested by CQA personnel, and the third retained in storage as prescribed in the CQA plan.

Weather played a critical role in the construction of the ALCD. Installation of all geosynthetic materials (including geosynthetic clay liners) and natural clay liners were particularly sensitive to weather conditions, including temperature, wind, humidity, and precipitation. The contractor or installer was responsible for complying with the contract plans and specifications (along with the MQC/CQC plans for the various components of the system). Included in the project specifications were restrictions covering the weather conditions under which certain activities can take place. It was the responsibility of the contractor or installer to make sure that these weather restrictions were observed during construction.

Unexpected work stoppages resulted from a variety of causes (e.g., testing by other Sandia groups on adjacent sites that required a half mile radius clearance, which encompassed the ALCD site). The MQA/CQA engineer was careful during such stoppages to determine (1) whether in-place materials were covered and protected from damage (e.g., lifting of a geomembrane by wind or premature hydration of geosynthetic clay liners); (2) whether partially covered materials were protected from damage (e.g., desiccation of compacted clay liners); and (3) whether manufactured materials were properly stored and properly or adequately protected (e.g., whether geotextiles were protected from ultraviolet exposure). The cessation of construction did not mean the cessation of MQA/CQA inspection and documentation.

Summary

The more materials and layers in a cover design leads to a more difficult construction project and consequently a more expensive one. A landfill closure design must consider the construction activities involved during installation. The final constructed product determines the quality of the closure. Landfill closures are generally firm-fixed price competitively bid projects. That means incentives exist to cut corners to maximize profits. Delicate or complex designs can be very challenging to construct where as simple designs are predictably the most reliable. Too much QA can slow a project and drive it beyond its allotted budget. A delicate balance must be reached between too much QA and not enough. Simple designs will minimize the QA required provided there is less complexity to ensure the design intent is met. Experience has shown inadequate, poor, or lack of QA on landfill closures leads to future problems that could have been avoided with proper planning and oversight.

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