CLOSURE OF A MIXED WASTE LANDFILL - LESSONS LEARNED

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ABSTRACT

Much experience has been gained during the closure of the Mixed Waste Management Facility (MWMF) at the Savannah River Site (SRS) and many lessons were learned. This knowledge was applied to other closures at SRS yielding decreased costs, schedule enhancement, and increased overall project efficiency. The next major area of experience to be gained at SRS in the field of waste site closures will be in the upkeep, maintenance, and monitoring of clay caps. Further test programs will be required to address these requirements.

INTRODUCTION

The Mixed-Waste Management Facility at the Savannah River Site is a 285,000-square-meter landfill that is being closed in accordance with South Carolina hazardous-waste management regulations. To provide technical support for the closure, four test programs were conducted to determine appropriate methods for stabilizing the waste and installing a landfill closure cap. Based upon these test programs, construction specifications were prepared for dynamic compaction of the waste trenches and installation of a 0.9-meter-thick kaolin clay cap. During actual dynamic compaction and installation of the kaolin cap, many lessons were learned about methods of conducting test programs, preparing construction specifications, implementing the specifications, and further research needs.

SITE DESCRIPTION AND OPERATION (1,2,3)

MWMF 643-28G is a portion of the Department of Energy (DOE) SRS 480,000-square-meter Low-Level Radioactive Waste Disposal Facility (LLRWDF) 643-7G located near Aiken, South Carolina. The LLRWDF is centrally located on the SRS, approximately ten kilometers from the nearest plant boundary. It is used for the disposal and storage of all radioactively contaminated solid waste produced at SRS.

Receipt of waste at the LLRWDF began in 1969 as use of the adjacent LLRWDF 643-G was being phased out. The waste was identified according to type, level of radioactive contamination, volume, waste form description, point of generation, date of disposal, and disposal location. The waste identification was primarily focused on the radioactive contamination and not the actual materials that were contaminated, and it was segregated for disposal by SRS as follows.

- Waste radiating less than 300 mrem/hr at 76 mm when unshielded was designated as low-level waste and was further segregated into alpha- and beta/gamma-contaminated waste.
- Waste radiating greater than 300 mrem/hr at 76 mm when unshielded; bulky, unpackaged waste; and packaged offsite wastes were designated as intermediate low-level waste.

The Disposal trenches were typically six meters wide and six meters deep and up to 460 meters long. Normally, three meters of undisturbed soil material was left between adjacent parallel trenches. The waste was received packaged in cardboard boxes, 55-gallon drums, and, beginning in 1983, in B-25 boxes (1.2 m x 1.2 m x 1.8 m metal boxes). Waste such as tanks, vessels, soil, and construction debris was received in bulk and was either dumped into the trench from the edge or placed in the trench with a crane if its bulk required such placement. A daily soil cover was placed over the waste, but no appreciable compaction was attempted. After each trench was filled, a minimum four-foot cover of clean soil was placed over the waste, which achieved surface radiation rates of less than five mrem/hr.

In 1984, the first Engineered Low-Level Trench (ELLT-1) was constructed for SRS low-level waste contained in B-25 boxes. ELLT-1 is 41 meters wide by 152 meters long and averages 6.7 meters in depth. It has a ramp at one end for transport of the boxed waste into the trench. Typically, the waste was not compacted within the boxes, which are assumed to contain 40 percent void space on the average. The 9,600 B-25 boxes were tightly packed and stacked four high with a forklift within ELLT-1. A daily soil cover was not provided because the waste was boxed; however, a final cover of clean soil, averaging six feet deep, was placed over the boxes in ELLT-1 to achieve surface radiation rates of less than five mrem/hr.

REGULATORY BASIS AND HISTORY (1)

Tritiated waste oil and scintillation solutions were disposed of at the LLRWDF until 1982, when it was recognized that, if this material was not radioactively contaminated, it would be classified and regulated as hazardous waste under state regulations. Such disposal ceased and the waste was stored by the generators on an interim basis. In 1984, DOE determined that mixed waste (containing both hazardous and radioactive components) may be subject to South Carolina Hazardous Waste Management Regulations.

A closure plan was prepared for that portion of the LLRWDF that was known , or had the potential, to have received waste oil and scintillation solutions. This portion of the LLRWDF was designated in the closure plan as Mixed-Waste Management Facility (MWMF) 643-28G.

The closure plan was filed with the state on November 23, 1985.

On March 10, 1986, lead used primarily for shielding purposes was determined to be a hazardous waste based upon Environmental Protection Department (EPD) toxicity test results from an independent laboratory. The LLRWDF was shut down; and, prior to resuming operation, procedures were implemented to certify that waste received by the LLRWDF did not contain mixed waste . Because no accurate record of mixed-waste disposal locations existed, the boundaries of the MWMF were revised to include all waste received by the 643-7G LLRWDF up until March 10, 1986.

On July 19, 1986, an updated closure plan was submitted to the state. Two revisions to the plan were required to accommodate state comments. The plan was approved by the state on December 14, 1987. It required a 0.9-meter-thick compacted clay cap over the MWMF covered with a 0.6-meter-thick, combined drainage/vegetative soil layer. Also, as the basis of the design specifications and construction methods, dynamic compaction, static surcharge, and clay cap tests were required. These tests were included in the state-approved, three-year construction schedule, which started on December 14, 1987.

TEST PROGRAMS AND INITIAL CONSTRUCTION SPECIFICATIONS

Dynamic Compaction Test Program (4)

This program was conducted in 1988 in order to evaluate the effectiveness and safety of dynamic compaction as a means of waste consolidation and to determine appropriate construction specifications. An existing SRS crane (Linkbelt LS4188); a 5.4-megagram, 1.8-meter-diameter cylindrical concrete weight; an 11.8-megagram, 1.8-meter-diameter cylindrical concrete weight; and an 18.1-megagram, 2.4-meter-diameter cylindrical concrete weight were used to perform single-point-drop and full-trench-width compaction tests on the following trenches.

- With ages ranging from 1973 to 1984
- With and without randomly dumped B-25 boxes (Only one B-25-box trench was tested.)
- With low-level beta-gamma, low-level alpha, and intermediate low-level waste (Only one low-level alpha and one intermediate trench was tested.)
- With soil overburdens ranging from 1.2- to 2.4-meters (1.8-meter overburdens predominated.)
- With compaction using 5.4-, 11.8-, and 18.1-megagram weights (A 5.4-megagram weight was used on only one single-point-drop test.)
- With drop heights of 3, 9, and 12.8 meters (12.8 meters was the maximum height the Linkbelt crane could lift the weight.)
- With 25 to 75 drops per drop location

The tests were performed in a graded fashion with extensive Health Protection Department coverage. Lesser weights were used from lower drop heights prior to proceeding to greater weights and drop heights. Low-level-waste trenches were tested prior to testing the intermediate-level-waste trenches. No radioactive release was detected throughout the test program.

During the test program, craters from 0.6 to 4.3 meters in depth were created, which resulted in a waste-volume reduction of 11 to 18 percent. Additional indicators of dynamic compaction effectiveness were developed by cone-penetration tests on undisturbed natural soil, undisturbed waste, compacted waste, and compacted crater backfill. The cone-penetration tests consisted of driving a 51-millimeter cone and 44-millimeter rod with a 63.5-kilogram weight dropped from a height of 0.76 meters. Tests on undisturbed natural soil produced blow counts of 20 to 50 per 0.15-meters driven. The count on undisturbed waste typically ranged from 4 to 15 blows per 0.15-meter. Compacted waste required from 4 to 30 blows per 0.15 meter, which indicated a 50-to-100-percent increase in resistance. Compacted backfill results were equivalent to those of undisturbed natural soils.

Based upon the data produced during the test program, the following conclusions were drawn.

- Dynamic compaction of the MWMF can be performed safely in both the low-level- and intermediate-level-waste trenches.
- The 18.1-megagram weight is more effective than the 5.4- or 11.8-megagram weight with the same total applied energy.
- The 12.8-meter drop height is more effective than either the 9- or 3-meter height.
- A secondary treatment pattern (alternating primary and secondary drop locations on a 3-by-3-meter grid) is adequate, and the tertiary treatment pattern is not required.
- Compaction effectiveness per unit energy applied (drop) decreases rapidly for the 18.1- megagram weight dropped from 12.8 meters when total applied drops exceeds 18 to 24.
- Trench age (11-year span) apparently makes no difference in compaction results.
- The presence of randomly dumped B-25 boxes apparently makes no difference in compaction results

Based upon these test conclusions, the following criteria were adopted for dynamic compaction of the MWMF trenches.

- A 2.4-meter diameter, 18.1-megagram weight should be dropped from 12.8 meters on each location a total of 20 times or until a maximum 1.8-meter crater is produced. (Twenty drops should produce craters between 0.9 and 1.5 meter deep.)
- A 0.6-meter soil blanket should be placed over the treatment area in addition to the existing 1.2-meter backfill over the waste for a total of 1.8 meter of cover.
- A secondary treatment pattern consisting of alternating primary and secondary drop locations on a 3-by-3-meter grid should be used.
- Each crater should be backfilled in maximum 1.2-meter lifts using five drops of the 18.1-megagram weight from 12.8 meters.

Static Surcharge Test Program (5)

This test was performed because of safety concerns associated with the proposed dynamic compaction of Engineered Low-Level Trench No.1 (ELLT-1). The estimated 40-percent-void space in the B-25 boxes contained in ELLT-1 raised the possibility that dynamic compaction would cause penetration into the boxes, thus exposing the waste and resulting in an airborne release. Therefore, a static surcharge test program was conducted on ELLT-1 to evaluate the effectiveness of soil surcharge to consolidate the stacked B-25 boxes.

ELLT-1 ranges from 6.1 to 7.3 meters deep. It was constructed in 1985, filled with B-25 boxes stacked four high over a period of 18 months, and covered with a fill that was 1.2 meter deep at the north end and gradually increased to 2.4 meters at the south end. The static surcharge test was conducted as follows.

1. Fifteen subsidence monitors were placed over the trench surface in rows of three.
2. Beginning on July 25, 1988, a 5.6-meter static soil surcharge (42,000 cubic meters) was placed over the entire trench.
3. Beginning on November 29, 1988, extra soil was added to bring the surcharge height to 7.6 meters.
4. Elevations of each subsidence monitor were taken weekly from July 29, 1988, to July 20, 1989.
5. Cone penetration tests in selected areas adjacent to subsidence monitors were performed to provide an indication of the condition and location of the B-25 boxes.

The following observations were made during the static surcharge test program.

- The initial 5.6-meter surcharge produced an average 0.73-meter subsidence over the entire trench. One area of higher subsidence that was created by an aisle space between rows of stacked boxes was discounted.
- All subsidence occurred between July 29 and September 23, 1988, after which, the trench remained stable.
- Addition of the extra surcharge height resulted in an average increased subsidence of 0.21 meter, which produced a final average subsidence of 0.94 meter. The bulk of this additional subsidence occurred between November 29 and December 30, 1988. The trench did not completely stabilize until June 1989.
- Rod penetration tests indicated that the bulk of the consolidation occurred within the original trench backfill rather than within the B-25 boxes.

Based upon the test observations and the level of induced subsidence possible through dynamic compaction, it was concluded that a static soil surcharge does not adequately consolidate stacked B-25 boxes. It was not determined during this program if static surcharge is an appropriate stabilization method for other types of disposal trenches.

Clay Cap Test Program (6,7,8)

Testing of the clay cap was conducted from September 1987 to April 1988 to determine if locally-available (within 24 to 40 kilometers of SRS), noncommercial grades of kaolin clays could be used to produce a cap with an in-situ permeability of one nanometer per second or less. In addition, it was necessary to establish the specifications required to construct such a cap and the QA/QV tests and inspections necessary to ensure the low permeability of the cap. The test program was conducted as follows.

1. One cretaceous and three tertiary mines were identified with sufficient quantities of potentially suitable, noncommercial-grade kaolin clay for closure of the MWMF.
2. Initial laboratory permeability tests were conducted on samples taken from each mine to determine if further testing was warranted. All clay tested demonstrated laboratory permeabilities of less than one nanometer per second.
3. Pre-placement testing was performed and included six sets of standard proctors, Atterberg limits, and percent fines from samples taken from each mine.
4. Approximately 2,270 megagrams (100 truckloads) of kaolin were brought from each mine and stockpiled separately at SRS. Samples taken from every other truckload were tested for natural water content.
5. Eight test caps were constructed, two from each clay source. Construction proceeded as follows.

a. Kaolin was placed in a conditioning area and reduced in size to less than 38 millimeters using either a stationary Gleason shredder or a BROS LSPRM-8A traveling pavement recycler. Use of the shredder soon ceased because of dust problems.

b. The kaolin was moisture conditioned by alternating passes of a water truck and recycler and then was covered with plastic and allowed to hydrate overnight.

c. Water content tests were performed on the conditioned clay, which yielded an average water content that ranged from minus one to plus four of the optimum moisture content.

d. The kaolin was moved to the placement area, which had a sand pad below the clay to ensure adequate drainage of the clay. A self-loading scraper was used to move the clay to the area where it was spread to the proper lift thickness with a motor grader.

e. Each lift was compacted with a CAT 815B tamping foot compactor. Four lifts, totaling 0.6 meter for each test cap, were placed. Testing was not conducted during actual construction.

6. To demonstrate that a cap could be adequately constructed in less time, an additional test cap was constructed without use of a separate conditioning area. The clay was moisture conditioned in the placement area and compacted immediately after conditioning without overnight hydration. Otherwise, the cap was constructed similar to the other caps.

7. After construction, the nine caps were tested for density, moisture content, laboratory permeability, and in-situ permeability. In-situ permeability was measured with a Trautwen-type Sealed Double-Ring Infiltrometer (SDRI) and with tensiometers installed at 0.15, 0.30, and 0.45 meter below the top of the clay. The in-situ SDRI tests took from 98 to 158 days to conduct.

The primary post-construction test data is summarized in Table I. Based upon this data, it was concluded that tertiary kaolin can be utilized to produce a clay cap with an in-situ permeability of one nanometer per second or less, and that water content at compaction was the most important soil property to ensure permeability. The following recommendations were incorporated into the construction specifications.

- Use tertiary kaolin with fine content (passing #200 sieve) of at least 90 percent and conforming to an Atterberg limit envelope defined by a liquid limit between 55 and 75 percent and a plasticity index between 26 and 44 percent.
- Prior to moisture conditioning, the kaolin shall be broken up to a maximum 38 millimeter clod size using a recycler or soil stabilizer.
- The kaolin shall be moisture conditioned with a recycler to between two- and four-percent-wet of standard proctor optimum water content in either the placement area or in a separate conditioning area.
- The conditioned clay shall be compacted with a CAT 815B compactor to 95 percent of standard proctor maximum dry density at two-to-four-percent wet of optimum water content. Compacted lifts shall be a maximum 0.15.
- The primary QA/QV tests and inspections, which shall be performed in the placement area, shall include moisture content tests done prior to compaction and in-place density tests done after compaction. If a second conditioning is utilized, water content testing would be primarily conducted in the conditioning area prior to compaction.

CLAY CAP SUBSIDENCE DEMONSTRATION (9)

A demonstration of the clay cap subsidence was conducted to: (1) evaluate the bridging capacity of kaolin caps, (2) determine the effect of hydraulic head on bridging capacity, and (3) determine the effect of subsidence upon cap permeability.

A 0.6-meter-thick kaolin test cap was constructed above a sand layer and three cavities were formed by extracting sand from under the cap. In the first cavity, formed from August 11 to September 21, 1988, sand was extracted until no further sand could be removed with the existing equipment. The cavity was 3.5 by 1.2 meters at its top and had a total volume of 3.0 cubic meters. The kaolin cap over this cavity collapsed on November 7, 1988. Prior to collapse, a 13-to-19-millimeter depression centered over the cavity was observed.

At the second cavity location, an SDRI was installed and allowed to equilibrate prior to cavity formation. The SDRI caused a 0.36-meter head on the clay. Cavity formation was conducted from September 26 to October 5, 1988. A 3.0-by-0.76-meter-wide cavity with a total volume of 2.0 cubic meters was completed prior to collapse. Information on how cavity formation affects permeability is presented in Table II.

The third cavity approximately 70 percent the size of the first cavity was formed from October 18 to October 21, 1988, to study the long term effects of subsidence. The final dimensions were 3.2-by-0.8 meters with a volume of 2.2 cubic meters. The cap above this portion had not collapsed by March 1989.

TABLE I

Summary of Clay Cap Test Data

Test Cap	Kaolin Type*	Ave. % Moist**	Ave. % Compact***	Ave. Lab Perm.****	Ave. Field Perm.*****
A1	Cyprus T	-1.3	105	0.81	1.6
A2	Cyprus T	2.0	100	0.28	0.32
B1	Dixie T	3.5	94	0.34	0.61
B2	Dixie T	3.6	98	0.25	0.56
B3	Dixie T	2.9	98	0.27	0.91
C1	Huber T	0.4	103	0.34	1.2
C2	Huber T	2.7	100	0.43	0.49
D1	Cyprus C	3.4	98	1.6	3.6
D2	Cyprus C	2.0	97	1.7	5.0

*T = Tertiary Kaolin; C = Cretaceous Kaolin

**Average percent above standard proctor optimum moisture content

***Average percent of standard proctor maximum dry density

****Average laboratory permeability (nanometer per second)

*****Average field permeability (nanometer per second)

TABLE II

Effect of Cavity Formation on Permeability

Date	Cavity Volume (cubic meters)	Permeability (nm/sec)	Notes
9/26/88	0	0.12	permeability at equilibrium
10/2/88	1.0	0.51	
10/3/88	1.4	4.0	collapse of soil layer below kaolin
10/5/88	2.1	16.0	kaolin collapse

As a result of this demonstration, the following conclusions were drawn.

- A 0.6-meter-thick kaolin cap can bridge a 0.9- to 1.1-meter-wide cavity. The dynamic compaction pattern utilized should be consistent with this finding.
- The hydraulic conductivity of a kaolin cap increases incrementally with cavity size until it collapses.
- Failure of the kaolin cap over a cavity is exacerbated by a hydraulic head on the cap, an indication that adequate internal drainage should be provided.

LESSONS LEARNED DURING CLOSURE

Dynamic Compaction

According to *Highway and Heavy Construction* magazine, dynamic compaction of the MWMF was "the largest-ever deep dynamic compaction project in the U.S. (10) Dynamic compaction of the 13,788 locations began in March 1989. The subcontractor used a Lampson "Thumper" Compactor that was especially built for dynamic compaction. The Thumper has a single-line hoist, which minimizes friction losses, rather than a two-part-line hoist, and it is capable of lifting weights to a height of 32 meters. Rather than producing 0.9-to-1.5-meter-deep craters per location with 20 drops of the weight (as was predicted during the test program), the Thumper produced 1.5-to-1.8-meter craters with an average of 13 drops. The subcontractor estimated that the Thumper would produce 88.9 percent of free fall energy, while the Linkbelt crane used during the test program produced only 43.2 percent of free fall energy.

Because of the increased efficiency of the Thumper, the construction specifications were modified to prevent intrusion into the waste zone and to allow increased efficiency of crater backfill. To prevent intrusion into the waste zone, compaction was discontinued if the crater reached 1.4 meter in four drops or less. Crater backfill efficiency was increased by allowing up to 1.8-meter (+0.3) lifts with a graded number of drops based upon lift thickness. The smaller the lift, the fewer drops were required. Additionally, it was demonstrated that drop heights of 24 meters could increase efficiency by 30 percent; however, this modification was not included in the specifications because such an increase of drop height also increased the potential for intrusion into the waste zone.

Dynamic compaction of the low-level-waste trenches was conducted first and proceeded without incident. However, two problems occurred in the intermediate low-level waste trenches that required special consideration. After completion of all primary craters in one intermediate trench, contaminated water was found in the first secondary crater and on the ground surface 4.6 meters away from the crater. Upon investigation, the source was determined to be water that had accumulated within the trench. The bottom of the trench at the area of occurrence was 1.5 meter lower in elevation than the other trench end. This area was also approximately 6.1 meters away from an area within the LLRWDF that had been designated as unsuitable for intermediate waste disposal because of perched groundwater. Special procedures including observation craters were instituted for completion of this trench and three adjacent trenches. No further problems were encountered in these trenches.

A second similar problem was encountered in another intermediate trench. During compaction of a secondary crater, contaminated water was detected within the crater at the high end of the trench and on the ground surface 9.1 meters away. This was not in an area subject to standing water. However, upon investigation, it was determined that an 82-cubic-meter piece of process equipment had been disposed of in the general area and was probably the source of the contaminated water. It had not been disposed of with water in it, but it apparently accumulated water by infiltration. Other trench areas with equipment of volumes over 14 cubic meters were identified and special procedures were instituted for compaction of these areas. The procedures included visual identification of the areas, extra monitoring by the Health Protection Department, and direct supervision by a field design engineer if necessary.

The primary lessons learned during the dynamic compaction phase of the closure included the following.

- Test programs that are performed to determine the applicability of dynamic compaction and to develop specifications must address the compaction equipment that will actually be used during the closure.
- The potential for liquids within the trenches should be investigated before compaction activity is started at a waste site because compaction can force contaminated liquids to the surface.
- The potential for waste with large void volume should be investigated before starting dynamic compaction because such voids may contain significant amounts of liquid and there is the potential for intrusion into the waste zone when dynamic compaction occurs.
- Areas within a waste site that won't be dynamically compacted or that require special consideration during compaction should be positively identified prior to the start of compaction.

Construction of Clay Caps (11,12,13)

Construction of the 260,000-cubic-meter MWMF clay cap began in August 1989. Construction began with reliance on the construction specification with no field engineering judgement or independent quality testing and inspection requirements and on the construction subcontractor to ensure production of a quality product at an acceptable rate. Initially, no onsite, full-time, qualified soils engineer was present to oversee all facets of clay placement. Additionally, the subcontractor tried to demonstrate that an unmetered water truck, rotovators, and a CAT 825 tamping foot compactor was equivalent to the specified recycler/soil stabilizer and CAT 815B for clay conditioning and compaction.

The results of this attempt to substitute farm-type equipment were problems with uniformity and consistency in moisture conditioning. Three to five attempts were required to obtain all conditioning area moisture samples within the specified range of two to four percent wet of optimum, which still did not mean that conditioning was consistent. It just meant that enough sets of samples were taken to obtain a set within the range. This was evidenced by the fact that, after compaction, the acceptance rate was approximately 25 percent because of the failure of the moisture measurements to meet specifications.

The subcontractor was forced to use a metered water truck and a recycler/soil stabilizer to achieve the specified uniformity of moisture conditioning. Additionally, to assure uniformity of moisture at compaction, moisture content tests were taken immediately after compaction rather than before, as had been done initially. Thereafter, moisture tests before compaction were taken only for the subcontractor's information.

Even with use of the proper equipment, the clay acceptance rate was too low to ensure that the regulatory schedule would be met because of the failure to consistently meet the moisture requirement. Therefore, the results and data of the clay cap tests were extensively reviewed, and it was determined that both the moisture and density requirements could be expanded to increase the production rate while maintaining the regulatory permeability requirement (one nanometer per second). The specification was modified first to the criteria outlined in Table III. Later, based upon more production experience and the knowledge that uniformity of moisture can be ensured, the specifications were modified to include the following.

- All moisture content tests shall be within the range of one to six percent wet of optimum moisture content. One test of over six percent may be allowed.
- The average of all tests (excluding the one allowed above six percent) shall be within the range of two to four percent wet of optimum.
- The density of samples shall be 95 percent of maximum dry density for moisture contents between one and four percent above optimum, and density must be 93 percent for moisture contents greater than four percent above optimum.

These specification revisions increased the acceptance rate from 25 percent to 70 percent.

Standard Proctor (ASTM 698 tests were performed to select the representative optimum water content and maximum dry density. All tests were performed in accordance with the ASTM standard; however, variations in the sample preparation and testing occurred over time. Both mechanical and manual rammers were utilized. The method and level to which samples were dried back varied. The method of size reduction of kaolin samples varied. Between January and April 5, 1990, approximately 34,400 cubic meters of clay were placed at optimum moisture two to three percent below previous placement optimum. Upon investigation, it was determined that a change in sample preparation led to lower Proctor optimum water contents. The clay so placed yielded higher densities and lower moistures. This clay was extensively reviewed and 15,300 cubic meters were reworked to ensure compliance with regulatory permeability requirements. This occurrence demonstrated the need for more stringent and consistent testing requirements beyond those specified by ASTM and the need for onsite inspection of production and acceptance.

The following lessons were learned during clay cap placement on the waste site.

- An onsite, full-time, qualified soils engineer is required to oversee and apply engineering judgement to all facets of clay placement and acceptance. It is recommended that this individual be independent from the testing, inspection, and construction organizations.
- Clay placement test programs should be conducted in a manner as consistent as possible with the anticipated production program. The equipment used and testing and inspection methods, including frequency and timing, should be consistent.
- Specifications developed from test programs should be as broad as can be legitimately supported by the test program to promote constructibility.
- ASTM testing methods should be evaluated to determine where the specified methods should be more stringent than the ASTM standard.
- Specifications should establish the critical time and location parameters for test samples to ensure representative results.
- Clay panel locations and the associated placement schedule should be determined prior to construction. During construction, the clay panels should be continuously mapped with the applicable test data to facilitate resolution of problems as they are encountered.
- Guidelines for engineering judgement in the selection of the proctor optimums should be established and issued to all organizations prior to construction.

TABLE III

Initial Modified Specification Requirements

	Wopt +1 to Wopt +2	Wopt +2 to Wopt +4	Wopt +4 to Wopt +6
Moisture content distribution	<20%	≥50%	<30%
Percent of maximum dry density (Standard Proctor)	95%	95%	93%

- In order to avoid blending the initial clay lift with the underlying soils, assuming the use of a CAT 815B compactor with 0.18-meter feet, a 0.25-meter initial lift should be specified and all subsequent lifts should be a maximum of 0.15 meter to promote tie-in between lifts.
- A clay maintenance program should be required during cap construction to prevent cracking caused by desiccation and rutting caused by use of heavy equipment on the clay. Cracking can be prevented by the application of protective cover layers or water, or both, to the clay surface. When the clay surface is exposed to hot, dry weather for an extended down time (i.e. three to four days) the application of water should be required.
- Closure plans should be written as generally as possible with only the specifics required by regulatory agencies. A listing of generic problems with associated solutions should be included in the plan to minimize the need to obtain regulatory approval for the resolution of field problems.

CONCLUSIONS

Rather than being "just a dirt job", adequate placement of a clay cap on a waste site is a highly technical and demanding project that requires attention to detail, qualified personnel, consistency between test and production phases, and much up-front planning. The technology exists to construct clay caps that meet regulatory requirements; however, long-term integrity of such caps has not been adequately addressed. The following is a partial list of the type of information required to build in long-term integrity of clay caps.

- How the moisture content of clay caps varies over time and its relationship to the cap design
- The affect of changes in clay moisture content on permeability and identification of the "critical moisture content", below which, permeability increases above that required
- The methods and cap designs that will maintain clay moisture content above the "critical moisture content"
- How the subsidence potential of solid waste can be more accurately assessed over time and how the effectiveness of waste stabilization methods can be more accurately predicted and assessed
- The quantitative effect of subsidence on cap integrity and permeability
- More cost effective, easily implemented repair methods for clay caps
- Edge effects and the impact of such effects upon the efficiency of a clay cap at unlined waste disposal sites

Answers to these and other questions will help to ensure the long term integrity of closure investments such as the 35 million dollar MWMF.

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