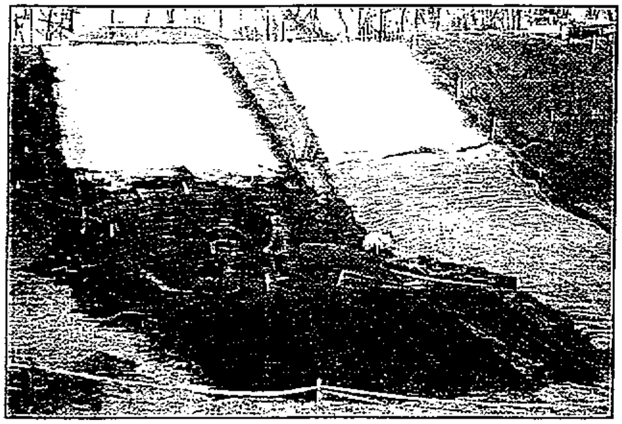
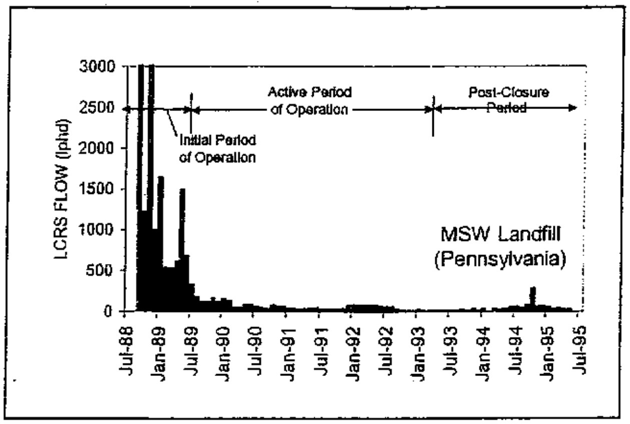
EPA United States Environmental Protection Agency   GeoSyntec Consultants   ILLINOIS   Drexel University

EPA/600/R-02/099
December 2002

Assessment and Recommendations for Improving the Performance of Waste Containment Systems





by

Rudolph Bonaparte, Ph.D., P.E.
GeoSyntec Consultants
Atlanta, GA 30342

David E. Daniel, Ph.D., P.E.
University of Illinois
Urbana, IL 61801

Robert M. Koerner, Ph.D., P.E.
Drexel University
Philadelphia, PA 19104

performed under

EPA Cooperative Agreement Number
CR-821448-01-0

Project Officer

Mr. David A. Carson
United States Environmental Protection Agency
Office of Research and Development
National Risk Management Research Laboratory
Cincinnati, OH 45268

VOLUME 1

189
Projet d'agrandissement du lieu d'enfouissement
sanitaire de Sainte-Sophie
DA15
Sainte-Sophie
6212-03-105

ABSTRACT

This broad-based study addressed three categories of issues related to the design, construction, and performance of waste containment systems used at landfills, surface impoundments, and waste piles, and in the remediation of contaminated sites. The categories of issues, the locations in this report where each category is addressed, and the principal investigator for the study of each category are as follows:

- geosynthetic tasks are described in Chapter 2 and Appendices A and B; the principal investigator for these tasks was Professor Robert M. Koerner, P.E.;
- natural soil tasks are described in Chapters 3 and 4 and Appendices C and D; the principal investigator for these tasks was Professor David E. Daniel, P.E.; and
- field performance tasks are described in Chapter 5 and Appendices E and F; the principal investigator for these tasks was Dr. Rudolph Bonaparte, P.E.

Each portion of the report was authored by the identified principal investigator, and individuals working with the principal investigator. However, each principal investigator provided input and recommendations to the entire study and peer-reviewed and contributed to the entire report.

Geosynthetic materials (e.g., geomembranes (GMs), geotextiles (GTs), geonets (GNs), and plastic pipe) have been used as essential components of waste containment systems since at least the early 1980's. Five separate laboratory and/or analytical tasks were undertaken to address technical issues related to the use of these materials in waste containment systems. The technical issues related to geosynthetics are: (1) protection of GMs from puncture using needlepunched nonwoven GTs; (2) behavior of waves in high density polyethylene (HDPE) GMs when subjected to overburden stress; (3) plastic pipe stress-deformation behavior under high overburden stress; and (4) service life prediction of GTs and GMs. Conclusions are: (1) needlepunched nonwoven GTs can provide adequate protection of GMs against puncture by adjacent granular soils; a design methodology for GM puncture protection was developed from the results of laboratory tests and is presented; (2) temperature-induced waves (wrinkles) in GMs do not disappear when the GM is subjected to overburden stress (i.e., when the GM is covered with soil), rather the wave height decreases somewhat, the width of the wave decreases even more, and the void space beneath the wave becomes smaller; (3) waves may induce significant residual stresses in GMs, which may reduce the GM's service life; residual stresses induced in HDPE GMs by waves may be on the order of 1 to 22% of the GM's short-term yield strength; (4) if GM waves after backfilling are to be avoided, light-colored GMs can be used, GMs can be deployed and seamed without intentional slack, GMs can be covered with an overlying light colored temporary GT until backfilling occurs, and backfilling can be performed only in the coolest part of the day or even at night; (5) based on finite element modeling results, use of the Iowa State

formula for predicting plastic pipe deflection under high overburden stress is reasonable; (6) polypropylene GTs are slightly more susceptible to ultraviolet (UV) light degradation than polyester GTs, and lighter weight GTs degrade faster than heavier GTs; (7) GTs that are partially degraded by UV light do not continue to degrade when covered with soil, i.e., the degradation process is not auto-catalytic; (8) buried HDPE GMs have an estimated service life that is measured in terms of at least hundreds of years; the three stages of degradation and approximate associated durations for each as obtained from the laboratory testing program described in this report are: (i) antioxidant depletion (≈ 200 years), (ii) induction (≈ 20 years), and (iii) half-life (50% degradation) of an engineering property (≈ 750 years); these durations were obtained from the extrapolation of a number of laboratory tests performed under a limited range of conditions; it is recommended that additional testing be performed under a broader range of conditions to develop additional insight into the ultimate service life of HDPE GMs, and other types of GMs as well.

Geosynthetic clay liners (GCLs) are a relatively new type of liner material, having first been used in a landfill in 1986. One of the key issues with respect to field performance of GCLs is their stability on permanent slopes, such as found on landfill final cover systems. Fourteen test plots, designed to replicate typical final cover systems for solid waste landfills, were constructed to evaluate the internal and interface shear strength of GCLs under full-scale field conditions on 2H:1V and 3H:1V slopes. Five different types of GCLs were evaluated, and performance was observed for over four years. All test plots were initially stable, but over time, as the bentonite in the GCLs became hydrated, three slides (all on 2H:1V slopes) that involved the GCLs have occurred. One slide involved an unreinforced GCL in which bentonite that was encased between two GMs unexpectedly became hydrated. The other two slides occurred at the interface between the woven GTs of the GCLs and the overlying textured HDPE GM. Conclusions are: (1) at the low normal stresses associated with landfill final cover systems, the interface shear strength is generally lower than the internal shear strength of internally-reinforced GCLs; (2) interfaces between a woven GT component of the GCL and the adjacent material should always be evaluated for stability; these interfaces may often be critical; (3) significantly higher interface shear strengths were observed when the GT component of a GCL in contact with a textured HDPE GM was a nonwoven GT, rather than a woven GT; (4) if bentonite sandwiched between two GMs has access to water (e.g., via penetrations or at exposed edges), water may spread laterally through waves or wrinkles in the GM and hydrate the bentonite over a large area; (5) if the bentonite sandwiched between two GMs does not have access to water, it was found that the bentonite did not hydrate over a large area; (6) current engineering procedures for evaluating the stability of GCLs on slopes (based on laboratory direct shear tests and limit-equilibrium methods of slope stability analysis) correctly predicted which test plots would remain stable and which would undergo sliding, thus validating current design practices; and (7) based on the experiences of this study, landfill final cover systems with 2H:1V sideslopes may be too steep to be stable with the desired factor of safety due to limitations with respect to the interface shear strengths of the currently available geosynthetic products.

To evaluate the field performance of compacted clay liners (CCLs), a database of 89 large-scale field hydraulic conductivity tests was assembled and analyzed. A separate database for 12 soil-bentonite admixed CCLs was also assembled and analyzed. In addition, case histories on the field performance of CCLs in final cover test sections were collected and evaluated. Conclusions are: (1) 25% of the 89 natural soil CCLs failed to achieve the desired large-scale hydraulic conductivity of 1×10^{-7} cm/s or less; (2) all of the 12 soil-bentonite admixed CCLs achieved a large-scale hydraulic conductivity of less than 1×10^{-7} cm/s; however, all of these CCLs contained a relatively large amount (more than 6%) of bentonite; soil-bentonite admixed CCLs will not be discussed further; (3) the single most common problem in achieving the desired low level of hydraulic conductivity in CCLs was failure to compact the soil in the zone of moisture and dry density that will yield low hydraulic conductivity; (4) the most significant control parameter of CCLs was found to be a parameter denoted "P_o", which represents the percentage of field-measured water content-density points that lie on or above the line of optimums; when P_o was high (80% to 100%) nearly all the CCLs achieved the desired field hydraulic conductivity, but when P_o was low (0 to 40%), fewer than half the CCLs achieved the desired field hydraulic conductivity; (5) practically no correlation was found between field hydraulic conductivity and frequently measured soil characterization parameters, such as plasticity index and percentage of clay, indicating that CCLs can be successfully constructed with a relatively broad range of soil materials; (6) hydraulic conductivity decreased with increasing CCL thickness, up to a thickness of about 1 m; and (7) analysis of CCLs constructed in the final cover test sections generally showed that CCLs placed without a GM overlain by soil tended to desiccate and lose their low hydraulic conductivity within a few years.

Liquids management data were evaluated for 187 double-lined cells at 54 landfills to better understand the field performance of landfill primary liners, leachate generation rates, and leachate chemistry. Conclusions are: (1) average monthly active-period leak detection system (LDS) flow rates for cells with HDPE GM primary liners constructed with construction quality assurance (CQA) (but without ponding tests or electrical leak location surveys) will often be less than 50 lphd, but occasionally in excess of 200 lphd; these flows are attributable primarily to liner leakage and, for cells with sand LDSs, possibly construction water; (2) average monthly active-period LDS flow rates attributable to leakage through GM/GCL primary liners constructed with CQA will often be less than 2 lphd, but occasionally in excess of 10 lphd; (3) available data suggest that average monthly active-period LDS flow rates attributable to leakage through GM/CCL and GM/GCL/CCL primary liners constructed with CQA are probably similar to those for GM/GCL primary liners constructed with CQA; (4) GM liners can achieve true hydraulic efficiencies in the 90 to 99% range, with higher efficiencies occasionally being achievable; (5) GM/GCL, GM/CCL, and GM/GCL/CCL composite liners can achieve true hydraulic efficiencies of 99% to more than 99.9%; (6) GMs should not be used alone in applications where a hydraulic efficiency above 90% must be reliably achieved, even if a thorough CQA program is employed, except perhaps in situations where electrical leak location surveys or ponding tests are used to identify GM defects and the defects are repaired; (7) GM/CCL and GM/GCL/CCL composite liners are capable of substantially preventing leachate migration over the entire period of significant leachate generation for typical landfill operations scenarios without leachate recirculation or disposal or liquid wastes of sludges; (8) leachate collection and removal system (LCRS) flow rates were highest at the beginning of cell operations and decreased as waste thickness increased and daily and intermediate covers were applied to the waste; leachate generation rates decreased on average by a factor of four within one year after closure and by one order of magnitude two to four years after closure; within nine years of closure, leachate generation rates were negligible for the landfill cells evaluated in this study; (9) municipal solid waste (MSW) cells produced, on average, less leachate than industrial solid waste (ISW) and hazardous waste (HW) cells; for cells of a given waste type, rainfall fractions were highest in the northeast and lowest in the west; the differences in leachate generation rates are a function of type of waste, geographic location, and operational practices; (10) in general, HW landfills produced the strongest leachates and coal ash landfills produced the weakest leachates; MSW ash leachate was more mineralized than MSW leachate and the other ISW leachates; (11) the solid waste regulations of the 1980s and 1990s have resulted in the improved quality of MSW and HW landfill leachates; and (12) the EPA Hydrologic Evaluation of Landfill Performance (HELP) computer model, when applied using an appropriate simulation methodology and an appropriate level of conservatism, provides a reasonable basis for designing LCRSs and sizing leachate management system components; due to the complexity and variability of landfill systems, however, the model will generally not be adequate for use in a predictive or simulation mode, unless calibration is performed using site-specific measured (not default) material properties and actual leachate generation data.

Waste containment system problems were identified at 74 modern landfill and surface impoundment facilities located throughout the U.S. The purpose of this aspect of the project was to better understand the identified problems and to develop recommendations to reduce the future occurrence of problems. Conclusions are: (1) the number of facilities with identified problems is relatively small in comparison to the total number of modern facilities nationwide; however, the search for problems was by no means exhaustive; (2) the investigation focused on landfill facilities: 94% of the identified problems described herein occurred at landfills; (3) among the landfill problems, 70% were liner system related and 30% were cover system related; however, the ratio of liner system problems to cover system problems is probably exaggerated by the fact that a number of the facilities surveyed were active and did not have a cover system; (4) based on a waste containment system component or attribute criterion, the identified problems can be grouped into the following general categories: (i) slope instability of liner systems or cover systems or excessive deformation of these systems (44%); (ii) defectively constructed liners, leachate collection and removal systems (LCRSs) or LDSs, or cover systems (29%); (iii) degraded liners, LCRSs or LDSs, or cover systems (18%); and (iv) malfunction of LCRSs or LDSs or operational problems with these systems (9%); (5) considering a principal human factor contributing to the problem criterion, the identified problems are classified as follows: (i) design (48%); (ii) construction (38%); and (iii) operation (14%); (6) the main impacts of the problems were: (i) interruption of facility construction and operation; (ii) increased maintenance; and (iii) increased costs; (7) problems detected at facilities were typically remedied before adverse environmental impacts occurred; (8) impact to groundwater or surface water was only identified at one facility, where landfill gas migrated beyond the edge of the liner system and to groundwater; (9) all of the identified problems can be prevented using available design approaches, construction materials and procedures, and operation practices; (10) although the environmental impact of problems has generally been negligible thus far, the landfill industry should do more to avoid future problems in order to: (i) reduce the potential risk of future environmental impact; (ii) reduce the potential health and safety risk to facility workers, visitors, and neighbors; (iii) increase public confidence in the performance of waste containment systems; (iv) decrease potential impacts to construction, operation, and maintenance; and (v) reduce costs associated with the investigation and repair of problems.

Chapter 6
Summary and Recommendations

6.1 Rationale and Scope of Chapter

The study discussed in this research report addressed three important areas of waste containment system design and performance, namely:

- geosynthetic materials (puncture protection of GMs using GTs, wave behavior in HDPE GMs, plastic pipe behavior under high overburden stresses, and service life prediction of GTs and GMs);
- natural soil materials (slope stability of final cover systems with GCLs, k_{field} of natural soil CCLs and soil-bentonite admixed CCLs, and hydraulic performance of CCLs in final cover systems); and
- field performance (LCRS and LDS flow quantities and chemical quality at landfills, assessment of EPA HELP computer code as a design tool using LCRS flow rate data, and lessons learned from waste containment problems at landfills).

All three areas were addressed through multiple tasks, each important in its' own right, but also complementary to the other tasks because of the interrelationships between waste containment system components. The ultimate goals of this study were to assess the field performance of waste containment systems and to develop recommendations for further improving the performance of these systems in comparison to the current state-of-practice.

This chapter presents a summary of the tasks conducted for this study and provides recommendations on practices to further improve the performance of waste containment systems. These recommendations were developed, in part, using the results of the various tasks. Some, however, go beyond the scope of this study and are offered by the authors with the understanding that the current level of "good" field performance can be further improved within current material, design, testing, and installation technology and practices.

6.1.1 Geosynthetics

As discussed in Chapter 1, geosynthetics, including GMs, GTs, GNs, GCs, plastic pipe, and GCLs, are used in waste containment systems for a variety of functions. Most modern waste containment systems contain one or more geosynthetic components. Notwithstanding their broad use, issues related to geosynthetic materials persist. Indeed, the relative newness of these materials compared to natural soil construction materials requires that they continue to be studied and evaluated. Chapter 2 of this report described the results of the geosynthetic-related tasks of this research project. These tasks addressed:

- Buried HDPE GMs have an estimated service life that is measured in terms of at least hundreds of years. The three stages of degradation and approximate associated times for each as obtained from the laboratory testing program described in this report are: (i) antioxidant depletion (≈ 200 years), (ii) induction (≈ 20 years), and (iii) half-life (50% degradation) of an engineering property (≈ 750 years). It is noted that these durations were obtained from the extrapolation of a number of laboratory tests performed under a limited range of conditions. It is recommended that additional testing be performed under a broader range of conditions to develop additional insight into the ultimate service life of HDPE GMs, and other types of GMs as well.

6.1.2 Natural Soils

CCLs, including those constructed from natural clay soils and those constructed from soil-bentonite mixtures, have long been used in waste containment systems as hydraulic barriers to inhibit liquid migration from the waste management unit. Either used alone, or with a GM component in the form of a GM/CCL composite liner, CCLs form an essential part of many liner systems and final cover systems. Other natural soil materials used in liner and final cover systems include sands and gravels used for gas conveyance systems or liquid drainage and collection systems, and soil layers used for filtration, separation, or protection. Notwithstanding the widespread use of natural soil materials in liner systems and final cover systems, questions and issues persist relative to their use. Several of these questions and issues were investigated, and the results were reported in Chapters 3 and 4 of this report. The subject areas that were addressed are:

- slope stability of GCLs in final cover systems, as assessed from field test plots;
- k_{field} of low-permeability natural soil CCLs;
- k_{field} of admixed (soil-bentonite) CCLs; and
- CCL hydraulic performance in final cover systems;

These topics were selected on the basis of past research indicating areas where additional insight was required, or on the basis of concerns developed from relatively recent field experience. Key findings of the natural soils related tasks are given below:

- Slope stability monitoring of final cover system test plots incorporating GCLs demonstrated acceptable performance for test plots constructed on 3H:1V slopes, but several of the test plots constructed on 2H:1V slopes failed. Importantly, for internally-reinforced GCLs, these failures were not due to inadequate internal strength, but inadequate interface strength. Clearly, proper characterization of GCL interface shear strength is an important design step.
- The key to achieving low k_{field} for natural soil CCLs is to ensure that 70 to 80%, or more, of the field-measured compaction (w vs. γ_d) points lie on or above the line of optimums for the particular CCL being placed.

- Single liner systems with GM liners (installed on top of a relatively permeable subgrade) should not be used in applications where a true hydraulic efficiency above 90% must be reliably achieved, even if a thorough CQA program is employed. In these cases, single-composite liner systems or double-liner systems should be used. An exception to this may be made for certain facilities where electrical leak location surveys or ponding tests are used to identify GM defects and the defects are repaired. Higher true hydraulic efficiencies of 99% to more than 99.9% can be achieved by GM/GCL, GM/CCL, and GM/GCL/CCL composite liners constructed with good CQA.
- Based on the existing data, GM/CCL and GM/GCL/CCL composite liners are capable of substantially preventing leachate migration over the entire period of significant leachate generation for typical landfill operation scenarios (i.e., for a landfill cell filled over a number of years, that does not undergo leachate recirculation or disposal of liquid wastes or sludges, and that is capped with a final cover system designed to minimize percolation into the landfill; based on our existing understanding of their performance capabilities, these types of composite liners are capable of substantially preventing leachate migration for a much longer period, although field performance data of the type presented in this report do not yet exist for this longer period.
- LCRS flow rates during operations (i.e., the initial and active periods of operation) can vary significantly between landfills located in the same geographic region and accepting similar wastes. Large variations in flow rates (e.g., one order of magnitude difference) can even occur between cells at the same landfill.
- LCRS flow rates were highest at the beginning of cell operations and decreased as waste thickness increased and daily and intermediate covers were applied to the waste. Leachate generation rates decreased, on average, by a factor of four within one year after closure and by one order of magnitude two to four years after closure. Within nine years of closure, LCRS flow rates were negligible for the landfill cells evaluated in this study.
- MSW cells produced, on average, less leachate than HW and ISW cells.
- For cells of a given waste type, rainfall fraction (RF) values were highest in the northeast U.S. and lowest in the west.
- In general, HW landfills produced the strongest leachates and coal ash landfills produced the weakest leachates. MSW ash leachate was more mineralized than MSW leachate and the other ISW leachates.
- The solid waste regulations of the 1980s and 1990s have resulted in the improved quality of MSW and HW landfill leachates.
- The EPA HELP computer model, when applied using an appropriate simulation methodology and an appropriate level of conservatism, provides a reasonable basis for designing LCRSs and sizing leachate management system components. Use of the HELP model for these purposes can be enhanced through calibration to leachate generation rates at other landfills in the region and through parametric analyses that consider the potential range of values for key input parameters (e.g., initial moisture contents of waste). Due to the

6.2.1 Construction Quality Assurance

CQA has been shown to be of direct benefit in minimizing the potential leakage through liner systems. This finding was originally put forth by Bonaparte and Gross (1990) on the basis of sparse data and has been reinforced with the considerable additional data generated since that time, including data presented in this study. Considerable guidance exists for the development and implementation of liner system and cover system CQA plans. Among the many requirements for such plans, the authors make note of the following:

- soil and geosynthetic material conformance with the project specifications;
- proper pre-conditioning and placement of CCL lifts;
- proper compaction moisture content and density of CCLs;
- protection of CCLs from desiccation and freezing;
- placement of GMs without excessive waves and covering or backfilling the GMs in a manner that minimizes the trapping of waves; the goal of these measures is intimate contact between the GM and the underlying CCL or GCL;
- prevention of premature GCL hydration;
- inspection of GM seams, including nondestructive and destructive testing; and
- protection of GMs from puncture by adjacent materials or equipment.

6.2.2 Liner System Stability

This category of stability involves the liner system prior to waste placement. The main concern regarding liner system stability is for natural soils (particularly sand and gravel drainage soils) or geosynthetics (particularly GTs and GNs) to slide on underlying geosynthetic surfaces. Sliding of drainage soils or sliding of drainage soils and GT cushions on underlying GMs is unfortunately too common. The instability is induced by low shear strength interfaces, steep and/or long slopes, equipment loads, seepage forces, and/or seismic forces. An area requiring particular attention is at access ramps into below-grade landfills. These ramps are needed for operations, but are sometimes overlooked in the assessment of landfill cell slope stability. In some cases, ramps have been installed by landfill operations personnel, without an evaluation of their effect on liner system stability. Another type of liner system stability problem that requires careful attention is sliding of GM layers on underlying CCLs or GCLs prior to waste placement.

Design of liner systems for adequate slope stability is well within the design state-of-practice. The available technical literature contains more than adequate information to design liner systems to be stable (see for example, Giroud and Beech, 1989; Koerner and Hwu, 1991; Giroud et al., 1995; and Koerner and Soong, 1998). However, in the authors' experience, the available methods are often not adequately utilized in design. For example, it is not uncommon for seepage forces to be inadequately addressed during the design process. Another significant design issue involves the inadequate characterization of interface shear strengths, apparently due to insufficient effort

Of particular importance in choosing waste and interface shear strengths is deformation compatibility. It must be recognized that the amounts of deformation needed to generate peak shear strengths in waste and along geosynthetic interfaces are very different. As discussed by Byrne (1994), Stark and Poeppel (1994), Gilbert et al. (1997), and Sabatini et al. (2001), careful consideration must be given to the shear strength deformation conditions used in design (i.e., peak, large displacement, or residual).

It is interesting to note that several of the larger waste failures reported in the literature occurred after periods of high rainfall, which had the effect of temporarily increasing the density of the waste (Reynolds, 1991). High rainfall can also impose seepage forces, which will decrease stability accordingly.

Also important in some cases is seismic stability of the waste mass. While the performance of several lined earthquakes in the 1994 California Northridge earthquake was very good (Matasovic et al., 1995; Matasovic and Kavazanjian, 1996) more needs to be learned about this subject, particularly with respect to the seismic response of the landfill and the determination of the acceptable magnitude of seismically-induced liner system deformation. With respect to this latter criterion, it is the authors' experience that design engineers often select a seismic deformation criterion of 150 to 300 mm based on Seed and Bonaparte (1992). However, these values may not be appropriate in all applications. Careful consideration should be given to selection of an acceptable level of deformation for design. For example, all other factors being equal, a lower allowable deformation should be used if the critical interface is below the GM component of the liner system (because excessive deformation would cause the GM to rupture) than above it. Guidance on the seismic design of landfills can be found in Richardson et al. (1995), Anderson and Kavazanjian (1995), and Kavazanjian (1998).

6.2.4 Performance of Composite Liner

For over a decade it has been known through theoretical analyses, laboratory tests, and limited field data that composite liners are superior to either GMs alone or CCLs alone for the containment of leachate or other liquids (Brown et al., 1987; EPA, 1987; Giroud and Bonaparte, 1989a,b; Bonaparte and Gross, 1990; Bonaparte and Othman, 1995). This report has presented significant new field data that confirms the very good performance characteristics of GM/GCL, GM/CCL, and GM/GCL/CCL composite liners versus current types of single liner materials.

As discussed in Section 1.4.1.4, the basic premise of using a composite liner is that leakage through a hole or defect in the GM upper component is impeded by the presence of a CCL or GCL lower component. The GM improves the performance of the composite liner relative to that for a CCL or GCL alone by greatly limiting the portion of the CCL or GCL exposed to leachate, and, for CCLs, lowering the potential for gas through the liner system. With respect to selection of the type of liner system for a specific project, the authors offer the following thoughts:

- Caution should be exercised in using the EPA HELP model to make a technical demonstration that the Subtitle D performance standard can be achieved with a liner system less (e.g., without a GM) than the federal minimum design criteria. Input parameters to the model can be selected to demonstrate a lesser potential for leachate generation than actually exists. For example, the discussion in Chapter 5 of this report indicated that modeled leachate generation rates are sensitive to the assumed initial moisture content of the waste. Because of the sensitivity of the HELP model results to the input parameters, when the model is used to make a technical performance demonstration, the model should be calibrated against data (i.e., LCRS flow rates) from lined landfills in the same geographic area. In addition, the potential for landfill gas impacts to groundwater should also be considered as part of the technical demonstration.
- Based on the landfill operation data presented in this report, Subtitle D single-composite liner systems meeting federal minimum design criteria can achieve a very high hydraulic efficiency and are capable of preventing adverse impacts to groundwater. This conclusion is consistent with the previous conclusion reached by EPA regarding the performance capabilities of liner systems meeting federal minimum design criteria.
- Caution should be exercised in substituting a GCL alone for the CCL as the low-permeability soil component of a Subtitle D single-composite liner on the base of a landfill. While the hydraulic efficiency of a GM/GCL composite liner is as good, or better, than a GM/CCL composite liner, the GM/GCL composite liner is more susceptible to diffusive transport (Rowe, 1998) and puncture than the GM/CCL composite liner. These concerns are less important for sideslope areas of the landfill where leachate heads are lower; thus, a GM/GCL composite liner is more likely be appropriate for sideslopes than for base areas from a hydraulic perspective. Also, a GM/GCL/CCL composite liner may be an effective low-permeability soil component for a single-composite liner. In this case, it may be acceptable to specify a maximum hydraulic conductivity on the order of 1×10^{-5} cm/s for the CCL of a three-component composite liner used at MSW landfills.
- There may exist situations for MSW landfills where a double-liner system would be preferred to a liner system meeting the federal minimum design criteria. In addition to the obvious situation where a state regulation requires use of a double-liner system, the project conditions favoring selection of a double-liner system include: (i) sites with especially vulnerable hydrogeology; (ii) sites where groundwater cannot be reliably monitored due to the presence of complex hydrogeology, karst, or other factors; and (iii) sites where, for whatever reason, a higher degree of reliability/redundancy is required of the liner system than can be achieved by the Subtitle D federal design criteria. In some cases, it may be desirable to use a double-liner system beneath the base of the landfill, and, for cost-effectiveness, a single-composite liner system beneath the sideslopes.

hours. (This is equivalent to a single point value, per ASTM D5397, of 200 hours). At the designer's discretion, these values can be increased, and, depending on site-specific conditions, this is encouraged. Regarding HDPE formulations, the antioxidant package included in the formulation is critically important, and specifications should include a minimum OIT along with a minimum OIT retained value after oven aging and laboratory simulated UV exposure.

6.3 Liquids Management

The liquids management strategy for a landfill generally refers to all liquids including:

- leachate collection and removal at the bottom of the waste mass, above the primary liner system;
- leakage collection and removal at the bottom of the waste mass between the primary and secondary liners;
- rainwater collection and removal via the final cover system drainage layer above the barrier material;
- gas condensate collection and removal via the gas collection piping system; and
- groundwater collection and control via the pore pressure relief system in areas of high groundwater.

For the first three systems, drainage layers transmit liquid by gravity to a low point where the liquid empties into a sump or gravity drain or is discharged from the waste containment system, in the case of a final cover system drainage layer. In the case of a sump, the liquid is withdrawn using submersible pumps or bailers. For a gravity drain, the liquid flows by gravity through a pipe that penetrates the liner system and discharges to a storage or treatment system outside the limits of the landfill. From final cover system drains, the liquid flows by gravity either as sheet flow to the surrounding land, or, more typically, into a perimeter stormwater collection and conveyance structure. For gas condensate collection and removal systems, liquids collected in gas collection piping systems typically drain to a low point in the piping system. From this location, condensate is usually introduced back into the waste; however, sometimes condensate is removed from the waste containment system and treated. With respect to pore pressure relief system, these systems may consist of a series of wells or perimeter trenches that are pumped to lower the groundwater table or may include a drainage layer and sump installed beneath the liner system.

These liquid collection and removal systems were discussed in Section 1.4.2 of this report. That discussion is not repeated in this chapter.

applications. Furthermore, a value of 1 x 10^{-3} cm/s, which is sometimes specified, will almost always be too low. Hydraulic conductivities at these values result in drainage layers with substantial liquid storage (capillary) capacity and slow drainage rates. These conditions result in increased hydraulic head on the liner and, consequently, increased potential for clogging and leakage. Design of LCRSs should be performed on a site specific basis, using an adequate factor of safety. The soil should be free draining, with few fines, and little or no capillarity.

- For design of LCRSs, the HELP model can be an appropriate design tool for estimating leachate generation rates (see Chapter 5). As previously indicated, however, HELP model results are sensitive to the input parameters provided. The authors believe design engineers can do much more to calibrate their HELP model runs using data from already active landfills in the region. In this regard, design engineers and landfill operators are encouraged to collect and disseminate this information.
- Landfill LCRS design should include not only an evaluation of leachate quantity, but also leachate quality. This report presents considerable new data on landfill leachate characteristics. From a design perspective, it is important to identify conditions (e.g., sludge co-disposal, special waste disposal) that would create a leachate with more than usual potential to clog a drainage layer. For example, Koerner et al. (1994) identified leachate with high TSS and/or BOD_5 values (e.g., above 10,000 to 15,000 mg/l) as a condition requiring special design consideration. Interestingly, in the study of liquids management data described in Chapter 5, none of the landfill cells for which leachate chemistry data are available had average BOD_5 values greater than 5,000 mg/l.
- For the internal drainage layer in a final cover system, water is the medium being transmitted and clogging of the drainage layer by water is generally not considered. The primary issue for this layer is inadequate drainage capacity and the buildup of seepage forces in the final cover system, leading to slope instability. A significant number of seepage-induced final cover system failures were identified in Chapter 5. The HELP model must be used with caution to calculate liquid heads in the final cover system drainage layer, as experience has shown that these heads may be underpredicted if the peak daily rainfall used in the model is too low. Guidance on using the HELP model for this purpose is given in the upcoming EPA technical guidance document titled, "*Technical Guidance for RCRA/CERCLA Final Covers*" (Bonaparte et al., 2002). Also, the manual procedure in Koerner and Daniel (1997) can be used to estimate liquid heads in the final cover system drainage layer.

6.3.3 Perched Leachate

Perched leachate (which does not have full hydraulic connection to the underlying LCRS) can occur as a result of a number of conditions in a landfill. Excessively clogged filters above the drainage layer, low-permeability buffer (or protection) soils placed above the LCRS, low-permeability daily cover, and high moisture content sludges (industrial or sewage) within the waste mass all can lead to the trapping of moisture in barriers, rather than low-permeability hydraulic barriers such as GMs, CCLs, and GCLs. ET and capillary barrier cover systems are finding increasing use at arid and semi-arid sites. These alternative cover systems are discussed in detail in the upcoming EPA technical guidance document titled, "*Technical Guidance for RCRA/CERCLA Final Covers*" (Bonaparte et al., 2002).

Both geosynthetics and natural soils are commonly used in final cover systems. Great care is required during both design and construction in order to achieve adequate performance. While many of the authors' comments in Section 6.2 of this report on liner systems also apply to the final cover systems, there are several differences between the two. For cover systems in comparison to liner systems:

- the barrier is meant to keep liquid out of the waste mass, rather than containing liquid within;
- the liquid to be managed is infiltrating rainwater (and snow melt) which percolates through the cover soil rather than leachate;
- upward rising gases from the waste may need to be captured beneath the barrier and effectively transmitted for proper management;
- the upward rising gases usually contain volatile constituents from the leachate, albeit at low concentrations for landfills (though potentially at higher concentrations at remediation sites), thus chemical mass transport and chemical compatibility of systems in contact with the gas should be considered;
- final cover systems slopes may be relatively steep and long, resulting in significant slope stability design issues;
- final cover systems are subjected to different environmental stresses than liner systems; these stresses include freeze-thaw and desiccation-wetting cycles; and
- the impact of waste settlements, both total and differential, on final cover system integrity should be considered for proper design of all system components.

Several of the more important issues with respect to design, construction, and maintenance of landfill final cover systems are discussed below.

6.4.1 Construction Quality Assurance

It seems intuitive that if proper CQA produces improved performance for liner systems, the same will be true for final cover systems. The authors believe that in addition to the CQA items for liner systems mentioned in Section 6.2.1 of this report, the following items require special attention when performing CQA of final cover systems:

- evaluation of the subgrade upon which the final cover system is to be placed to assure adequate bearing capacity and that buried waste will not damage overlying final cover system components;
- careful construction according to the design details for connections of GMs and GCLs to pipe vents;

6.4.3 Final Cover System Stability

Notwithstanding the availability of proven slope stability design methods (e.g., Koerner and Hwu, 1991; Giroud et al., 1995), the sliding of cover soils on underlying soil/geosynthetic and geosynthetic/geosynthetic interfaces has been a relatively common problem for landfill final cover systems. In evaluating final cover system stability, consideration must be given to a variety of potential destabilizing forces (i.e., the gravitational mass of the cover soil, equipment loadings, seepage forces, and seismic forces). As for liner systems, attention to detail by a qualified design engineer has sometimes been lacking. This attention to detail should apply to the selection of the input parameters to the slope stability analysis, to the evaluation of seepage, seismic, and/or equipment forces to be applied to the cover system, the factor of safety used in the analysis, and the analysis itself. As for the evaluation of liner system stability, it is recommended that the shear strengths of cover system materials and interfaces be evaluated using the results of project-specific laboratory shear tests conducted in a manner to simulate the anticipated field conditions.

In the experience of the authors, factors that contribute to the observed high frequency of final cover system slope failures include:

- relatively steep slopes with long uninterrupted surfaces; these conditions can be mitigated by using flatter slopes, benches, intermediate berms, and/or tapered cover soil thicknesses;
- equipment loadings, which can be minimized by limiting the ground pressure of equipment and orienting the equipment in predetermined (and properly designed) paths; the effect of even low ground pressure equipment on cover system stability should be checked by the design engineer;
- build-up of seepage forces within the drainage layer and/or cover soils due to inadequate drainage capacity, which is often the result of not performing a water balance for the internal drainage layer and evaluating the potential for seepage forces; if the HELP model is used to estimate seepage forces, considerable care is needed in selecting a design storm event and other input parameters that do not lead to an underestimate of liquid head buildup in the drainage layer; as previously noted, the manual calculation method of Koerner and Daniel (1997) can also be used to estimate liquid heads;
- inadequate design of drain transitions and outlets, such that water backs up in the drain and causes a buildup of pore pressure within the cover soil mass; and
- instability caused by seismic forces, which is clearly a site-specific situation and one requiring careful design and interpretation; paradoxically, current regulations require seismic design of many MSW landfills but do not do so for HW landfills or abandoned landfills.

6.4.4 Cover Soil Erosion

The evaluation of cover soil erosion is also an important step in the design of a landfill cover system. A possible design strategy to avoid seepage forces within a cover soil is

D5617. At lower pressure rates, where stress relaxation can occur, the situation is different but the test is rarely conducted in a slow strain rate or creep mode.

- In the current state-of-practice, chemical compatibility is rarely considered for final cover system GMs since the upper surface of the GM is only exposed to water infiltrating the cover soil. However, the lower surface of the GM may be exposed to landfill gas, which invariably contains low concentrations of volatile components present in the leachate. Thus, chemical resistance is an issue that should be considered based on site-specific conditions.
- Both durability and chemical compatibility are issues with respect to the reinforcing fibers or yarns of reinforced GCLs placed on sideslopes. While the GCL test plots described in Chapter 3 go far to show the validity of such GCL reinforcement, GCLs have not been installed for a long enough time to demonstrate the adequacy of this reinforcement over a 30 or 100-year time frame.
- The design of internal drainage layers in final cover systems is too often inadequate, i.e., the flow capacity is too low and outlets and transitions do not have adequate flow capacity. The potential for fines migration through the drainage layer filter is not always considered. The potential for freezing or other blockage of the drainage layer outlets is sometimes not assessed.
- The design of final cover systems in seismic impact zones requires careful consideration. The potential for amplification of free-field ground motions by the waste mass combined with low shear strength geosynthetic interfaces makes seismic performance an important consideration. EPA guidance (Richardson et al. 1995) and Anderson and Kavazanjian (1995) provide procedures for evaluating the potential for seismically-induced final cover systems deformations. Considerations applicable to seismically-induced deformations of liner systems (discussed in Section 6.2.3) are also applicable to final cover systems. An additional consideration for final cover systems is that in high seismic zones (e.g., near major active faults in California), it may not be feasible to design sloping final cover systems containing geosynthetics to sustain non-damaging deformations during major earthquakes. As discussed by Kavazanjian (1998), in these circumstances, it may be appropriate to design the final cover system to an acceptable damage criterion. Acceptable damage levels would be based on preventing adverse environmental impact, cost of repair, ease of repair, and any other impacts associated with the damage (e.g., loss of serviceability). This approach would necessitate development of a detailed post-earthquake response action plan coupled with financial assurances to provide the required funds to make the repairs at the time when they are needed.
- The fact that the waste mass is subsiding over time means that sideslope angles are progressively decreasing. The amount is waste-dependent, but the mechanism is one that tends to progressively increase final cover system slope stability factors of safety.

cause GM uplift. Even if the GM is not physically lifted, positive gas pressure beneath the GM can lower the effective stress at the interface between the GM and underlying material (e.g., GCL), thereby reducing interface shear strength and potentially contributing to a slope failure.

6.5.1 Construction Quality Assurance

As with all aspects of a waste containment system, CQA plays an important role in achieving acceptable performance of a gas management system. For deep wells, the number, location and extent of the pipe perforations are important. Also, the wells must be kept safely above the liner system beneath the waste. Several examples exist where gas well borings have extended into the liner system because of inadequate survey control and not accounting for landfill settlement. For continuous gas transmission layers beneath the barrier, continuity is important for either soil or geosynthetic gas transmission layers. If the latter, the material is often a GN with GTs bonded to both sides. The overlapping of the GN along its edges and ends is important as well as its joining with plastic ties per the specifications. Both upper and lower GTs need to be continuous with generous overlaps (often 300 mm) or sewn together to prevent soil from entering and clogging the GN.

Lastly, the penetration of gas wells or vents through a GM barrier should have tightly fitting prefabricated boots. Unlike boots for liner penetrations at the bottom of the landfill, boots for the final cover system GM must be designed to function while accommodating the anticipated landfill settlement. GCL tie-ins have similar considerations.

6.5.2 Gas Uplift

As indicated above, when using a GM in an MSW landfill final cover system, gas uplift pressures will be exerted on the GM unless the gas is efficiently conveyed to the wells, vents, or collection trenches. If gas is not adequately managed, uplift pressure will either cause GM bubbles (or "wales") to occur displacing the cover soil and appearing at the surface, or it will decrease the normal stress between the GM and the underlying material. At several facilities, this latter effect has led to slippage of the GM and overlying cover materials creating high tensile stresses as evidenced by compression ridges in the cover soil and folding of the GM at the slope toe and tension cracks in the cover soil near the slope crest. Three situations need careful design consideration:

- if gas removal is by deep wells, the uppermost pipe perforations should be effective in capturing gas in the upper layers of waste;
- if gas removal is by a gas transmission layer beneath the GM and vents, the gas transmission layer should be designed with adequate long-term transmissivity; and

The time frames over which both total and differential settlement may occur are quite long and depend on the many factors including the liquids management strategy practiced at the site. Table 6-1 presents a framework for evaluating likely post-closure total and differential settlements at MSW landfills and abandoned dumps.

Table 6-1. Impact of Liquids Management Practice on Final Cover System Settlement at MSW Landfills and Abandoned Dumps[1,2] (Koerner and Daniel, 1997).

Leachate Management Practice	Total Settlement		Differential Settlement[3,4]	
	Amount	Time	Amount	Time
Standard leachate withdrawal	10-20%	≤ 30 yrs.	Little to moderate	≤ 20 yrs.
Leachate recirculation	10-20%	≤ 15 yrs.	Moderate to major	≤ 10 yrs.
None, e.g., at abandoned landfills or dumps	Up to 30%	> 30 yrs.	Unknown	> 20 yrs.

[1] HW landfills, ISW landfills, and MSW ash monofills usually have much less settlement than the amounts listed in this table.

[2] The estimates in this table regarding the impact of the liquids management practice on settlement of landfill final cover systems are based on sparse data. They are meant to be a guide only, and site-specific estimates are required to develop more appropriate figures for any particular final cover system project.

[3] The estimates in this table regarding differential settlement amount and time are also based on very sparse data. Clearly, field monitored data is needed in this regard.

[4] These qualitative assessment terms are also affected by the density of the waste; well-compacted waste produces less differential settlement than poorly-compacted waste.

6.5.4 Landfill Fires

While the incidence of landfill fires in MSW landfills has greatly diminished since the days of the "open dump", they still sometimes occur. Air-to-methane mixture ratios of 20 to 50% have given rise to at least one fire, which damaged a geosynthetic final cover system. The vulnerable time frame of a facility with respect to landfill fires appears to be after the GM is seamed and before cover soil is placed. Wind uplift of the GM can draw air in through vents providing the oxygen necessary to create ignitable conditions.

Fires at depth within a waste mass may occasionally occur. The origin of such fires is apparently spontaneous combustion and an air source is required for sustenance. The key to preventing such a fire is to block air entry. Identifying and blocking all potential sources of air entry can sometimes be difficult.