CHAPTER 11
CASE STUDIES — RCRA/CERCLA CLOSURES

INTRODUCTION
This chapter presents five waste closure case studies. Each study examines both design details that confirm the suitability of the individual cap and those that may detrimentally affect the long-term service of the facility. The first four caps have been permitted and placed over RCRA/CERCLA wastes. The fifth cap has been proposed for a major municipal solid waste (MSW) landfill and demonstrates the design problems that may be associated with such facilities.

Each design example is intended to highlight problems that may be encountered in satisfying all aspects of closure criteria. The criteria that must be satisfied are:

1. Specific minimum technology guidance (1) (MTG) applicable or appropriate and relevant to the site-specific waste. MTG is discussed in greater detail in Chapter 1.

2. Erosion control to limit the loss of cover soil to less than 2 ton/acre/year, as discussed in Chapters 1 and 8.

3. Gas control systems to minimize movement of waste-generated gases off site.

4. Ability for all systems to survive both local and global subsidence potentials, as discussed in Chapters 1 and 2.

This chapter also raises specific concerns regarding the use of MTG guidance blindly, without engineering confirmation of its suitability.

CASE 1: RCRA COMMERCIAL LANDFILL
The first closure case presents a cap over a commercial hazardous waste disposal cell that is designed to satisfy the basic MTG cap profile. Figure 11-1 shows details of the general cap profile and geometry. Note that the slope of the cap does exceed the 5 percent maximum contained in the MTG criteria but is significantly flatter than the caps on the other examples. The use of low slopes on such facilities recognizes that the solidified waste placed within them is very stable and will not produce significant long-term subsidence. Such low slopes cannot be used in applications where high long-term subsidence is a concern, such as with many CERCLA and MSW closures. This chapter examines two significant design considerations for such facilities: 1) calculation of localized subsidence and its impact on the cover barrier layer, and 2) the impact of gas collection systems.

Calculation of Localized Subsidence
During the service life of this facility, it received nearly 10,000 transformers containing PCB oils (TSCA permitted). The regulator expressed concern about the long-term impact of the loss of oil and eventual collapse of the transformer cases. Fortunately, available records provided the location and size of the transformers. The general subsidence model used to predict the surface displacement of the cap due to transformer collapse was adapted from an EPA study by Murphy and Gilbert (2) (see Figure 11-2). The key assumption in this model is that the volume of the surface depression is equal to the volume of the oil leaking from the transformer. This is a conservative assumption because it neglects the arching that will occur within both the waste and operational soils placed around the waste. An additional key assumption must be made regarding the friction angle of the waste itself. For this case, the friction angle was assumed to be that of the operational soils placed around the waste. For wastes in general, such values can be measured in actual field tests (3).

The simple model for subsidence due to a single transformer collapse then must be applied to the actual cover for all 10,000 transformers. The subsidence is accumulated and plotted as shown on Figure 11-3. By examining the cap’s elevation contour, one can estimate the maximum long-term relative vertical displacement of the cap. For this case, the maximum relative displacement is approximately 0.5 m in 6 m (1.8 ft in 20 ft.)

Calculation of the maximum vertical relative displacement is important only if the designer can estimate the impact of such displacement on the site-specific cap profile. MTG barrier systems consist of a geomembrane and a clay layer, both of which must be separately evaluated for strain. The strains in the geomembrane can be estimated using one of two models, depending on the type of anticipated subsidence.
For trench-like subsidence, the strains can be calculated using the model shown in Figure 11-4. The maximum strain that the geomembrane can tolerate in such a plane strain condition is given by the uniaxial test data commonly reported by geomembrane manufacturers (see Figure 11-5).

For spherical-type subsidence, the strains in the geomembrane can be calculated using the method discussed in Chapter 3 of this manual. For such an assumed failure mode, the designer must compare the predicted strain with the ultimate strain limit of the geomembrane, as obtained from biaxial testing (see Figure 11-5). Chapter 3 gives additional data on typical ultimate strains of common geomembranes in biaxial loading. Most geomembranes can easily tolerate vertical differential settlement of the cover in excess of 0.9 m in 3 m (3 ft in 10 ft) of run. This results in a factor of safety based on an ultimate strain of 3.3 for the geomembrane in Case 1.

The strain in the soil component of the barrier can be estimated using the chart in Figure 11-6. The specific ultimate tensile strain of the onsite soil can be evaluated in a triaxial Consolidated Isotropic Undrained (CIU) test or can be estimated from the chart in Figure 11-7. For this particular soil barrier, the ultimate relative strain allowable under this criteria is 0.4 m in 3 m (1.2 ft in 10 ft) of run. This results in a factor of safety of 1.33 for the clay component in Case 1. If the settlements are occurring over an extended length of time, this low factor of safety may be acceptable due to the ability of a clay to creep. The creep deformation of the clay allows long-term strains to develop in the layer without a comparable increase in stress. This is commonly referred to as "stress relaxation."

Gas Collection Systems

Commercial hazardous waste facilities generate minimal gas due to the solidified nature of the waste. Typically, gas collection systems for such facilities are simple linear French drain collectors, as shown in Figure 11-8.

Extreme caution must be exercised in designing gas removal systems for wastes that have a long anticipated lifetime. A gas removal system is a very efficient vehicle for surface water to gain access to the waste if the vent pipes become damaged. Thus, if long-term maintenance of the cap cannot be assured, a gas collection system may eventually cause failure of the cap to perform its primary function—preventing surface water from reaching the waste. Provisions should be made in the permit of
such facilities for removing and sealing the gas vents if postclosure monitoring indicates that no appreciable quantities of gas are being generated.

As a final comment, the HELP analysis (see Chapters 8 and 9) for such caps must assume an effective leakage for the geomembrane component of the barrier. This leakage is commonly calculated by assuming from 9 to 13 penetrations (1 cm) per acre in the geomembrane. The leakage through such penetrations can then be calculated using the following equation (5):

\[ Q = 3 \ a^{0.75} \ h^{0.75} \ K_d^{0.5} \]

where

- \( Q \) = steady-state leakage rate (\( \text{m}^3/\text{sec} \))
- \( a \) = area of hole (\( \text{m}^2 \))
- \( h \) = head of leachate (\( \text{m} \))
- \( k \) = permeability of underlying soil (\( \text{m}/\text{s} \))

A revised version of HELP is being developed that will accept such penetration data directly.

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**CASE 2: RCRA INDUSTRIAL LANDFILL**

The second case study shows a cap profile that is becoming increasingly common in Europe and the United States due to the high cost per acre of composite lined landfills. As shown in Figure 11-9, the cap has two significant profiles: a steep perimeter that provides for the volume of the facility and a flatter top that covers the majority of the waste. Figure 11-9 also shows a detail of the cap profile which is a typical MTG profile. The key design problems for this case involve the steep perimeter of the cap, including both the sliding stability of such covers and the erosion resistance of their protective surface.

The slope stability of covers, or liner systems, containing geosynthetic layers is typically of concern if the slope exceeds 8 degrees. The three horizontal to one vertical (3H:1V) slopes of the perimeter are 18.4 degrees and, therefore, of concern. The stability of cover and liner systems on such slopes is evaluated by performing laboratory direct shear tests on each suspect interface to determine the minimum factor of safety against sliding.
Figure 11-3. Case 1—Cumulative subsidence.

Figure 11-4. Case 1—Geomembrane strains in trench subsidence.
Figure 11-5. Case 1—Uniaxial and biaxial geomembrane response.

Figure 11-6. Case 1—Subsidence strain in soil barrier.
Figure 11-7. Case 1—Ultimate tensile strain in clays.

This testing procedure is described in greater detail in Chapter 3 (pp. 3-4) and Appendix A. Steep covers requiring a geomembrane commonly use three liner/drainage layer profiles to provide a stable slope:

1. A textured HDPE or VLDPE geomembrane with either a sand drainage layer or a drainage layer formed using a geonet with filter fabric bonded to both faces.
2. A geomembrane having nonwoven geotextiles bonded to both faces and a sand drainage layer.
3. A smooth geomembrane, sand, or geonet drain, with an added geogrid reinforcement in the cover soil layer to hold the layer on the slope.

The first two alternatives are examined for this case; Case 3 discusses the third alternative.

Figure 11-10 shows direct shear data for the first alternative. Because the nonwoven material used in the bonded geomembrane will develop the full shear strength of the adjacent soil, direct shear tests are not commonly performed for this material. Therefore, with both the tested textured and bonded geomembrane, the minimal interface friction angle will be significantly greater than the 18.4 degree sideslope angle. It must be noted that such interface friction angles must be verified in laboratory testing; not all textured geomembranes are effective.

The owner/operator must use caution in interpreting direct shear data from evaluations of interface friction angles. A recent full-scale field test of various cover profiles demonstrated that the interface friction angle is very dependent on the normal force acting on the layers (6). Thus, direct shear data from tests for cap design using low normal loads should not be used for designing liner interfaces where high normal loads are anticipated. This dependency also makes the use of interface friction angles obtained from the literature very suspect.

Laboratory direct shear tests should be performed using the soils, geosynthetics, and normal loads associated with the site-specific conditions.

The steep perimeter slopes must be verified as satisfying the MTG criteria of a cover soil loss of less than 2 tons/acre/year. The rate of soil loss is verified using the Universal Soil Loss Equation (USLE) given by:

$$ A = R K L S C P $$

where

- $K$ = soil erosion factor from Table 11-1
- $LS$ = slope constant from Figure 11-11
- $R$ = rainfall and runoff index
- $C$ = cover management factor
- $P$ = practice factor, 0.3 to 1.0

EPA proposed a procedure to calculate an effective LS factor for caps having two distinct slopes, as found in this case (7). This method, however, is not currently recommended because it underestimates true soil loss. For caps having two very distinct slopes, it is more effective to evaluate each slope independently and to provide a runoff collection ditch, e.g., swale, between the slopes to hydraulically disconnect these features in the field. Thus, the 3H:1V perimeter slopes of Case 2 should be evaluated using their maximum slope length and full
slopes. Calculations of annual soil loss for the 3H:1V side slopes were performed using the following values for the USLE variables:

- R = 140 — from local SCS
- K = 0.3, sandy loam from Table 11-1
- C = 0.006 — from local SCS
- P = 1.0, maximum value
- L = slope length = 15 m (50 ft)
- S = slope = 3H:1V = 33 percent

These values and the LS topographic factor obtained from Figure 11-11 yielded an annual soil loss of 1.8 tons/acre/year, which is acceptable.

Caps having two distinctive slopes may be designed using two distinctive methods of cover protection.

Figure 11-12 shows one early scheme that incorporated an armoring cover of coarse gravel on the steeper slope. In this example, a swale is not provided between the slopes due to the high transmissivity value of the gravel. In general, however, such slopes should be separated by a swale to make them hydraulically independent.

CASE 3: CERCLA LAGOON CLOSURE

In this case, sediments from three industrial settling lagoons were consolidated to a single mound, as shown in Figure 11-13. The sediments contained RCRA constituents, but the age of the waste and the use of existing lagoons for the consolidated facility made RCRA MTG not applicable. The nature of the sediments and general site conditions, however, made RCRA MTG appropriate and relevant (see Chapter 1). Thus, the cap for the consolidated sediment mound is essentially an MTG cap.
Figure 11-9. Case 2—Cap profile and geometry.

Figure 11-10. Case 2—Direct shear data: texture HDPE.
Table 11-1. Soil Texture Constant for Soil Loss Evaluation

<table>
<thead>
<tr>
<th>Texture class</th>
<th>Organic matter content</th>
<th>K</th>
<th>K</th>
<th>K</th>
</tr>
</thead>
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<tr>
<td></td>
<td>&lt; 0.5 per cent</td>
<td>0.05</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>2 per cent</td>
<td>0.16</td>
<td>0.14</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>4 per cent</td>
<td>0.42</td>
<td>0.36</td>
<td>0.23</td>
</tr>
<tr>
<td>Sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine sand</td>
<td></td>
<td>0.12</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>Very fine sand</td>
<td></td>
<td>0.34</td>
<td>0.20</td>
<td>0.16</td>
</tr>
<tr>
<td>Loamy sand</td>
<td></td>
<td>0.44</td>
<td>0.38</td>
<td>0.30</td>
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<td></td>
<td>0.27</td>
<td>0.24</td>
<td>0.19</td>
</tr>
<tr>
<td>Loamy sandy loam</td>
<td></td>
<td>0.35</td>
<td>0.20</td>
<td>0.24</td>
</tr>
<tr>
<td>Fine sandy loam</td>
<td></td>
<td>0.47</td>
<td>0.41</td>
<td>0.33</td>
</tr>
<tr>
<td>Very fine sandy loam</td>
<td></td>
<td>0.38</td>
<td>0.34</td>
<td>0.29</td>
</tr>
<tr>
<td>Loam</td>
<td></td>
<td>0.48</td>
<td>0.42</td>
<td>0.33</td>
</tr>
<tr>
<td>Silt</td>
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<td>0.60</td>
<td>0.52</td>
<td>0.42</td>
</tr>
<tr>
<td>Sandy clay loam</td>
<td></td>
<td>0.27</td>
<td>0.25</td>
<td>0.21</td>
</tr>
<tr>
<td>Clay loam</td>
<td></td>
<td>0.28</td>
<td>0.25</td>
<td>0.21</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td></td>
<td>0.37</td>
<td>0.32</td>
<td>0.26</td>
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<tr>
<td>Sandy clay</td>
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<td>0.14</td>
<td>0.13</td>
<td>0.12</td>
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<tr>
<td>Silty clay</td>
<td></td>
<td>0.25</td>
<td>0.23</td>
<td>0.19</td>
</tr>
<tr>
<td>clay</td>
<td></td>
<td>0.13-0.39</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The values shown are estimated averages of broad range of specific-soil values. When a texture is near the borderline of two textural classes, use the average of the two K values. For specific soils, use of Figure 2.6 or Soil Conservation Service K-value tables will provide much greater accuracy. From ARS, 1978.

Figure 11-11. Case 2—Slope factors for soil loss evaluation.

Figure 11-12. Case 2—Slideslope armoring scheme.

(see Figure 11-13). A key variation, however, is the use of a commercial bentonite board in place of the compacted clay component of the composite barrier system.

As in Case 2, the combination of steep slopes and geosynthetic interfaces made slope stability a concern for this cap. Direct shear tests of the geosynthetic interfaces indicated that the governing interface was between the PVC geomembrane and the geotextile forming the surface water of the bentonite board. Additionally, as the bentonite board hydrates, it loses significant shear strength. In general, the hydrated bentonite board is not stable on slopes steeper than 9 degrees. To ensure stability of the drainage layer and cover soil, the design incorporated geogrid soil reinforcement into the cap. Chapter 3 discusses the calculations required to confirm the ability of the geogrid. It is important that the strain assumed in selecting available geogrid tensile strength be small enough that excessive elongation of the geogrid does not occur. The 5 percent strain assumed in this Case 3 analysis is the maximum strain that should be used.
In addition to having sufficient tensile strength, the geogrid must be anchored sufficiently to develop this strength. It cannot be anchored using an anchor trench without impinging on the waste. The geogrid in Case 3, therefore, is anchored by running the grid continuously over the cap and counterbalancing the weights of the cover soils on opposing faces. While this procedure is technically simple, it restricts, construction significantly; the cover soil and drain must be placed in a symmetrical manner, preferably from the top down, to tension the geogrid. Figure 11-14a shows the geogrid being placed over the geomembrane, and Figure 11-14b shows the drain layer being placed on top of the geogrid.

Water collected in the surface water drainage layer must be allowed to freely leave that system to avoid building up head on the liner, and to maintain stability. Figure 11-15a shows the sideslope toe drainage detail used in Case 3. From a long-term maintenance standpoint, this drainage system is very poor. The thin layer of loam topsoil will readily erode at the surface interface with the geotextile and trap rock, as shown on Figure 11-15b. Surface water drainage layers in caps having significant slopes, such as in Case 3, should outlet using pipe laterals placed at a minimum of one 40-cm (4-in.) drain pipe every 61 m (200 ft) around the perimeter of the surface drain.

**CASE 4: CERCLA LANDFILL CLOSURE**

The fourth case study is of a cover placed over an existing MSW landfill that received 20,000 yd$^3$ (15,292 m$^3$) of baghouse dust containing cadmium, chromium, and lead. The baghouse dust was placed on top of the MSW waste and was, therefore, highly exposed. The landfill itself was adjacent to a community park and the local youths had established biking paths over the landfill. Both the state and the principal responsible party (PRP) wanted to close the landfill in a manner that prevented surface water from reaching the dust and discouraged the recreational use of the cap. For these reasons, they selected a unique hardened cap profile. Such hardened caps do not promote recreational use of the cover and, therefore, do
Figure 11-14a. Case 3—Placement of geogrid over geomembrane.

Figure 11-14b. Case 3—Placement of drainage layer over geogrid.
Figure 11-15a. Case 3—Outlet detail for sideslope toe surface water drainage layer.

Figure 11-15b. Case 3—Erosion at drainage layer outlet.
not create an attractive nuisance in terms of maintenance and security. Figure 11-16 shows the final cap profile and contours.

The cap profile is significantly different than the MTG cap in that it uses no drainage or agricultural layers. The asphalt and paving fabric form a unique composite barrier with the compacted clay cap. The chip seal added to the top of the barrier is provided to protect the asphalt and paving fabric from ultraviolet (UV) light degradation, not for erosion control. The "hardened" cap is advantageous since it is not an attractive nuisance, requires very low maintenance, and minimizes the problem of volunteer vegetation.

The geotextile was placed over the asphalt on a surface of asphalt emulsion (see Figure 11-17a). Rolling the fabric over the hot emulsion fully impregnated the geotextile so that it acts as a water barrier. The chip seal placed on top of the geotextile (see Figure 11-18b) is bonded to the geotextile by the emulsion, in a manner similar to an industrial roofing system.

While the hardened cap is low maintenance, it does require an annual inspection and renewal of the chip seal surface every 5 years. Additionally, the perimeter drainage must be cleaned regularly to promote surface water drainage. Allowable differential subsidence criteria must be established for such caps in the same manner as described for Case 1.

Similar hardened caps have been used on RCRA closures in the Southeast. One particular closure at a Department of Energy facility in Tennessee functions as a parking lot. This particular cap replaced the agricultural layer of the MTG profile with an asphalt and subbase parking surface. While such caps must obviously be inspected on a regular basis, they can offer significant maintenance and land use advantages.

**CASE 5: MSW COMMERCIAL LANDFILL**

This last example, Case 5, shows how the basic RCRA/CERCLA closure profiles are being adapted for the more common MSW landfills. The cap profile shown in Figure 11-18 includes a composite barrier layer and a protective/agricultural soil cover. It does not include a drainage layer between the barrier layer and the cover soil. The drainage layer is often omitted in MSW caps. In particular, states such as New York (8) have chosen not to require the drainage layer due to concerns regarding

**Figure 11-16. Case 4—Cap profile and geometry.**
Figure 11-17a. Case 4—Placement of geotextile on asphalt emulsion.

Figure 11-17b. Case 4—Placement of chip seal on geotextile.
the impact of this layer on the agricultural growth placed over the cap. It should be noted, however, that New York requires a liner system beneath all new landfills that actually exceeds RCRA MTG criteria. Thus, the omission of the drainage layer was not for financial reasons.

Contours for the Case 5 cap are shown in Figure 11-18 and reflect the dual slope profile developed in Case 2. The general goals for the MSW cap are low maintenance, minimization of infiltration, and aiding in gas collection/containment. MSW caps commonly cannot be constructed on new landfills in a single stage as can RCRA and CERCLA caps. The staged construction of a MSW cap is required because lined MSW landfills typically are divided into adjacent cells, with each cell built to contain 4 to 6 years of waste. Figure 11-19 shows the profile of the MSW facility with two cells having a common cover.

Facilities have been permitted with more than 10 such cells beneath a common cover. Such facilities eliminate the long-term exposure of the liner system that would result if a single large cell was constructed, and do not lose the airspace between the cells that would occur if individual covers were placed on each cell.

It is necessary to incrementally cap a facility that has multiple adjacent cells to prevent excessive leachate generation. Strategies for incremental cap construction should be reviewed as part of the permitting process. Such strategies should provide for drainage swales spaced at intervals of no more than 6.1 m (20 ft) of vertical grade change over the cap to control surface water runoff.

MSW gas collection systems are commonly either blanket collectors with passive vents or active systems.
using discrete wells. Figure 11-20 shows the proposed active well array for Case 5. Each well consists of a perforated plastic pipe within a gravel screen. The top of the pipe will penetrate the low hydraulic conductivity barrier, and must be sealed at the soil barrier using a bentonite seal and at the geomembrane barrier using a boot/clamp fixture. As the waste subsides, the gas well pipe will move upward relative to the cap geomembrane. The flexible boot between the pipe and the cap geomembrane must be installed to allow such differential movements. The boots commonly are improperly installed upside down, e.g., they allow movement of the pipe downward relative to the cap geomembrane. This installation, however, must be avoided to prevent damage to the geomembrane seal. This seal not only limits surface water infiltration, but also aids in maintaining the low vacuum required for active gas removal.

The use of a geomembrane in the liner and the cap will eliminate the lateral migration of gas if the geomembranes are intact. Perimeter gas monitoring wells (see Figure 11-21) provide an indication of the condition of the liner and the cap. Such wells are installed at 152- to 305-m (500- to 1,000-ft) spacings around the perimeter of the landfill. Most states now limit gas concentrations in such wells to less than 25 percent of the lower explosive limit of the methane.

CONCLUSIONS

The five case studies presented in this chapter illustrate the need to closely evaluate the stability of closure systems related to sliding at the interfaces of the layers making up the cap, and alternatives for controlling surface erosion. Additionally, these cases highlight the following permit considerations:

1. The permit should contain requirements for regular monitoring of cap subsidence, criteria for allowable differential cap subsidence, and an agreed-upon method for repair of excessive subsidence.

2. Poorly maintained gas collection systems can allow surface water through the cap. Passive vents should be minimized and protected from damage. Active gas wells will move upward relative to the cap and may damage the cap barrier. Such wells should be inspected regularly and removed when no longer in production.

3. All erosion control systems require maintenance and regular inspection. The limits of both should be established in the permit.

CERCLA caps in particular require careful evaluation to determine which of the RCRA MTG cover components are appropriate for the specific site and waste.

REFERENCES


Figure 11-19. Case 5—Profile showing MSW subcells.
Figure 11-20. Case 5—Gas collector well array.

Figure 11-21. Case 5—Perimeter gas monitoring well.


ADDITIONAL REFERENCES


CHAPTER 12
POSTCLOSURE MONITORING

INTRODUCTION
The owner/operator of a facility must give significant consideration during the closure permit process as to the nature and extent of postclosure monitoring that will be required. While regulatory postclosure monitoring time frames range from 30 years for RCRA wastes to 500 years for mixed wastes (10 CFR 61), the actual monitoring period will be influenced by the stability of the waste and cover system. The permit should establish monitoring procedures, acceptance criteria, and remediation methods for the following key parameters:

1. **Ground-water quality** and potentiometric surface should remain within the limits established in permitting.

2. **Leachate quantities** and chemical makeup should remain predictable.

3. **Gas release concentrations** and general air quality must remain within guidelines. Such guidelines will become stricter with time.

4. **Differential subsidence** of the cover must be limited and repaired if allowable limits are exceeded.

5. **Surface erosion** must stay within the 2 ton/year allowable and be repaired on an annual basis.

The key elements in the monitoring program that must be established during permitting are detection methods, allowable limits, and the plan for remediation when limits are exceeded.

GROUND-WATER MONITORING
Key monitoring variables in a comprehensive ground-water monitoring program include both changes in the potentiometric surface that could bring the landfill liner system in contact with the ground water and the chemical quality of the ground water that is an indicator of leachate release. In RCRA facilities, both the potentiometric and background water quality will be established during permitting of the landfill prior to placement of the waste. For CERCLA facilities, such information should be established during the closure permit process.

A ground-water well network must be established that both tracks changes in the ground-water potentiometric surface and detects leakage from the facility. In both RCRA and CERCLA facilities, the background quality of the ground water must be documented prior to closure. Individual monitoring wells must be designed to reflect both the anticipated contaminant and the site-specific stratigraphy. Figure 12-1 shows a typical well configuration. The well casing will commonly be PVC for inorganic contaminants and stainless steel for organic contaminants. While monitoring wells have become very standardized, it is important to specify locking well caps that prevent tampering of the well, well seals that restrict surface water flow into the well, and solvent free well pipe connections that do not contaminate the well.

In CERCLA sites, great care must be taken during the placement of monitoring wells and during any soil borings to avoid penetrating an aquiclude (low hydraulic conductivity soil layer) that may lie underneath contaminated ground water. Figure 12-2 shows such a potential stratigraphy. When placing monitoring wells through an aquiclude, a casing must first be installed from the ground to the aquiclude. A grout seal is then established to hydraulically isolate this casing from the aquiclude, and the monitoring well is drilled to the upper aquifer within the casing. In this manner, the contamination from the upper aquifer will not contaminate the lower aquifer.

Ground water should be sampled at a frequency defined by the level of anticipated contamination and the site conditions. Generally, it is useful to have monthly ground-water background data prior to permitting operation or closure of a facility. Post-operation sampling frequency then can be decreased to quarterly monitoring, which should be maintained unless the consistency of measurements and operation justify sampling less frequently. Postclosure monitoring frequencies commonly range from quarterly for lined RCRA facilities to annually for common MSW landfills.

LEACHATE MONITORING
Both the quantity and composition of leachate generated within a RCRA facility provide significant information on the performance of the closure system. If the closure system is properly designed and installed, the rate of leachate generation in the primary collector will decrease with time. If the closure is not complete, then the rate of
Figure 12-1. Monitoring well configuration.

Figure 12-2. Monitoring interbedded aquifer.
leachate generation in the primary collector may reflect precipitation trends. Therefore, the integrity of the closure can be verified by evaluating leachate quantity records. A sudden increase in the quantity of leachate generated will clearly indicate failure of the closure. Unfortunately, many CERCLA facilities will lack a liner and primary collector system.

The concentration of contaminants in a facility’s leachate will increase with time until an equilibrium condition is established. A sudden reduction in this level of contaminants is a good indication that the cover has been breached, allowing a slug of surface water to enter the waste and dilute the leachate. Biological growth, however, can also have a significant impact on the monitoring system over the long term. Figure 12-3 shows impact of biological growth in municipal solid waste (MSW) leachate on the permeability of a geotextile filter commonly used in collector systems (1). The time, T, for significant reduction in permeability may be as short as 6 weeks. Thus, a long-term decrease in the amount of leachate generated may indicate biological clogging of the collector, which may prevent detecting failure of the closure. Such biological clogging occurred recently in a MSW landfill in Delaware. A significant head of perched leachate was discovered within the waste while the quantity of leachate generated was actually decreasing. This clogging required excavation of the waste and replacement of the primary collector system.

GAS GENERATION

Gas generation within a waste containment system must be monitored both to ensure that such gas does not
Table 12-1. Threshold Limits of Air Contamination

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>TLV</th>
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<tr>
<td>Dust</td>
<td>1 mg/m³</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>50 ppm</td>
</tr>
<tr>
<td>Asbestos</td>
<td>0.2 to 2 fibers/cm³ (depending on asbestos type)</td>
</tr>
<tr>
<td>Benzene</td>
<td>10 ppm</td>
</tr>
<tr>
<td>Coal dust</td>
<td>2 mg/m³</td>
</tr>
<tr>
<td>Cotton dust</td>
<td>0.2 mg/m³</td>
</tr>
<tr>
<td>Grain dust</td>
<td>4 mg/m³</td>
</tr>
<tr>
<td>Hydrogen sulfide</td>
<td>10 ppm</td>
</tr>
<tr>
<td>Nuisance particulates</td>
<td>10 mg/m³</td>
</tr>
<tr>
<td>Phenol</td>
<td>5 ppm</td>
</tr>
<tr>
<td>Vinyl chloride</td>
<td>5 ppm</td>
</tr>
<tr>
<td>Wood dust</td>
<td></td>
</tr>
<tr>
<td>Hard wood</td>
<td>1 mg/m³</td>
</tr>
<tr>
<td>Soft wood</td>
<td>5 mg/m³</td>
</tr>
</tbody>
</table>

*Values of TLV obtained from the American Conference of Governmental Industrial Hygienists (1987).

...migrate off site and to indicate closure performance. The rates of gas generation vary from more than 900 liters/kg waste/year in MSW wastes (2) to insignificant rates in RCRA commercial landfills. The rate of gas generation in future MSW landfills is anticipated to decrease as these landfills are constructed with liners and leachate collection systems. The addition of a geomembrane in the cover will significantly decrease the amount of surface water infiltration and also lead to lower gas generation rates.

When geomembranes are used in a cover, very little gas can escape vertically. Therefore, in an unlined facility, such as a typical CERCLA closure, escaping gas will move to the perimeter of the cover. Simple gas monitoring wells (described in Chapter 11, Case 5) must be installed around the perimeter of the cover to detect laterally moving gas. The level of gas at such wells must remain below 25 percent of the lower explosive limit (LEL). The level of gas production can vary significantly with the weather; therefore, the monitoring frequency should be increased when the surrounding ground is saturated or frozen.

Gas odors detected above a closure system that includes a geomembrane indicate that the geomembrane has a significant penetration. A regular survey of gas levels on the surface of the closure is a good method of verifying the integrity of the cap barrier.

As detailed in Chapter 11, gas removal systems must be designed with a minimal number of penetrations through the cover system. Each vent is a potential major leak. For passive systems, a maximum of one vent per acre should be included initially. If monitoring of these vents reveals excessively high gas concentrations, then additional wells can be installed. In active systems, gas wells must be removed when they are no longer productive to prevent damage to the cover.

As with leachate quantities, the rate of gas generation should also decrease with time if the cover system is functioning properly such that moisture does not reach the waste. Figure 12-4 shows the result of laboratory column gas generation tests (3). In the figure, methane production rate and the level of carboxylic acids in the leachate decrease with time. A properly functioning cover will ensure that the leachate will remain acidic and that gas production will be low.

SUBSIDENCE MONITORING

Chapter 11 discusses the ability of the cap barrier components to tolerate differential settlements due to waste subsidence. In Case 1, differential settlements as large as 0.5 m in 6 m (1.8 ft in 20 ft) were tolerated by composite barriers. Thus, the level of differential settlements of interest during postclosure monitoring can be quite large. Such levels can commonly be found by walking the cover after a rain storm and looking for major puddles or ponding. Subsidence depressions also can be found through an annual survey of the cover using either conventional or aerial survey methods.

Subsidence depressions must be remediated below the level of the barrier system to avoid long-term acceleration of the subsidence due to a "roof ponding" mechanism. Roof ponding refers to the common failure in flat roof systems where ponding water causes the roof ratters to deflect, thus allowing more water to pond, causing more deflection, and so on. This mechanism continues until the roof collapses. Remediation requires removing the cover system in the region of subsidence and backfilling the depression with lightweight fills. This fill may either be
more waste or commercial lightweight aggregates. The full cover profile must then be rebuilt over the new fill.

**SURFACE EROSION**

All cover systems will erode and require long-term maintenance. Cover systems with moderate slopes and an agricultural cover will typically require annual maintenance of 0.5 percent of their surface area; this percentage increases with slope. Thus, all covers that use agricultural covers require an annual inspection and repair program. Such repair may include cleaning out surface water swales, replacing cover soil, and reestablishing vegetation. Areas of the cover requiring repeated repair may benefit from hardening or the use of geosynthetic erosion control blankets. Covers that use hardened erosion control systems should also be inspected annually, though annual maintenance should not be required.

The annual inspection should verify that the agricultural cover is being mowed at least annually to prevent the growth of deep-rooted volunteer vegetation. In arid regions of the country or during droughts, full RCRA covers may not be able to maintain vegetation unless the plants are very drought resistant. This loss of vegetation is due to moisture loss in the root zone of the cover soil, resulting from the underlying drainage system.

**AIR QUALITY MONITORING**

Air emissions from waste storage facilities will come under increasing scrutiny in the next decade. Monitoring techniques will be similar to those used at industrial facilities and include passive samples obtained using collection media, grab samples obtained in evacuated sample vessels, and active pump and filter samples. The most common air contaminants coming from the waste disposal cell obviously are waste dependent; for MSW wastes, these are methane, vinyl chloride, and benzene. Table 12-1 presents typical allowable limits of selected air contaminants. Such limits are currently undergoing extensive review; significantly lower allowable levels are anticipated for future operations.

The geomembrane component of the MTG cover composite barrier system controls air emissions significantly. In fact, the presence of emissions indicates that the geomembrane cover has failed and needs to be repaired immediately.

**REFERENCES**

1. Unpublished research at Geosynthetic Research Institute, personal communication with R.M. Koerner.