Lecture 23

Requirements for Landfill Closure and Monitoring
6.2 FINAL COVER DESIGN

40 CFR §258.606.2.1 Statement of Regulation

(a) Owners or operators of all MSWLF units must install a final cover system that is designed to minimize infiltration and erosion. The final cover system must be designed and constructed to:

1. Have permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, or a permeability no greater than 1 × 10⁻⁵ cm/sec, whichever is less, and

2. Minimize infiltration through the closed MSWLF unit by the use of an infiltration layer that contains a minimum of 18-inches of an earthen material, and

3. Minimize erosion of the final cover by the use of an erosion layer that contains a minimum 6-inches of earthen material that is capable of sustaining native plant growth.
Solid waste landfill closure under RCRA

<table>
<thead>
<tr>
<th>Vegetative Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topsoil (6 inches minimum)</td>
</tr>
<tr>
<td>Infiltration Cover with $K &lt; 1 \times 10^{-5}$ (18 inches minimum)</td>
</tr>
<tr>
<td>Solid waste</td>
</tr>
</tbody>
</table>
Closure of hazardous waste landfill

Requirements for RCRA hazardous waste facilities (Subtitle C) are substantial:

Includes multi-layer cap:
- Low hydraulic conductivity soil/geomembrane layer
- Drainage layer
- Vegetation soil layer

Closure of hazardous waste landfill

- Solid waste
- Gas Vent Layer (optional)
- Geotextile
- FML
- Compacted clay
- Geotextile
- Drainage Layer
- Protection (cobble) layer
- Top Soil Cover
- Vegetative Cover
Components of RCRA cap

Vegetation layer
  Provides vegetation growth
  Provides erosion control
  Reduces infiltration by plant transpiration

Protection layer is optional but provides:
  Freeze-thaw protection
  Medium for root growth
  Possibly rodent protection using cobbles
Components of RCRA cap

Drainage layer
- Drains infiltrated water
- Gravel or geonet
- Designed based on results of HELP model (usually with factor of safety)

Low-permeability barrier layer
- Made of compacted clay, GCL, or composite
- 60-cm (2-ft) clay liner is considered minimum
- 40 mil minimum thickness
Components of RCRA cap

Gas vent layer

Usually coarse grained sand or geonet or thick geotextile
Provides stable layer for construction of barrier layer

Maintenance issues (particularly for compacted clay liners):

Desiccation cracking
Freeze/thaw
Differential settlement of waste and tensile cracking of cover
Evapotranspiration landfill

Relatively new alternative for capping landfills in arid areas
Relies on evapotranspiration to keep moisture out of waste
EPA Fact Sheet:
http://www.epa.gov/superfund/new/evapo.pdf
### Monolithic ET cover

<table>
<thead>
<tr>
<th>Vegetative Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine-grained layer (silt or clayey silt)</td>
</tr>
<tr>
<td>(2 feet to 10 feet)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interim cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid waste</td>
</tr>
<tr>
<td>Layer</td>
</tr>
<tr>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>Vegetative Cover</td>
</tr>
<tr>
<td>Fine-grained layer (silt or clayey silt)</td>
</tr>
<tr>
<td>Capillary barrier (coarse-grained layer)</td>
</tr>
<tr>
<td>Interim cover</td>
</tr>
<tr>
<td>Solid waste</td>
</tr>
</tbody>
</table>

Capillary barrier ET cover
ET cover design

Fine-grained layer stores water until evaporated or transpired
Capillary barrier minimizes downward percolation from fine-grained layer
Layers are designed using water-balance model like HELP to select proper soils and layer thicknesses for climate at the landfill
Alternative Landfills Test Site

## Tested landfill cover designs

### Table 1. Landfill cover design characteristics

<table>
<thead>
<tr>
<th>Landfill Cover Design</th>
<th>Thickness</th>
<th>Layers</th>
<th>Components Description/Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCRA Subtitle D Cover</td>
<td>60 cm</td>
<td>2</td>
<td>Top vegetation/soil layer – 15 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Compacted native soil -- 45 cm</td>
</tr>
<tr>
<td>RCRA Subtitle C Cover</td>
<td>150 cm</td>
<td>4</td>
<td>Top vegetation/soil layer – 60 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sand drainage layer – 30 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Geomembrane -- 40-mil</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Compacted bentonite-amended soil – 60 cm</td>
</tr>
<tr>
<td>Geosynthetic Clay Liner (GCL) Cover</td>
<td>90</td>
<td>4</td>
<td>Top vegetation/soil layer – 60 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Geotextile filter fabric</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sand drainage layer – 30 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Geomembrane -- 40 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Geosynthetic clay liner</td>
</tr>
<tr>
<td>Capillary Barrier Cover</td>
<td>140 cm</td>
<td>4</td>
<td>Top vegetation/soil layer – 30 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Upper sand drainage layer -- 15 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Upper gravel drainage layer -- 22 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Compacted barrier soil layer -- 45 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower sand drainage layer -- 15 cm</td>
</tr>
<tr>
<td>Anisotropic Barrier Cover</td>
<td>105 cm</td>
<td>4</td>
<td>Top vegetation/soil layer – 15 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Native soil cover layer -- 60 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Fine sand interface layer -- 15 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pea gravel sublayer -- 15 cm</td>
</tr>
<tr>
<td>Evapotranspiration Soil Cover</td>
<td>90 cm</td>
<td>2</td>
<td>Top vegetation/soil layer – 15 cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Compacted native soil layer -- 75 cm</td>
</tr>
</tbody>
</table>
Cover performance

![Graph showing flux rates (mm/yr) for different cover types: Subtitle D, GCL, Subtitle C, Capillary barrier, Anisotropic barrier, and ET cover.](https://apps.em.doe.gov/ost/pubs/itsrs/itsr10.pdf)

Landfill settlement

Initial Configuration

Waste fill
Daily cover
Lift of waste fill
Daily cover
Waste fill

Final Configuration

Assimilated daily cover

Boundaries of waste fill

Absorption of daily cover into waste fill.

Landfill settlement

Possible settlement curves for dense and light fills.

Landfill settlement

Results of nine-year study of three landfills in Los Angeles

Diagram showing notations used in analysis.

Landfill settlement

 Settlement rates versus time elapsed for fill depths between 40 ft and 80 ft (12 m and 24 m).

Equations for landfill settlement

Qian et al. (2002) formula for long-term secondary settling:

\[ \Delta H_\alpha = C_\alpha \, H_0 \, \log(t_2/t_1) \]

where:

- \( \Delta H_\alpha \) = settlement (length units)
- \( C_\alpha \) = secondary compression index = 0.03 to 0.1
- \( H_0 \) = initial waste thickness (length units)
- \( t_1 \) = starting time
- \( t_2 \) = ending time
Equations for landfill settlement

Numerous empirical equations to predict settlement are in the literature—see Qian et al. (2002) for good summary.
Surface-water runoff & drainage control

Runoff-induced erosion can be an important factor in safe landfill closure.

Control of stormwater runoff is an issue since capped landfill is likely to have greater runoff than pre-development condition and must be controlled to prevent effects on neighbors.
Stormwater design

Usually based on rational formula

In English units:

\[ Q = CiA \]

- \( Q \) = peak rate of runoff (ft^3/sec)
- \( C \) = runoff coefficient
- \( i \) = rainfall intensity (inches) during time of concentration of drainage area (in/hr)
- \( A \) = basin area (acres)
Stormwater design

In Metric units:

\[ Q = \frac{CiA}{360} \]

- \( Q \) = peak rate of runoff (m\(^3\)/sec)
- \( C \) = runoff coefficient
- \( i \) = rainfall intensity (mm) during time of concentration of drainage area (mm/hr)
- \( A \) is basin area (ha)

Rational formula recommended for basins up to 200 acres (81 hectares)
Rainfall intensity

i comes from rainfall-frequency-duration data for location of landfill

Rainfall-frequency-duration data come from long-term rainfall records

Usual source in US:

National Weather Service TP40

IDF curve for Boston
Stormwater calculations

Pick $i$ corresponding to basin time of concentration

(Note inconsistency in EPA requirements which specify 25-year, 24-hour storm. This should apply only to basin with 24-hour time of concentration.)
Time of concentration

$T_C = \text{travel time from hydraulically most distant point in watershed to outlet}$

Rainfall intensity, $i$

Basin outflow, $Q$

$T_C$
Time of concentration

Determined by routing flow over different portions of flow path:
- Overland flow
- Shallow concentrated flow
- Channel flow

Use nomograph for small area like a landfill
Time of concentration nomograph for overland flow

A nomograph of overland flow time. (10) Enter left margin with slope length; move right to slope curve and down to $C$ value; and find overland travel time on right margin.

Time of concentration nomograph for small drainage basins

Example
Height = 100 Ft.
Length = 3,000 Ft.
Time of concentration = 14 Min.

Note:
Use nomograph $T_c$ for natural basins with well defined channels, for overland flow on bare earth, and for mowed grass road-side channels.
For overland flow, grassed surfaces, multiply $T_c$ by 2.
For overland flow, concrete or asphalt surfaces, multiply $T_c$ by 0.4.
For concrete channels, multiply $T_c$ by 0.2.
Rational coefficient, C

James Dooge’s rule of thumb:

\[ C = \frac{\sqrt{H}}{10} \]

where:

\[ H = \text{houses/acre} \]
# C for landfills:

<table>
<thead>
<tr>
<th>Soil</th>
<th>Slope</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy</td>
<td>Flat (≤ 2%)</td>
<td>0.05-0.10</td>
</tr>
<tr>
<td></td>
<td>Average (2-7%)</td>
<td>0.10-0.15</td>
</tr>
<tr>
<td></td>
<td>Steep (≥ 7%)</td>
<td>0.15-0.20</td>
</tr>
<tr>
<td>Clayey</td>
<td>Flat (≤ 2%)</td>
<td>0.13-0.17</td>
</tr>
<tr>
<td></td>
<td>Average (2-7%)</td>
<td>0.18-0.22</td>
</tr>
<tr>
<td></td>
<td>Steep (≥ 7%)</td>
<td>0.25-0.35</td>
</tr>
</tbody>
</table>

Example runoff calculation

One side of a landfill on the MIT campus has these characteristics:
   - Area of 2 acres
   - Side slope of 3%
   - Slope length of 150 feet
   - Grassy cover on clayey topsoil

Want to design for 25-year storm

Estimate $C = 0.2$ from previous chart
Example runoff calculation

$T_C = 15$ minutes

A nomograph of overland flow time. (10) Enter left margin with slope length; move right to slope curve and down to $C$ value; and find overland travel time on right margin.
Example runoff calculation

\[ i = 4 \text{ inches/hour} \]
Example runoff calculation

A = 2 acres
C = 0.2
i = 4 inches/hour

Q = CiA = 0.2 \times 4 \times 2 = 1.6 \text{ cfs}
Alternative stormwater calculation method

SCS (NRCS) Method:

- Developed by U.S. Department of Agriculture Soil Conservation Service starting in the 1950s
- Now called Natural Resources Conservation Service
- Originally developed for agricultural basins, extended to urban land uses in 1970s
SCS Method

Basis is the SCS Curve Number – an empirical measure of soil runoff characteristics

An impervious surface such as roof or road has a curve number of 98
Thick woods on sandy soil has CN = 30
Table 2-2a Runoff curve numbers for urban areas

<table>
<thead>
<tr>
<th>Cover description</th>
<th>Average percent impervious area</th>
<th>Curve numbers for hydrologic soil group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td><strong>Fully developed urban areas (vegetation established)</strong></td>
<td></td>
<td>68</td>
</tr>
<tr>
<td>Open space (lawns, parks, golf courses, cemeteries, etc.)</td>
<td>Poor condition (grass cover &lt; 50%)</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Fair condition (grass cover 50% to 75%)</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>Good condition (grass cover &gt; 75%)</td>
<td>98</td>
</tr>
<tr>
<td><strong>Impervious areas:</strong></td>
<td>Paved parking lots, roofs, driveways, etc. (excluding right-of-way)</td>
<td>98</td>
</tr>
<tr>
<td>Streets and roads:</td>
<td>Paved; curbs and storm sewers (excluding right-of-way)</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>Paved; open ditches (including right-of-way)</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>Gravel (including right-of-way)</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>Dirt (including right-of-way)</td>
<td>72</td>
</tr>
<tr>
<td><strong>Western desert urban areas:</strong></td>
<td>Natural desert landscaping (pervious areas only)</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)</td>
<td>96</td>
</tr>
<tr>
<td><strong>Urban districts:</strong></td>
<td>Commercial and business</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>Industrial</td>
<td>72</td>
</tr>
<tr>
<td><strong>Residential districts by average lot size:</strong></td>
<td>1/8 acre or less (town houses)</td>
<td>66</td>
</tr>
<tr>
<td>1/4 acre</td>
<td>38</td>
<td>61</td>
</tr>
<tr>
<td>1/3 acre</td>
<td>30</td>
<td>57</td>
</tr>
<tr>
<td>1/2 acre</td>
<td>25</td>
<td>54</td>
</tr>
<tr>
<td>1 acre</td>
<td>20</td>
<td>51</td>
</tr>
<tr>
<td>2 acres</td>
<td>12</td>
<td>46</td>
</tr>
<tr>
<td><strong>Developing urban areas</strong></td>
<td>Newly graded areas (pervious areas only, no vegetation)</td>
<td>77</td>
</tr>
<tr>
<td>Idle lands (CN's are determined using cover types similar to those in table 2-2c).</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SCS Method

Predicts runoff as a function of precipitation
Provides standard rainfall design storm distributions
Provides procedure to compute hydrographs from runoff distribution over time
SCS Method

Figure 2-1  Solution of runoff equation.

Curves on this sheet are for the case \( I_a = 0.2S \), so that

\[
Q = \frac{(P-0.2S)^2}{P + 0.8S}
\]
References for SCS Method


Stormwater control

Typically landfills require drainage swales: grassed channels to convey flow to stormwater detention/retention ponds
Detention ponds release water slowly so as to reduce flow rates and potential for downstream flooding
Retention ponds retain water, recharging it into the ground
To cap or not to cap?

Two alternative approaches:

Dry tomb – capped to keep waste dry

Digester (bioreactor) – kept moist to encourage biodegradation
Dry tomb

Prevalent U.S. practice
Minimizes moisture, maximizes compression
Capped to keep out moisture

Advantages:
- Low O&M cost
- Low leachate volume and associated treatment costs
- Established design procedure

Disadvantages:
- Encapsulates waste only—waste breakdown is minimal
- Waste remains hazardous for a long time after closure
Biodigester

Popular in Europe
Maintains high moisture content (40 to 50%) to promote bacterial growth and waste biodegradation
Leachate recirculated to maintain moisture
Waste is not compacted in order to facilitate moisture migration
Biodigestor

Advantages:
- Less leachate to be treated
- Increased methane production
- Biodegradation reduces contaminants in waste
- Waste settles more, creating room for more waste
- Eventual leachate will be much less contaminated or hazardous
Biodigester

Disadvantages:

- Design difficulties: less stable material and greater settlement
- Leachate lines more easily clogged as waste settles
- Greater capital and O&M costs
- Potential for vector problems
Leachate recirculation

Concept: add supplemental water and/or recirculating leachate to enhance decomposition

First proposed in mid-1970s
Field implementation in US in late 1990s
Side-by-side test of leachate recirc

Control cell
- 7932 metric tons MSW
- 930 m² area
- 12 m deep
- No addition of water or recirculation of leachate

Enhanced cell
- 7772 metric tons MSW
- 930 m² area
- 12 m deep
- 14 injection pits for water addition/leachate recirc
- 4430 m³ leachate and clean ground water added over 1231 days

Settlement with leachate recirculation

Methane generation with leachate recirculation

Waste character from soil borings

Landfill monitoring

Monitoring indicates:

whether facility is performing as intended (operational performance)

whether facility is polluting the environment (regulatory performance)
Monitored parameters

Head in leachate collection systems
Leachate leakage
Ground-water quality around landfill
Gas content in landfill
Gas migration through liner
Gas in soil and air around landfill
Leachate quality and quantity
Condition of cover: erosion, etc.
Settlement
Closure plans

Landfill operators are required to submit a closure plan as a part of their operating permit application.

Closure plans primarily describe capping procedure.

Operators are also required to provide post-closure care for a period of 30 years.
Post-closure care

Primary requirements address:
  Cover
  Leachate collection
  Gas monitoring
  Ground-water monitoring
Post-closure cover maintenance

Quarterly inspection of cap for cracks, erosion, settlement, and undesired vegetation
Repair of cover to maintain grades if needed
Inspection and repair of drainage and runoff control systems
Post-closure leachate collection

Leachate collection system inspection and cleaning

Repair and replacement of pumps, etc.

Leachate collection, pumping, and treatment must be continued until leachate quality does not pose a threat
Post-closure monitoring

Monitoring conducted on regular schedule established in the plan
Both ground-water and gas
Monitoring for COD, TDS, TOC, pH, various ions, metals, and VOCs
Ground-water monitoring is a priority
  Regulations require monitoring of the “uppermost aquifer” both upgradient and downgradient
  Multiple downgradient wells required: enough to assess effect of entire facility
“One-up, three-down” monitoring system

Minimum monitoring system:

One upgradient well to monitor background water quality

Three downgradient wells to monitor background landfill effects on water quality
Post-closure

Post-closure care is a major expense since it continues for such a long time.
Owner must demonstrate financial resources to provide long-term care as part of landfill licensing process.
Innovative post-closure

Reuse – capped landfills used for recreational or other low-development uses

Building on landfills is difficult: differential settlement and landfill gases create substantial impediments to building
Cambridge landfill closure

Mid-1800s – 50-acre industrial center with clay pit, a kiln, and brick yard.
Landfill reclamation

Reclamation – landfill mining to recover recyclable or reusable materials
Reduces waste volume and creates more room for waste disposal

Process:
- Excavator digs up landfilled waste
- Waste is screened to remove metal, plastic, glass, and paper
- Combustible waste is sometimes sent to waste-burning facility
Landfill reclamation

Disadvantages:

- Expensive
- Can release gases and cause odors
- Can uncover hazardous waste