Lecture 18

Leachate and gas production in landfills
Mass balance for MSW landfill

Waste in → Leachate + gas + transformed mass + waste remaining

Precipitation and ground-water inflow → leachate + moisture in waste
<table>
<thead>
<tr>
<th>Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetative Cover</td>
</tr>
<tr>
<td>Top Soil Cover</td>
</tr>
<tr>
<td>Barrier Protection</td>
</tr>
<tr>
<td>Geotextile</td>
</tr>
<tr>
<td>Drainage Layer</td>
</tr>
<tr>
<td>FML</td>
</tr>
<tr>
<td>Gas Vent Layer</td>
</tr>
<tr>
<td>Geotextile</td>
</tr>
<tr>
<td>Solid waste</td>
</tr>
<tr>
<td>Drainage/protection layer with primary leachate collection system</td>
</tr>
<tr>
<td>Primary FML</td>
</tr>
<tr>
<td>Drainage/protection layer with secondary leachate collection system</td>
</tr>
<tr>
<td>Secondary FML</td>
</tr>
<tr>
<td>Compacted soil liner</td>
</tr>
</tbody>
</table>
Factors that influence leachate generation

Precipitation
Ground-water intrusion
Moisture content of waste
  Particularly if sludge or liquids are disposed
Daily cover during filling period
Final cover design
Leachate generation at MSW landfill

**LCRS = Leachate Collection and Removal System**

**lphd = Liters per hectare per day**  
1 lphd = 3.65 mm/yr.

**Average annual precipitation: 1000 mm/yr (39.4 in/year). Closure included placement of a geomembrane cover.**

1000 mm/yr = 27,400 lphd

Estimating leachate generation in active landfill

\[ L_A = P + S - E - WA \]

- \( L_A \) = leachate from active area
- \( P \) = precipitation
- \( S \) = pore squeeze liquid from waste
- \( E \) = evaporation
- \( WA \) = waste moisture adsorption

(all in units of \( L^3/T \))
Precipitation

Pore squeeze liquid

Negligible for most wastes
Can be significant for wastewater sludges – measured in laboratory tests
## Moisture adsorption by waste

<table>
<thead>
<tr>
<th>Description</th>
<th>In/ft</th>
<th>cm/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical initial moisture content of waste</td>
<td>1.5</td>
<td>12</td>
</tr>
<tr>
<td>Field capacity of waste</td>
<td>4</td>
<td>33</td>
</tr>
<tr>
<td>Available moisture adsorption capacity of waste</td>
<td>2.5</td>
<td>21</td>
</tr>
</tbody>
</table>

Leachate generation at active MSW landfill

Leachate collection system

Example of Leachate Collection System with Sloped Subgrade

Installing leachate collection pipe

Installing drainage layer

See image at the Web site of Biometallurgical Pty Ltd.  
Drainage layers are considered as small aquifers: 
flow characteristics defined in terms of transmissivity (or thickness and hydraulic conductivity), length, and width

Use Darcy’s Law to predict flow per unit width

Darcy’s Law may not apply to some geonets, etc., because flow may be turbulent

Geonet manufacturers quote the transmissivity of geonets however since there is not a good alternative calculation procedure
Primary leachate collection system (PCLS)

EPA minimum technology guidance regulations in 1985

Requirements:
- Granular soil drainage material
- 30 cm thick
- \( K \geq 0.01 \, \text{cm/sec} \) (\( T > 3 \times 10^{-5} \, \text{m}^2/\text{sec} = 0.02 \, \text{ft}^2/\text{min} \))
  (equivalent to sand and gravel)
- Slope > 2%
- Include perforated pipe
- Include layer of filter soil
- Must cover bottom and side walls of landfill
  (side walls can be difficult to construct and maintain)

Geonet drainage layer

Geonets of equivalent performance can be substituted for sand and gravel drainage layer

\[ T \approx 10^{-4} \text{ m}^2/\text{sec} \] for typical geonet

Geonet installation

Leachate collection system

Example of Leachate Collection Pipe and Trench for Double Geomembrane/Compacted Clay Composite Liner System

Drainage pipe

See images at the following Web sites:


Pipe installation at landfill

See image at the Web site of Camino Real Environmental Centers, Inc.,
http://www.creci.com/operations.htm
Pipe installation

Usually plastic pipe (PVC or HDPE) is used. Perforated pipe is manufactured with perforations separated by 120 degrees – centerline between perforations faces down.

Perforation 60°
Design goal: $h_{\text{max}} < 30$ cm
Keep leachate mounding within 12-inch (30-cm) drainage layer
Drain design configurations

“Saw-tooth” configuration:

Continuous slope configuration:
Mound model for drainage spacing

Mound model gives mounding height for “saw-tooth” as:

\[
h_{\text{max}} = \frac{L\sqrt{c}}{2} \left[ \frac{\tan^2 \alpha}{c} + 1 - \frac{\tan \alpha}{c} \sqrt{\tan^2 \alpha + c} \right]
\]

where:

- \( h_{\text{max}} \) is height of mound [L]
- \( L \) is drain spacing [L]
- \( c = q/k \)
- \( q \) = infiltration rate [L/T]
- \( k \) = hydraulic conductivity of drainage layer [L/T]
- \( \alpha \) = slope of ground surface between pipes
Sizing of leachate collection pipes

Pipe size is designed based on Manning’s equation.
Following design chart gives flow versus slope for range of pipe diameters assuming $n = 0.010$. 
Leachate collection pipe design

Other design considerations include:
- pipe strength (to resist crushing)
- chemical resistance of pipe
- maintenance – annual pipe cleaning is typical
Leachate collection via riser pipes above single liner

Cross Section of a Landfill Leachate Collection and Removal System

Leachate sump design

Leachate generally does not leave a landfill by gravity flow—not a recommended design configuration due to difficulty in capturing and controlling leachate.

Sumps are depressions in liner filled with gravel to accommodate collected leachate.

Liner is usually doubled up at sumps.
Leachate sump design

Sumps can be accessed by:
- Sideslope riser pipes that follow the landfill sideslope
- Access ways (manholes) or vertical risers
  - But HDPE or special concrete is required due to high sulfates in leachate!
- Leachate is extracted by pumps—often cycled intermittently using level-sensing switches
- Pump must be sized for lift and anticipated flow
Leachate collection – double liner

Sideslope Riser Pipe to Remove Liquid from Leachate Collection Sump

Leachate collection pump

Schematic Diagram of Installation of a Leachate Collection Pump in Sideslope Riser Pipe

Leachate pipes at Crapo Hill landfill

Image courtesy of Peter Shanahan.
New cell and leachate storage at Crapo Hill landfill

Image courtesy of Peter Shanahan.
Leachate sump riser pipe

See image at the Web site of Tompkins County Solid Waste Management Program, Solid Waste Management Division Office. www.co.tompkins.ny.us/solidwaste/collects.html

Filter layer design

Filter medium keeps sediment out of drainage layer
Must not clog over decades of use and post-closure
Design flow parameter is “permittivity” [1/T]
\[ \Psi = \frac{k}{t} \]

where
- \( k \) = cross-plane (vertical) hydraulic conductivity [L/T]
- \( t \) = thickness [L]
Filter layer design

Consider drainage layer design goal to limit $h_{\text{max}}$

\[ Q = k_i A \]
\[ \frac{Q}{A} = q = k \left( \frac{h_{\text{max}}}{t} \right) \]
\[ q = \frac{k}{t} h_{\text{max}} \]
\[ q = \Psi h_{\text{max}} \]
Filter layer design

Required permittivity is:

\[ \Psi = \frac{q}{h_{\text{max}}} \]

where:

- \( q = \frac{Q}{A} = \text{vertical inflow per unit area of landfill} \) \( \text{[(L}^3/\text{T})/\text{L}^2] \)
- \( h_{\text{max}} = \text{maximum allowable mounding height} \) \( \text{[L]} \)
Filter layer design

Criteria:
- Soil from above cannot penetrate into filter layer
- Filter layer must have adequate K
- Soil from filter layer must not penetrate drainage layer

See Qian et al. for formulae for soil filter layers and geotextiles
Geotextile clogging

Long-term clogging potential evaluated with gradient ratio test:

\[
\text{Ratio} = \frac{\text{Hydraulic gradient through 1 inch of soil plus geotextile}}{\text{Hydraulic gradient through 2 inches of soil}}
\]

Ratio > 3 indicates geotextile will probably clog with sediment

Secondary leachate collection system (SLCS)

EPA requirements for secondary leachate collection systems:

- 30 cm thick drainage layer
- \( K \geq 0.01 \text{ cm/sec} \) \( (T > 3 \times 10^{-5} \text{ m}^2/\text{sec} = 0.02 \text{ ft}^2/\text{min}) \)
  - (equivalent to sand and gravel – same as PLCS)
- Cover bottom and side walls of landfill
- Must have response time for leak detection of less than 24 hours
Secondary leachate collection system (SLCS)

If SLCS performs as desired, it will generate very little leachate

Often drained with geonet – reduces space and eliminates pipe requirement

Response time calculated from velocity by Darcy’s Law:

\[ v = k \frac{i}{n} \]

Calculate separately for side slope and bottom

For gradient, i, use constructed side or bottom slope

For geonets use \( n = 0.5 \)
Prefabricated drains

See the following images at the Web site of American Wick Drain Corporation:

AMERDRAIN® sheet drain and AKWADRAIN™ strip drain keep landfills dry and remove leachate:
http://www.americanwick.com/landfill.html

AKWADRAIN™ soil strip drain:

Landfill Biogeochemistry

1. Aerobic decomposition:
   Degradable waste + O₂ → CO₂ + H₂O + biomass + heat

   \[ \text{CH}_a\text{O}_b\text{N}_c + \frac{1}{4}(4a - 2b - 3c)\text{O}_2 \rightarrow \text{CO}_2 + \frac{1}{2}(a - 3c)\text{H}_2\text{O} + c\text{NH}_3 \]

2. Acid-phase (nonmethanogenic) anaerobic decomposition
   Degradable waste → CO₂ + H₂O + biomass + organic acids
Landfill Biogeochemistry

3. Methanogenic anaerobic decomposition:
   Degrade products of Stage 2

   \[ 4H_2 + CO_2 \rightarrow CH_4 + 2H_2O \]
   \[ CH_3COOH \rightarrow CH_4 + CO_2 \]
Landfill Gas Production

Landfill Gas Production Pattern Phases

<table>
<thead>
<tr>
<th>Phases</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Aerobic</td>
</tr>
<tr>
<td>II</td>
<td>Anoxic</td>
</tr>
<tr>
<td>II</td>
<td>Anaerobic, Methanogenic, Unsteady</td>
</tr>
<tr>
<td>II</td>
<td>Anaerobic, Methanogenic, Steady</td>
</tr>
</tbody>
</table>

Problems with landfill gas

Explosive hazard !!!
Methane is explosive above 5 to 15% by volume
Subsurface migration offsite (up to 150 m)
Accumulation beneath buildings or structures
Vegetation stress
Toxicity due to H$_2$S and VOCs
Corrosion due to CO$_2$–created acidity
Greenhouse gases and air emissions
## Landfill gas composition

### Typical Landfill Gas Composition

<table>
<thead>
<tr>
<th>Component</th>
<th>Source</th>
<th>Typical concentration (% by volume)</th>
<th>Concern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (CH₄)</td>
<td>B&lt;sup&gt;a&lt;/sup&gt;</td>
<td>50-70</td>
<td>Explosive</td>
</tr>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>B</td>
<td>30-50</td>
<td>Acidic in groundwater</td>
</tr>
<tr>
<td>Hydrogen (H₂)</td>
<td>B</td>
<td>&lt;5</td>
<td>Explosive</td>
</tr>
<tr>
<td>Mercaptans (CHS)</td>
<td>B</td>
<td>.1-1</td>
<td>Odor</td>
</tr>
<tr>
<td>Hydrogen Sulfide (H₂S)</td>
<td>B</td>
<td>&lt;2</td>
<td>Odor</td>
</tr>
</tbody>
</table>

**Solvents**

<table>
<thead>
<tr>
<th>Component</th>
<th>Source</th>
<th>Typical concentration (% by volume)</th>
<th>Concern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toluene</td>
<td>C&lt;sup&gt;b&lt;/sup&gt;</td>
<td>.1-1</td>
<td>Hazardous</td>
</tr>
<tr>
<td>Benzene</td>
<td>C</td>
<td>.1-1</td>
<td>Hazardous</td>
</tr>
<tr>
<td>Disulfates</td>
<td>C</td>
<td>.1-2</td>
<td>Hazardous</td>
</tr>
<tr>
<td>Others</td>
<td>B and C</td>
<td>traces</td>
<td>Hazardous</td>
</tr>
</tbody>
</table>

<sup>a</sup>B = Product of biodegradation  <sup>b</sup>C = A contaminant in the MSW

Landfill gases

Methane is lighter than air – accumulates beneath structures, buildings

Carbon dioxide is heavier than air – accumulates in landfill
Landfill gas production

Theoretical estimate: 520 L / kg of MSW (53% is methane)
Actual: 160 L / kg (mean), 50 – 400 L / kg (range)
Theoretical estimate is based on complete degradation of wastes such as:
  cellulose – 829 L/kg, 50% methane
  protein – 988 L/kg, 52% methane
  fat – 1430 L/kg, 71% methane
Theoretical gas production is CO₂ + CH₄
## Hydrocarbons in Landfill Gas

### Hydrocarbons in Landfill Gas in mg/m³ Based on Airless Landfill Gas

<table>
<thead>
<tr>
<th>Hydrocarbon</th>
<th>Formula</th>
<th>mg/m³</th>
<th>Hydrocarbon</th>
<th>Formula</th>
<th>mg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethane</td>
<td>C₂H₆</td>
<td>0.8-48</td>
<td>Undecane</td>
<td>C₁₁H₂₄</td>
<td>7-48</td>
</tr>
<tr>
<td>Ethene (ethylene)</td>
<td>C₂H₄</td>
<td>0.7-31</td>
<td>Dodecane</td>
<td>C₁₂H₂₄</td>
<td>2-4</td>
</tr>
<tr>
<td>Propane</td>
<td>C₃H₈</td>
<td>0.04-10</td>
<td>Tridecane</td>
<td>C₁₃H₂₈</td>
<td>0.2-1</td>
</tr>
<tr>
<td>Butane</td>
<td>C₄H₁₀</td>
<td>0.3-23</td>
<td>Benzene</td>
<td>C₆H₆</td>
<td>0.03-7</td>
</tr>
<tr>
<td>Butene</td>
<td>C₄H₈</td>
<td>1-21</td>
<td>Ethylbenzene</td>
<td>C₈H₁₀</td>
<td>0.5-238</td>
</tr>
<tr>
<td>Pentane</td>
<td>C₅H₁₂</td>
<td>0-12</td>
<td>1,3,5-Methylbenzol</td>
<td>C₇H₈</td>
<td>10-25</td>
</tr>
<tr>
<td>2-Methylpentane</td>
<td>C₆H₁₄</td>
<td>0.02-1.5</td>
<td>Toluene</td>
<td>C₇H₈</td>
<td>0.2-615</td>
</tr>
<tr>
<td>3-Methylpentane</td>
<td>C₆H₁₄</td>
<td>0.02-1.5</td>
<td>m/p-xylol</td>
<td>C₈H₁₀</td>
<td>0-378</td>
</tr>
<tr>
<td>Hexane</td>
<td>C₆H₁₄</td>
<td>3-18</td>
<td>o-Xylol</td>
<td>C₆H₁₀</td>
<td>0.2-7</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>C₆H₁₂</td>
<td>0.03-11</td>
<td>Trichlorofluoromethane</td>
<td>CCl₃F</td>
<td>1-84</td>
</tr>
<tr>
<td>2-Methylhexane</td>
<td>C₆H₁₆</td>
<td>0.04-16</td>
<td>Dichlorofluoromethane</td>
<td>CHCl₂F</td>
<td>4-119</td>
</tr>
<tr>
<td>3-Methylhexane</td>
<td>C₆H₂₀</td>
<td>0.04-13</td>
<td>Chlorotrifluoromethane</td>
<td>CClF₂</td>
<td>0-10</td>
</tr>
<tr>
<td>Cyclohexane</td>
<td>C₆H₁₂</td>
<td>2-6</td>
<td>Dichloromethane</td>
<td>CH₂Cl₂</td>
<td>0-6</td>
</tr>
<tr>
<td>Heptane</td>
<td>C₇H₁₆</td>
<td>3-8</td>
<td>Trichloroethene</td>
<td>(chloroform)</td>
<td>CHCl₃</td>
</tr>
<tr>
<td>2-Methylheptane</td>
<td>C₈H₁₈</td>
<td>0.05-2.5</td>
<td>Tetrachloromethane</td>
<td>(carbon tetra-chloride)</td>
<td>CCl₄</td>
</tr>
<tr>
<td>3-Methylheptane</td>
<td>C₈H₁₈</td>
<td>0.05-2.5</td>
<td>1,1,1-Trichloroethene</td>
<td>C₂H₃Cl₃</td>
<td>0.5-4</td>
</tr>
<tr>
<td>Octane</td>
<td>C₈H₁₈</td>
<td>0.05-75</td>
<td>Chloroethane</td>
<td>C₂H₅Cl</td>
<td>0-284</td>
</tr>
<tr>
<td>Nonane</td>
<td>C₉H₂₀</td>
<td>0.05-400</td>
<td>Dichloroethene</td>
<td>C₂H₄Cl₂</td>
<td>0-294</td>
</tr>
<tr>
<td>Cumole</td>
<td>C₉H₁₂</td>
<td>0-32</td>
<td>Trichloroethene</td>
<td>C₂HCl₃</td>
<td>0-182</td>
</tr>
<tr>
<td>Bicyclo(3,2,1)-octane-2,3-methyl-4</td>
<td>-methylethylene</td>
<td>C₁₀H₁₆</td>
<td>Tetrachloroethene</td>
<td>C₂H₂Cl₄</td>
<td>0.1-142</td>
</tr>
<tr>
<td>Decane</td>
<td>C₁₀H₃₂</td>
<td>0.2-137</td>
<td>Chlorobenzene</td>
<td>C₆H₅Cl</td>
<td>0-0.2</td>
</tr>
<tr>
<td>Bicyclo(3,1,0)hexane-2,2-methyl-5- methylethylene</td>
<td>C₁₀H₁₃</td>
<td>12-153</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<p>| Hydrocarbons in Landfill Gas in mg/m³ Based on Airless Landfill Gas |
|---|---|
| (mg/m³) | (mg/m³) |
| <strong>Ethane</strong> | C₂H₆ | 0.8-48 |
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| <strong>Propane</strong> | C₃H₈ | 0.04-10 |
| <strong>Butane</strong> | C₄H₁₀ | 0.3-23 |
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| <strong>Undecane</strong> | C₁₁H₂₄ | 7-48 |
| <strong>Dodecene</strong> | C₁₂H₂₄ | 2-4 |
| <strong>Tridecane</strong> | C₁₃H₂₈ | 0.2-1 |
| <strong>Benzene</strong> | C₆H₆ | 0.03-7 |
| <strong>Ethylbenzene</strong> | C₈H₁₀ | 0.5-238 |
| <strong>1,3,5-Methylbenzol</strong> | C₇H₈ | 10-25 |
| <strong>Toluene</strong> | C₇H₈ | 0.2-615 |
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| <strong>o-Xylol</strong> | C₆H₁₀ | 0.2-7 |
| <strong>Trichlorofluoromethane</strong> | CCl₃F | 1-84 |
| <strong>Dichlorofluoromethane</strong> | CHCl₂F | 4-119 |
| <strong>Chlorotrifluoromethane</strong> | CClF₃ | 0-10 |</p>
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<thead>
<tr>
<th>Compound</th>
<th>Formula</th>
<th>(mg/m³)</th>
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<td>C₉H₁₂</td>
<td>0-32</td>
</tr>
<tr>
<td>Bicyclo(3,2,1)-octane-2,3-methyl-4-methylethylene</td>
<td>C₁₀H₁₆</td>
<td>15-350</td>
</tr>
<tr>
<td>Decane</td>
<td>C₁₀H₃₂</td>
<td>0.2-137</td>
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<td>0-284</td>
</tr>
<tr>
<td>Dichloroethene</td>
<td>C₂H₄Cl₂</td>
<td>0-294</td>
</tr>
<tr>
<td>Trichloroethene</td>
<td>C₂HCl₃</td>
<td>0-182</td>
</tr>
<tr>
<td>Tetrachloroethene</td>
<td>C₂H₂Cl₄</td>
<td>0.1-142</td>
</tr>
<tr>
<td>Chlorobenzene</td>
<td>C₆H₅Cl</td>
<td>0-0.2</td>
</tr>
</tbody>
</table>

Waste degradation is generally modeled as a first-order process:

\[ V = V_0 \ e^{-kt} \]

where

- \( V \) = gas production rate (function of time)
- \( V_0 \) = initial gas production rate
- \( t \) = time
- \( k \) = first-order degradation rate = \( 0.69 / t_{1/2} \)
- \( t_{1/2} \) = half-life

Half-lives of degradation:

- Food, garden wastes – \( \frac{1}{2} \) to \( 1\frac{1}{2} \) years
- Paper, wood – 5 to 25 years

Landfills typically generate gas for 5 to 20 years
Landfill gas collection

Large landfills are required by EPA Clean Air regulations to implement a gas collection and control plan – concern is non-methane organic compounds (NMOC)

Gas collection may be passive or active
Collection systems

Leachate collection

Gas collection

Gas vent layer

Waste

Vegetative Cover
Top Soil Cover
Barrier Protection
Geotextile
Drainage Layer
FML
Gas Vent Layer
Geotextile
Solid waste

Drainage/protection layer with primary leachate collection system
Primary FML
Drainage/protection layer with secondary leachate collection system
Secondary FML
Compacted soil liner
Passive gas venting

Vent layer atop waste – typically 12 to 30 cm thick (5 to 12 inches)
Perforated pipe (usually only short section at landfill high points) leading to “candy-cane” vent pipe or flares
Design is by trial and error since it is site-specific
Rule of thumb is 1 vent for 7500 m³ of waste
Active gas collection at Crapo Hill Landfill

Image courtesy of Peter Shanahan.
Active gas collection

Utilized when gas emissions create problems, gas is desired for commercial use, passive venting is inadequate
Entails connecting a vacuum pump or blower to discharge end of piping system
Gas extraction wells may be installed during operating period or as an “after design”
Rules of thumb: space wells at three times the waste depth
Radii of influence of gas extraction wells in MSW landfills are 100 to 500 feet
Design considerations for gas collection

Flexible connection (bellows) required at perforations of cap liner

Condensate can collect in gas collection pipes – require water traps to remove accumulated condensate
Flare for gas disposal at Crapo Hill Landfill

Flares work when methane is greater than 20% by volume

Generally enclosed in stack to effect longer residence times and greater combustion

Contains flame sensor which turns off valve when flame goes out

Image courtesy of Peter Shanahan.