Landfill Process Modeling

Morton Barlaz, PhD, PE
Professor and Head

James Levis, PhD
Research Assistant Professor

go.ncsu.edu/swolf

www.easetech.dk
Outline

• Introduction
  – Functional unit: landfill vs 1 ton of waste
  – Site-specific vs. typical?
• Carbon Flows
• Key Sub-Processes
Solid Waste Systems: Landfill is Final Repository; Waste Disposed May Vary
Analyzing **Landfills or Waste in Landfills**

• Appropriately defining the functional unit is essential for landfill life-cycle modeling.

• Emissions from a landfill or emissions associated with disposing a ton of waste in a landfill?
  – Modeling a landfill requires modeling waste disposal over many years in different cells with phased gas collection and cover systems; or a snapshot in time
  – Modeling a ton of waste in a landfill requires developing temporally averaged emissions from the waste placed at different times in the landfill

• LCA of SWM systems models what happens when we put 1 ton of waste into a landfill
Analyzing Waste in Typical Landfills or a Specific Landfill

- The functional unit can be further specified by determining whether analyzing a specific landfill or a “typical” or “average” landfill.
  - Unit of government may model their specific landfill
  - A waste generator or product manufacturer may model “average” landfills because their products could be disposed in any landfill
- Ideal process model will be flexible as to user objective
  - Specific or average landfill
The Landfill Process Model

Incoming Waste Materials (Mg\textsuperscript{in})

User Inputs

Landfill Process Model

- Direct Emissions (kg/Mg\textsuperscript{in})
- Equipment Fuel Use (L/Mg\textsuperscript{in})
- Electricity Use (kWh/Mg\textsuperscript{in})
- Transportation Use (kg-km/Mg\textsuperscript{in})
- Amortized Capital Cost ($/Mg\textsuperscript{in})
- Operating Cost ($/Mg\textsuperscript{in})

Stored Mass (Mg\textsuperscript{stored}/ Mg\textsuperscript{in})
Landfill carbon flows

- Decomposing Waste (MSW, commercial, biosolids, ash, inert, other)
  - Stored Carbon
  - C in leachate

- Electricity Offset
- Capture & Combust for Energy

- Oxidized
  - Fugitive
  - Emissions
  - Generated Methane
  - Capture & Flare

- Fossil Fuel Use
Illustrative Contributional Results

Bulk MSW L0 = 100 m³/Mg

Emphasis on whether net carbon positive or negative versus best available control technology

Results based on Levis and Barlaz, 2014
Landfill Fuel and Electricity Use

GHG Emissions (kg CO$_2e$/Metric Ton)

- Equipment fuel use
- Material use (liner, soil, pipes)
- Electricity Use (buildings, leachate, blowers)
- Material and leachate transport
- Total
Gas Management is Dominant Contributor to Carbon Footprint

- Gas collection system installation schedule is important
- Life of landfill or time to final cover is important because collection efficiency is highest after final cover installation
- Times over which
  - gas is converted to energy
  - gas is flared
  - gas is vented
Sardinia Symposium 2015 - Solid Waste Life-Cycle Modeling Workshop

Well 1
Well 2
Well 3
Well 4
Well 5
Well 6

1’ of Soil

Cell 5
Cell 6
Cell 8
Cell 10
Cell 11

Cell 7
Cell 9
Gas collection efficiency will change over time and vary based on when the waste was disposed.

Not important for an inert waste landfill or a landfill in a developing country with no gas collection.
Landfill gas modeling

\[ V_t = M L_0 \left( e^{-kt} - e^{-k(t-1)} \right) \]

- \( V_t \)- Volume of methane produced from a mass of waste in year \( t \) (m\(^3\) CH\(_4\)/Mg).
- \( M \)- Dry mass of waste (Mg).
- \( L_0 \)- Total methane potential (m\(^3\) CH\(_4\)/dry Mg).
- \( k \)- First order decay rate constant (1/yr).
- \( t \)- Time since waste burial (years).

Use an approach in which each waste component is modeled individually
Material Properties

Carbon Storage and Methane Yield (kg C/dry Mg)

Decay Rate (1/yr)

Leaves, Grass, Branches, Food Waste, Wood, Textiles, ONP, OCC, OFF, OMG

Carbon Storage
Methane Yield
Decay Rate
Landfill gas modeling - Effect of decay rate on methane generation

$L_0 = 100 \text{ m}^3/\text{dry Mg}$

![Graph showing the effect of decay rate on methane generation](image)
Effect of decay rate on methane collection

- $L_0 = 100 \text{ m}^3/\text{wet Mg}$
- Values for waste buried in first year.
- Collection efficiency varies with time, decay rate, and landfill operation.
Temporally Averaged Waste Age Landfill Gas Collection and Oxidation Efficiency

- 200,000 tons/yr
- 35 year operation
- Typical gas collection
- Gas collection ceases at year 75 (not enough gas to generate electricity)
Leachate Generation

Alternative would be to assign a value in liters/ha-day that varies with time and climate.
## Leachate Collection Periods: Length of time and % of Leachate Collection for Treatment

<table>
<thead>
<tr>
<th>Period</th>
<th>Time (yr)</th>
<th>Traditional</th>
<th>Leachate Recirculation Landfill</th>
<th>Ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: After waste placement and before recirculation</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2: During landfill operations</td>
<td>1-20</td>
<td>100</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>3: After landfill closure</td>
<td>21-100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>4. Between some time post-closure and the end of the modeling period</td>
<td>0</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

User may assume release to the environment or accumulation of leachate
Leachate Composition

• Pollutants that vary with time (BOD) and others that are constant (TSS)

• BOD concentration varies with time
  – Multiply concentration by generation to obtain mass BOD/ton total waste
    • Allocate BOD based on fraction of total gas
      – 0 for plastic, non-zero for food waste

• N and P: derived allocation fractions based on total N and P in leachate from waste component specific lab studies

• Metals: Allocated according to their presence in waste components
Leachate Treatment

• Estimated treatment efficiencies and energy requirements
  – Treated leachate is released to the environment

• Model is formulated so that user can specify release of untreated leachate to the environment
Research Needs

• Inclusion of non-engineered facilities (e.g., open dumps)
Additional Resources


• NC State University and Eastern Research Group, 2011, Background Information Document for Life-Cycle Inventory Landfill Process Model, EPA Contract No. EP-C-07-015


Questions and Discussion

go.ncsu.edu/swolf

www.easetech.dk
Extras
Landfilling in the U.S.

- The purpose of sanitary landfills is to permanently and safely dispose of solid waste without endangering human health or the environment.
- Approximately 1900 landfills are operating in the U.S.
### Landfill gas collection scenarios

Data values developed based on discussions among the WARM Landfill Working Group

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Aggressive</th>
<th>Typical</th>
<th>CAA Min</th>
<th>CA Regs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time until initial gas collection (yr)</td>
<td>0.5</td>
<td>2</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Initial gas collection efficiency (%)</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Time to increased gas collection efficiency (yr)</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Increased gas collection efficiency (%)</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>80</td>
</tr>
<tr>
<td>Time from initial waste placement to long term cover (yr)</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>Gas collection efficiency under long term cover (%)</td>
<td>82.5</td>
<td>82.5</td>
<td>82.5</td>
<td>85</td>
</tr>
<tr>
<td>Time from final waste placement to final cover (yr)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Gas collection efficiency under final cover (%)</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Collection System Downtime (%)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Flare and Energy Recovery Operational Parameters

<table>
<thead>
<tr>
<th>Flare Cutoff Criteria</th>
<th>Aggressive</th>
<th>Typical</th>
<th>CAA Min</th>
<th>CA Regs</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMOC Emissions Cutoff (Mg/yr)</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Minimum Operation Time (yr)</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Collected LFG Cutoff (cfm)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>100</td>
</tr>
</tbody>
</table>

Energy Recovery Parameters (all scenarios)

- Minimum LFG collection flow rate for energy recovery – 350 cfm
- Time above 350 cfm required before energy recovery begins – 1 yr
- Total time above 350 cfm required for energy recovery – 5 yrs
Oxidation Parameters

- Percent oxidation values were developed based on new EPA guidance.
- Rates reflect the fact that
  - Percent oxidation is a function of methane flux (g CH₄/m²-s)
  - Flux is of collection efficiency and methane generation rate (g CH₄/kg waste)
  - Collection efficiency and methane generation rate are functions of time

<table>
<thead>
<tr>
<th>Oxidation Situation</th>
<th>Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without gas collection or final cover</td>
<td>10</td>
</tr>
<tr>
<td>With gas collection before final cover</td>
<td>20</td>
</tr>
<tr>
<td>After final cover installation</td>
<td>35</td>
</tr>
</tbody>
</table>
Illustrative Results

$k = 0.04 \text{ yr}^{-1}$

Typical Gas Collection
How Long Do Landfills Operate?

• Length of operations affects total landfill gas generation and collection.

• Flare and beneficial use are dependent on gas collection.
  • Flare CAA requirements
  • Ability to run engines

Data (landfills w/ at least 100,000 tons in place)
  Mean – 46.6
  StDev – 37.4
  10th percentile – 16
  Median – 38
  90th percentile – 87
How Big is a Landfill?

• Annual waste acceptance affects total landfill gas generation and collection.

• Flare and beneficial use are dependent on gas collection.
  • Flare CAA requirements
  • Ability to run engines

Data (landfills w/ at least 100,000 tons in place)
Mean – 159 (1000 tpy)
StDev – 236
10\textsuperscript{th} percentile – 14
Median – 77
90\textsuperscript{th} percentile – 385

Annual Waste Acceptance (1000 tons per year)
Modeling an “Average” Landfill

- Ran 2000 Monte Carlo simulations with randomly selected operating life and waste acceptance
- Modeled four (4) collection scenarios with and without beneficial energy recovery.
  - Aggressive Collection (Aggressive)
  - Typical Collection (Typical)
  - CAA Regulatory Minimum Collection (CAA Min)
  - California AB-32 Regulatory Collection (Cali Regs)
- Modeled four (4) bulk decay rates
  - $k = 0.02, 0.04, 0.06, 0.12 \text{ yr}^{-1}$
  - Influences waste component decay rate
- Modeled 12 degradable waste components
  - Branches
  - Grass
  - Leaves
  - Food Scraps
  - Corrugated Cardboard
  - Magazines/3rd Class Mail
  - Newspaper
  - Office Paper
  - Lumber
  - Medium-density Fiberboard
  - Wood flooring
  - Mixed MSW
• 12-41% of generated methane is emitted (22-41% outside California).
• Increasing decay rate leads to greater emissions.
• Little difference between Aggressive and Typical collection scenarios.
• California regulations significantly decrease emissions.
• 17-48% of generated methane is emitted (34-48% outside California).
• Emissions increase by 7 to 22% over Energy Recovery scenario for non-California scenarios
  – More at lower decay rates
• Effect of decay rate is more complicated
  – Faster decay is better in Aggressive and Typical.
  – Decay rate of 0.04 and 0.06 best in CAA Min and CA Regs scenarios
For landfills with energy recovery, Californian regulations decrease fugitive emissions by 35-50% by increasing effective collection efficiency by 12-18%.

For landfills without energy recovery, Californian regulations decrease fugitive emissions by 51-57% by increasing effective collection efficiency by 27-34%.
Effect of Material Decay Rate on Methane Emissions

- **Grass**
- **Food**
- **Branches**
- **Mixed MSW**

Bulk MSW $k = 0.04 \text{ yr}^{-1}$
Effect of decay rate on methane collection

- \( L_0 = 100 \text{ m}^3/\text{wet Mg} \)
- Values for waste buried in first year.
- Collection efficiency varies with time, decay rate, and landfill operation.