Emissions of Selected Greenhouse Gases  
from a Landfill  

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F-Gases

- Chlorinated and fluorinated hydrocarbons used as blowing agents (BAs) in foam insulation materials (building applications, appliances, temperature control applications)
BA Substitution

- Specific compounds used have changed with time due to regulations and changes in formulations:
  
  \[
  \text{(CFCs} \quad \rightarrow \quad \text{HCFCs} \quad \rightarrow \quad \text{HFCs})
  \]

- Formation of F-gas \textit{banks} (in service and in landfills)
How to Assess Relative Harm to Ozone Layer?

• *Ozone Depletion Potential (ODP)* – the ratio of ozone column change for each mass unit of a gas emitted into the atmosphere, relative to CFC-11 (ODP = 1.0) (Fisher et al. 1990)
How to Assess Relative GHG Potential?

- *Radiative forcing* – a measure of the change in the balance of incoming solar radiation to the earth and outgoing infrared radiation to the atmosphere (W/m$^2$)
  
  (IPCC 2007)
How to Assess Relative GHG Potential?

- *Global Warming Potential* – the ratio of the time integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of CO$_2$
- The concept of “CO$_2$ equivalents” (IPCC 2007)
Summary of CFCs

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Principal Uses</th>
<th>Atmospheric Lifetime (years)</th>
<th>ODP</th>
<th>Radiative Forcing (W/m²)</th>
<th>GWP – 100 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFCS (11, 12, 113, 114)</td>
<td>Foam blowing agents, Refrigerants, Solvents, Propellants</td>
<td>45-190</td>
<td>0.8-1</td>
<td>0.07-0.17</td>
<td>4660-10,200</td>
</tr>
</tbody>
</table>

- CFC-11 has a substantially high ODP, moderate to high GWP, and long atmospheric lifetime
### Summary of HCFCs

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Principal Use</th>
<th>Atmospheric Lifetime (years)</th>
<th>ODP</th>
<th>Radiative Forcing (W/m²)</th>
<th>GWP – 100 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCFCs (21, 22, 141b, 142b, 151a)</td>
<td>Refrigerant blends, Foam blowing agents</td>
<td>1.7-17.2</td>
<td>0.004-0.11</td>
<td>0.003-0.04</td>
<td>148-1980</td>
</tr>
</tbody>
</table>

- **HCFC-141b** has a significantly reduced ODP and atmospheric lifetime, moderate GWP
### Summary of HFCs

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Principal Use</th>
<th>Atmospheric Lifetime (years)</th>
<th>ODP</th>
<th>Radiative Forcing (W/m²)</th>
<th>GWP – 100 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFCs (134a, 152a, 245fa)</td>
<td>Refrigerant blends, foam blowing agents, fire suppressants, and propellants</td>
<td>1.5-13.4</td>
<td>0</td>
<td>0.003-0.01</td>
<td>138-1120</td>
</tr>
</tbody>
</table>

- HFC-134a/HFC-245fa replacements have no ODP, moderate to low GWP
CO₂ has relatively long atmospheric lifetime and high radiative forcing.

CH₄ is a more potent greenhouse gas, higher GWP than CO₂ (significantly smaller GWP than CFCs, HCFCs, and HFCs).
Emissions from Landfills

- F-gases represent high global warming potential gases with high CO$_2$ equivalents
- The phased-out compounds remain in service and are expected to enter landfills for a timeline on the order of decades
- Field data on emissions of F-Gases from landfill covers is extremely limited, especially for U.S. landfills
Field Testing Program

- Large-scale static flux chambers used
- Emissions as a function of cover type, season (cool-wet / warm-dry), waste age/depth
- Targeted CFC, HCFC, HFC, and Principal LFGs
Test Site: Northern California
Test Site Characteristics

- Subtitle D landfill
- Temperate climate (with hot and dry summer)
- Average daily air temperature: 15.8°C
- Average annual precipitation: 869 mm
- Permitted disposal area = 140 ha
- Total design capacity = 64 million m³
- Annual waste intake = 900,000 tonnes
- Waste composition: 17% C&D, 30% soil, remainder MSW
Locations for Tests

Cell 1
Cell 10
Cell 12
Cell 15

Scalehouse
Administration Building
Flare System

0 m
450 m
## 7 Locations for Testing

<table>
<thead>
<tr>
<th>Test</th>
<th>Cover Type</th>
<th>Material Description</th>
<th>Waste Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF</td>
<td>Daily</td>
<td>Auto Fluff</td>
<td>0 to 7</td>
</tr>
<tr>
<td>GW</td>
<td>Daily</td>
<td>Green Waste</td>
<td>0 to 7</td>
</tr>
<tr>
<td>ED</td>
<td>Daily</td>
<td>Poorly graded gravel with clay and sand</td>
<td>0 to 7</td>
</tr>
<tr>
<td>IC-1</td>
<td>Interim</td>
<td>Fat Clay</td>
<td>16 to 30</td>
</tr>
<tr>
<td>IC-10</td>
<td>Interim</td>
<td>Clayey sand with gravel</td>
<td>4 to 19</td>
</tr>
<tr>
<td>IC-15</td>
<td>Interim</td>
<td>Clayey sand with gravel</td>
<td>4 to 9</td>
</tr>
<tr>
<td>FC</td>
<td>Final</td>
<td>Fat clay with gravel</td>
<td>16 to 30</td>
</tr>
</tbody>
</table>
Static Flux Chambers

1 m x 1 m x 300 mm chamber size

4 chambers per test location for statistical significance
Deployment and Testing
Gas Sampling Procedure

• Gas samples collected with time for test periods ranging between 60 and 150 minutes
• Analytical testing conducted at University of California – Irvine to determine concentrations with time from gas samples from the chambers
• Gas concentration => calculate flux => CO\textsubscript{2} equivalent emissions
Analytical Testing
Flux Determination

HFC-134a (IC-15 - Wet Season)

\[y = 77.534x + 1609.3\]
\[R^2 = 0.99861\]

\[y = 45.376x + 1942.2\]
\[R^2 = 0.87532\]
Flux Determination

y = 77.534x + 1609.3
R² = 0.99861

y = 45.376x + 1942.2
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HFC-134a (IC-15 - Wet Season)
Flux Determination

HFC-134a (IC-15 - Wet Season)

\[ y = 77.534x + 1609.3 \]
\[ R^2 = 0.99861 \]

\[ y = 45.376x + 1942.2 \]
\[ R^2 = 0.87532 \]

- No Point Removed
- Last Point Removed
• Highest flux values for daily cover, lowest values for final cover
• Flux values ranged 6+ orders of magnitude
Estimation of Scaled Emissions

\[
\frac{CO_2\text{eq Tonnes}}{yr} = [(Flux)]
\]

1. Estimate Flux (g/m²/day) – min or max across all DC, IC, or FC sites in wet or dry season
Estimation of Scaled Emissions

\[
\frac{CO_2eq\ Tonnes}{yr} = [(Flux) \times (WF \times Landfill\ Area)]
\]

2. Define the weighting factor (WF) and scale to the actual landfill area (m\(^2\))

(0.03 for DC, 0.84 for IC, 0.13 for FC)
Estimation of Scaled Emissions

\[
\frac{CO_2eq \text{ Tonnes}}{yr} = [(Flux) \times (WF \times \text{Landfill Area}) \times (\text{Seasonal Period})]
\]

3. Delineate the Seasonal period – 7 months for “wet” season, 5 months for “dry” season
Estimation of Scaled Emissions

\[
\frac{CO_2\text{eq Tonnes}}{yr} = [(\text{Flux}) \times (WF \times \text{Landfill Area}) \times (\text{Seasonal Period})] \times \text{GWP}
\]

4. Don’t forget to multiply by the GWP!
Summary of Scaled Emissions

<table>
<thead>
<tr>
<th>Compound</th>
<th>Surface Emissions (CO₂ Eq. Tonnes/year)</th>
<th>%</th>
<th>Maximum</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFC-11</td>
<td>1.01E+03</td>
<td>15.8</td>
<td>3.40E+03</td>
<td>3.0</td>
</tr>
<tr>
<td>HCFC-141b</td>
<td>7.64E+00</td>
<td>0.1</td>
<td>6.80E+02</td>
<td>0.6</td>
</tr>
<tr>
<td>HFC-134a</td>
<td>2.89E+01</td>
<td>0.5</td>
<td>1.37E+02</td>
<td>0.1</td>
</tr>
<tr>
<td>HFC-245fa</td>
<td>9.45E+00</td>
<td>0.1</td>
<td>1.14E+02</td>
<td>0.1</td>
</tr>
</tbody>
</table>

• Range in CFC-11 emissions was highest of all F-gases, followed by HCFC-141b, HFC-134a, and HFC245fa
Summary of Scaled Emissions

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<th>%</th>
<th>Maximum</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total F-Gas Emissions</td>
<td></td>
<td>1.08E+03</td>
<td>16.9</td>
<td>4.79E+03</td>
<td>4.3</td>
</tr>
<tr>
<td>CH₄</td>
<td></td>
<td>5.31E+02</td>
<td>8.3</td>
<td>8.04E+04</td>
<td>72.0</td>
</tr>
<tr>
<td>CO₂</td>
<td></td>
<td>4.78E+03</td>
<td>74.8</td>
<td>2.65E+04</td>
<td>23.7</td>
</tr>
<tr>
<td>Total Surface Emissions (F-Gases + CH₄ + CO₂)</td>
<td></td>
<td>6.39E+03</td>
<td>100.0</td>
<td>1.12E+05</td>
<td>100.0</td>
</tr>
</tbody>
</table>

- Total F-gas emissions are a relatively small, but detectable portion of the total surface emissions (4-17%)
- Principal LFGs a significant portion of the total equivalent emissions
Summary and Conclusions

- Large-scale static flux chambers were effective for use at determining emissions of F-gases through a range of landfill cover conditions.

- Fluxes of F-gases were highest for DC, IC, then FC conditions
  
  - *Large spatial and temporal (seasonal) variation*

- Greenhouse gas emissions were highest for principal landfill gases (CO$_2$ and CH$_4$)

  - *Proportional to high magnitude of fluxes observed for all cover conditions*
Summary and Conclusions

• CFC-11 was the F-gas that contributes most to GWP at this particular site

  • *High GWP may contribute, not necessarily the highest measured flux out of all F-gases for all locations*

• The ranking of F-gases associated with the range in magnitude of emissions reflects the same order of phase out and BA substitution historically observed

  • *Reflects waste age (30+ years) for some locations*

• F-gas emissions constitute a moderate and detectable portion of the total LF GHG emissions (4-17%)
References


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