Instrumentation and Monitoring for Bioreactor Landfills
Monitoring Parameters

- Liquids
  - Amount, Characteristics, Depth/Pressure
- Gases
  - Amount, Characteristics, Pressure
- Waste
  - Characteristic, Temperature, Mass/Volume, Loss
Options for Monitoring

• Labor intensive
  – Collect a sample and have analyzed
    • Sample leachate and analyze BOD
  – Take a measurement in the field
    • Measure the depth of water in a well

• In situ instrumentation
  – Moisture content
  – Temperature
  – Pressure
Monitoring Approaches for Landfill Bioreactors (US EPA 2004)

- Physical Monitoring Parameters
  - Geotechnical Considerations
  - Head on Liner and Leachate Management
  - Mass Balance
  - Moisture Balance

- Analytical Monitoring Parameters
  - Leachate Monitoring
  - Solids Monitoring Parameters
  - Gas Monitoring Parameters
Primary Bioreactor Landfill Gas Monitoring Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total gas</td>
<td>At least once a week</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>Weekly</td>
</tr>
<tr>
<td>Oxygen</td>
<td>Weekly</td>
</tr>
<tr>
<td>Methane</td>
<td>Weekly</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>Weekly</td>
</tr>
<tr>
<td>Parameter</td>
<td>Frequency</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>Average Temperature</td>
<td>Once every 18 months</td>
</tr>
<tr>
<td>Average pH</td>
<td>Once every 18 months</td>
</tr>
<tr>
<td>Average Volatile Solids (% M/M)</td>
<td>Once every 18 months</td>
</tr>
<tr>
<td>Average Wet Based Moisture Content (%)</td>
<td>Once every 18 months</td>
</tr>
</tbody>
</table>
### Secondary Bioreactor Landfill

#### Leachate Monitoring Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatile Organic Compounds (VOCs) (μg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Semi-Volatile Organic Compounds (SVOCs)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Volatile Fatty Acids (mg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Arsenic (mg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Barium (mg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Cadmium (mg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Calcium (mg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Copper (mg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Chromium (mg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Iron (mg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Lead (mg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Magnesium (mg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Potassium (mg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Sodium (mg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Selenium (mg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Silver (mg/L)</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Zinc (mg/L)</td>
<td>Quarterly</td>
</tr>
</tbody>
</table>
## Primary Bioreactor Landfill
### Leachate Monitoring Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static head on Liner</td>
<td>£</td>
</tr>
<tr>
<td>Temperatur</td>
<td>Monthly</td>
</tr>
<tr>
<td>pH</td>
<td>Monthly</td>
</tr>
<tr>
<td>Conductance (μSm/cm)</td>
<td>Monthly</td>
</tr>
<tr>
<td>Total Dissolved Solids (mg/L as CaCo₃)</td>
<td>Monthly</td>
</tr>
<tr>
<td>Alkalinity (mg/L)</td>
<td>Monthly</td>
</tr>
<tr>
<td>Chloride (mg/L)</td>
<td>Monthly</td>
</tr>
<tr>
<td>Bromide (mg/L)</td>
<td>Monthly</td>
</tr>
<tr>
<td>Floride (mg/L)</td>
<td>Monthly</td>
</tr>
<tr>
<td>Sulfate (mg/L)</td>
<td>Monthly</td>
</tr>
<tr>
<td>Chemical Oxygen Demand (mg/L)</td>
<td>Monthly</td>
</tr>
<tr>
<td>Biochemical Oxygen Demand (mg/L)</td>
<td>Monthly</td>
</tr>
<tr>
<td>Total Organic Carbon (mg/L)</td>
<td>Monthly</td>
</tr>
<tr>
<td>Total Phosphorous (mg/L)</td>
<td>Monthly</td>
</tr>
<tr>
<td>Ortho Phosphate (mg/L)</td>
<td>Monthly</td>
</tr>
<tr>
<td>Ammonia (mg/L)</td>
<td>Monthly</td>
</tr>
<tr>
<td>Nitrite (mg/L)</td>
<td>Monthly</td>
</tr>
<tr>
<td>Nitrate (mg/L)</td>
<td>Monthly</td>
</tr>
</tbody>
</table>
Bioreactor Liquid Addition Monitoring Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of Leachate Added</td>
<td>Daily</td>
</tr>
<tr>
<td>Rainfall</td>
<td>Daily</td>
</tr>
<tr>
<td>Volume Outside Liquid Added (e.g. Groundwater, Industrial Waste Water)</td>
<td>Daily</td>
</tr>
<tr>
<td>Volume of Leachate Generated</td>
<td>Daily</td>
</tr>
<tr>
<td>Mass of Sludge Added</td>
<td>Daily</td>
</tr>
<tr>
<td>Wet Basis Moisture Content of Sludge Added</td>
<td>Daily</td>
</tr>
</tbody>
</table>
# Mass Loading Calculation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Landfill Inspection</td>
<td>Daily</td>
</tr>
<tr>
<td>Mass of Landfilled MSW</td>
<td>Daily</td>
</tr>
<tr>
<td>Mass of Landfilled Construction and Demolition Waste</td>
<td>Daily</td>
</tr>
<tr>
<td>Mass of Soil (other than daily cover)</td>
<td>Daily</td>
</tr>
<tr>
<td>Type of Daily Cover</td>
<td>Daily</td>
</tr>
<tr>
<td>Mass of Daily Cover</td>
<td>Daily</td>
</tr>
<tr>
<td>Landfill Volume</td>
<td>Quarterly</td>
</tr>
<tr>
<td>Settlement</td>
<td>Quarterly</td>
</tr>
</tbody>
</table>
Monitoring Issues

• Leachate quality measurements
• Chemical nature of leachate has been used as an indicator of “stability”
• The BOD:COD ratio has been considered a good stability parameter
• BOD:COD < 0.1 indicates that the leachate is typical of that from stabilized landfill area
Boundary of bioreactor area

Injection well cluster

Landfill Surface

10 ft Safety zone

2 ft bottom liner

2 ft thick bottom liner

100 ft
Monitoring Issues

- Landfill gas
- One issue learned at NRRL is that many meters that claim to measure carbon monoxide are not very effective
Monitoring Issues

• Measuring chemical nature of the waste in a landfill provides great data, but is very difficult
Biochemical Methane Potential

Methane Yield (L / g VS added)

Number of samples

0~0.05 0.05~0.10 0.10~0.15 0.15~0.20 0.20~0.25 0.25~0.30 0.30~0.35
0 2 4 6 8 10 12

BMP Assay Bottle
Monitoring Issues

• Moisture Content
Review of state of the art methods for measuring water in Landfills

Dr Debra Reinhart
University of Central Florida
Flowchart of the presentation

- Introduction
- Background
- Water Balance Approach
- Liquid Measurement Methods in Solid Waste
- Summary
- Cost Analysis
- Discussion
- Conclusions
Introduction

• Moisture control - the most critical parameter for bioreactor operation.
  – Insufficient liquid limits biodegradation rate
  – Excess liquid results in side seeps, poor gas collection and geotechnical instability.
  – Sensors to assess moisture distribution within the landfill, controlled liquid addition

• Review of moisture sensor devices that have been tested in the field and hold promise for monitoring moisture within landfills
Background

• Liquid in bioreactor landfills
  – While optimum moisture content for degradation is above 65%, typically it is between 15 and 40%.
  – Liquid and gas transport
  – Geotechnical stability due to increase in unit weight

• Sources of liquid
  – Non-indigenous liquid required
  – Fresh water (expensive); storm water; ground water; industrial wastewater;
  – Additional gas potential for anaerobic bioreactors by using industrial wastewater
Background

• Requirements of a liquid injection systems
  – Distribute uniformly
  – Minimal increase in pore water pressure
  – Be easy and economical to install
  – Types (horizontal trenches; high conductivity material blanket; vertical injection wells)

• Type of liquid measurement
  – Moisture content
  – Water saturation and volumetric water content
Background

- Relationship between moisture content, water saturation and volumetric water content

\[ \theta_w = n \times S_w \]

\[ M_c = \frac{S_w \times n \times P_w}{P_{wb}} \]

Where

- \( \theta_w \) = volumetric water content;
- \( S_w \) = water saturation;
- \( n \) = total porosity of refuse sample;
- \( M_c \) = moisture content;
- \( S_w \) = water saturation;
- \( P_w \) = density of water;
- \( P_{wb} \) = wet bulk density of waste.
Moisture Content Calculation

\[ PMC = \frac{(L_o \times M) + P + LA - LCH}{M} \times 100 \]

- \( L_o \): Moisture entering with waste mass (kg/kg of Waste Mass)
- \( M \): Total waste mass in bioreactor cell (kg)
- \( P \): Total precipitation infiltrating in bioreactor (kg)
- \( LA \): Liquids added to waste mass including recirculation (kg)
- \( LCH \): Total Leachate collected (kg)

Source: EPA-456/R-03-007
Moisture Content Calculation

• A typical value of $L_o$ in most MSW landfills in the United States is about 25% on wet basis (wt of water/(wt of water + dry solids))

• $M$: Waste mass is calculated from waste acceptance and waste placement data

• $P$: Total precipitation infiltrating in the cell can be calculated using a rigorous approach (HELP or EPA spreadsheet - lfmassbalbxl.xls)
Moisture Content Calculation

• LA: Liquids added is the sum of leachate recirculated through Horizontal/Vertical wells, and/or horizontal trenches, and/or liquids introduced at the top via truck

• LCH: Total amount of leachate as indicated by flow meter readings, and leachate, if any, collected and directly sent for treatment
WS1.0: A Numerical Tool for Calculation of Moisture Balance in Landfill

- A FORTRAN program to calculate moisture balance for bioreactor landfill.
- Numerical tool that calculates liquids addition from different sources.
- The actual leachate generation of leachate may differ from the model results given the preferential flow of liquids.
- Based on EPA Moisture Content Calculation (EPA-456/R-03-007)
WS1.0 Input Data – Landfill Description

- Aerial spread (acres)
- One longitudinal dimension and the height
- Assumes a side slope of one vertical to two parts horizontal in order to calculate the top area of landfill.
- Number of lifts
- Total quantity of solid waste on as received basis (or specific weight)
- Cover is assumed to be ten percent of solid waste
- Initial moisture content value on wet weight
WS1.0 Input Parameter - Time

- Time in years for running the simulation
- Time in years for the landfill to complete the waste placement
WS1.0 Input Parameter – Moisture Addition

• Volume of moisture addition due to precipitation infiltration
• Volume of liquids hauled to the top of the open landfill,
• Volume of liquids injected using vertical wells.
WS1.0 Liquid Injection

• Method described by Jain et al. (2006) is the basis for calculating the maximum injection capacity of a vertical well.
• 50-ft spacing is assumed
• The model checks that the maximum injection capacity of a vertical well is not exceeded.
• The maximum head is kept such that it does not exceed a level of five feet from the top of landfill.
WS 1.0 Input Parameter – Liquid Injection

• Number of wells,
• Depth of well
• Screen length,
• Diameter of well,
• Total flow rate for all wells together.
• Start and stop time
• In its present form the model is unable to handle wells of different depths and intermittent injection of liquids.
Output

- Indication of operation outside flow capacity of wells
- Average MC within each lift as a function of time
- Liquids balance as a function of time
  - Leachate production once field capacity is exceeded
  - Contribution from infiltrating precipitation
  - Contribution from injection wells
  - Net change in liquid content
Liquid measurement methods

• Neutron probe
• Electrical resistance sensors (ERS)
• Electromagnetic techniques
  – Time domain reflectometry (TDR)
  – Time domain transmissivity (TDT)
• Electrical resistivity tomography (ERT)
• Partitioning gas tracers test (PGTT)
• Fiber optic sensors
Neutron probe

• Principle
  – Emitted neutrons thermalized by hydrogen atoms provided by water molecules
  – Calibration curve between volumetric water content and thermalized neutrons

• Limitations
  – Hydrogen atoms may originate from wood and plastic materials
  – Neutrons may also be captured by elements like iron, potassium and chloride.
  – Can not be used to measure absolute values but may assess changes in moisture conditions.
Neutron probe

• Field applications
  – Requires installation of aluminum access tubes in the field which ultimately requires a relatively large hole
  – Regulatory safety standards may be hindrance
  – Storage of equipment and disposal of probe
Electrical resistance sensors

- **Principle**
  - Relates electrical resistance to a current passing through the sensor to the matric potential of surrounding media.
  - Composed of gypsum, fiberglass, nylon or PVC tubes
  - Readings are affected by temperature and conductivity

\[
C_{25} = \frac{C_m}{1 + 0.02(t_m - 25)}
\]

Where
- \(C_{25}\) = corrected conductivity value adjusted to 25\(^\circ\)C
- \(C_m\) = actual conductivity measured
- \(t_m\) = water temperature at time of \(C_m\) measurement in \(^\circ\)C
Electrical resistance sensors

• Limitations
  – Cannot work reliably above the entry air pressure or below the field capacity
  – Other sources of error include sensor hysteresis, dependence on waste porosity and density, poor contact with the media, and deterioration of sensor over time

Yolo County Sensor
Resistivity Probe For Moisture Measurements
Electrical resistance sensors

• Field applications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>New River Regional Landfill</th>
<th>Anaerobic and Aerobic Test Cells at Yolo County, CA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between sensors (m)</td>
<td>15</td>
<td>3-5 (horizontally), 15-20 (vertically)</td>
</tr>
<tr>
<td>Number of sensors</td>
<td>134</td>
<td>161</td>
</tr>
<tr>
<td>Approximate measurement volume (m³)</td>
<td>914,400</td>
<td>410,884</td>
</tr>
<tr>
<td>Data collection mode</td>
<td>Automatic, every 12 hours</td>
<td>Automatic, every 6 minutes</td>
</tr>
<tr>
<td>Comparison of $M_c$ with gravimetric measurements</td>
<td>MTG Sensors $M_c=0.48$; Gravimetric $M_c=0.28$</td>
<td>See Figure</td>
</tr>
<tr>
<td>Duration of data collection period (years)</td>
<td>4</td>
<td>3 to 4 (depending on landfill cell)</td>
</tr>
<tr>
<td>Sensor costs</td>
<td>US$10,000</td>
<td>US$2,400</td>
</tr>
<tr>
<td>Installation equipment costs</td>
<td>US$30,000</td>
<td>US$48,000</td>
</tr>
<tr>
<td>Installation labor costs</td>
<td>US$10,000</td>
<td>US$11,000</td>
</tr>
</tbody>
</table>
Electrical resistance sensors

- Relationship between sensor resistance readings and $M_c$ is shown in Fig. 1 for three specific conductivity values 4, 8 and 16 mS/cm at room temperature.

![Fig. 1 Calibration curve for electrical resistance sensors developed at the University of Central Florida for varying moisture conductivities.](image)
Electrical resistance sensors

- 134 sensors installed at New River regional landfill (NRRL)
- 161 sensors installed at Yolo county
- Distances shown are between sensors

Results from Yolo County compared with gravimetric measurements

Fig. 2: Gravimetric Moisture Content (%) vs. Sensor Readings

- 0-3.0 m
- 3.0-4.6 m
- 4.6-6.1 m
- 6.1-7.6 m
- 7.6-9.1 m

Moisture Zones for Sensor Readings

- Completely Saturated
- Some Free Liquid
- No Free Liquid

Sensor Readings

Gravimetric Moisture Content (%)
Electromagnetic Techniques

• Principle
  - Relates the time of travel of EM waves to the dielectric constant of the waste which in turn can be correlated to $\theta_w$.
  - While TDR looks at time of travel of waves reflected back to the pulse generator, TDT measures the total time of travel through media and connecting cables.
  - Affected by changes in liquid electrical conductivity and temperature.
TDR Device Used in Florida
Electromagnetic Techniques

• Field applications
  – used at NRRL site, permeable blanket test in Michigan (Khire and Haydar, 2005) and San Sophie landfill in Quebec, Canada
  – 25% failed after two years at NRRL
  – Reported the passage of leachate front, but showed moisture contents above actual levels
Electrical resistivity tomography

• Principle
  – Based on measurement of the potential distribution arising when electrical current is injected into the underground via galvanic or capacitive contact.
  – Resistivity variations that occur during leachate injection trials indicate changes in the waste moisture content.
# Field application of ERT

<table>
<thead>
<tr>
<th>Parameters</th>
<th>La Vergne bioreactor (ONYX), Vendée (France)</th>
<th>Sydom bioreactor, Jura (France)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection system</td>
<td>Vertical wells</td>
<td>Horizontal trenches</td>
</tr>
<tr>
<td>Distance between injection wells/trenches (m)</td>
<td>30</td>
<td>19</td>
</tr>
<tr>
<td>Leachate injection flow (m³ h⁻¹)</td>
<td>5 to 30</td>
<td>5 to 10</td>
</tr>
<tr>
<td>Number of electrical lines</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Number of electrodes</td>
<td>176</td>
<td>48</td>
</tr>
<tr>
<td>Distance between electrodes along electrical line (m)</td>
<td>1</td>
<td>2.25</td>
</tr>
<tr>
<td>Interval between ERT on each electrical line</td>
<td>large time: ~2 months; short time (during leachate injection): 30 minutes</td>
<td>large time: 1 week; short time (during leachate injection): 15 minutes</td>
</tr>
<tr>
<td>Number of ERT</td>
<td>~700</td>
<td>~500</td>
</tr>
<tr>
<td>Number of measurements per ERT</td>
<td>360 to 1374</td>
<td>84</td>
</tr>
<tr>
<td>Range of volumetric water content deduced from ERT (%)</td>
<td>15 to 25</td>
<td>not available because of insufficient temperature sensors</td>
</tr>
<tr>
<td>Man hours per ERT (data processing, report, not including field measurements)</td>
<td>~1</td>
<td>~1</td>
</tr>
<tr>
<td>Man hours to install all electrodes and electrical lines</td>
<td>56</td>
<td>24</td>
</tr>
<tr>
<td>Capital costs for one electrical line embedded in the waste</td>
<td>US$3,750</td>
<td>US$2,500</td>
</tr>
</tbody>
</table>
Variations of electrical resistivity during an injection on the middle horizontal trench at the Sydom (Jura, France) test site during a short-time study. Gray-scale images show measured electrical resistivity, while color images indicate changes in resistivity during and after leachate injection. Axis scales are in meters.
Partitioning Gas tracers Technique (PGTT)

• Principle
  – The partitioning gas tracer test (PGTT) involves the injection and extraction of two tracers under steady gas flow within solid waste.
  – Because the tracers are separated “chromatographically” in time due to the influence of water, the difference in mean arrival times is a measure of the fraction of the pore space occupied by water, i.e. $S_w$.
  – Key thermodynamic parameter is Henry’s law constant, $K_H$, which in turn depends on temperature and dissolved solutes.
Instrumentation shed where all field analyses were conducted (Yolo County). Anaerobic bioreactor test cell is in background.

Photos courtesy of Paul Imhoff
Gas cylinders containing helium and difluoromethane for injection in tracer tests.
Adjustment of tracer gas flows from gas cylinders outside of shed.
Injection of tracer gases into desire tubes that terminate at different locations in bioreactor test cells.

Tube carrying tracers from outside of shed

One of ~50 locations to inject tracers into landfill.
Collection of tracer gases from the aerobic bioreactor in horizontal gas collection well.
Header pipe carrying landfill gas (and tracers) from landfill back to blower. Samples extracted from piping and directed into instrument shed.
A subset of samples analyzed in the field with field-portable gas chromatograph.
A subset of samples transported back to the lab to “check” field analysis of samples
Field applications of PGTT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Aerobic Bioreactor, Yolo County, California</th>
<th>Sandtown Landfill, Delaware Solid Waste Authority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between injection/extraction wells (m)</td>
<td>3.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Approximate measurement volume (per test) (m³)</td>
<td>20</td>
<td>1.5</td>
</tr>
<tr>
<td>Number of tests</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Range of $S_w$ measured</td>
<td>0.082 – 0.30</td>
<td>~0.0 – 0.32</td>
</tr>
<tr>
<td>Range of $M_c$ measured</td>
<td>0.086 – 0.29</td>
<td>~0.0 – 0.245</td>
</tr>
<tr>
<td>Comparison of $M_c$ with gravimetric measurements</td>
<td>PGTT: $M_c = 0.29 \pm 0.03$</td>
<td>PGTT: $M_c = 0.245 \pm 0.02$</td>
</tr>
<tr>
<td></td>
<td>Gravimetric $M_c = 0.24$</td>
<td>Gravimetric $M_c = 0.26 \pm 0.06$</td>
</tr>
<tr>
<td>Duration of each test (h)</td>
<td>22.7 and 43.9</td>
<td>6.2 - 12</td>
</tr>
<tr>
<td>Expendable costs per test</td>
<td>US$550</td>
<td>US$250</td>
</tr>
<tr>
<td>Capital costs</td>
<td>US$2,500</td>
<td>US$4,000</td>
</tr>
<tr>
<td>Man hours per test (h)</td>
<td>35 and 60</td>
<td>8-15</td>
</tr>
</tbody>
</table>
Tracer gas concentrations (He = Helium, DFM = difluoromethane) measured at the gas extraction well for Test #6 at the Sandtown Landfill (Delaware Solid Waste Authority). Gas concentrations are normalized with the maximum influent concentration of each tracer. Lines indicate exponential extrapolations of the data.
Fiber Optic Sensors

• Principle
  – Distributed temperature sensing method based on Raman scattering
  – Equipment sends a short laser pulse into the sensing fiber.
  – Local reflections are received along the fiber length.
  – Measuring the optical signal received at different times can give temperature readings.
  – Changes in volumetric water content can be detected directly or by combining temperature measurements with heat pulses
## Field application of Fiber Optic Sensors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ämmässuo landfill site</th>
<th>Mustankorkea landfill site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality of surface-sealing layer</td>
<td></td>
<td>Effects of leachate recirculation (municipal solid waste and two different ashes)</td>
</tr>
<tr>
<td>Installation year</td>
<td>2001</td>
<td>2003</td>
</tr>
<tr>
<td>Installation geometry</td>
<td>one horizontal layer</td>
<td>two horizontal layers</td>
</tr>
<tr>
<td>Length of monitoring cable (m)/test location</td>
<td>3800</td>
<td>90</td>
</tr>
<tr>
<td>Number of test target</td>
<td>1</td>
<td>4 (four test cells)</td>
</tr>
<tr>
<td>Number of sensor points</td>
<td>7,600 – 15,200</td>
<td>4 x 180-360</td>
</tr>
<tr>
<td>Approximate measurement area (m²) or volume (m³)</td>
<td>20,000 m²</td>
<td>112 m³</td>
</tr>
<tr>
<td>Spatial resolution (m)</td>
<td>0.25-5</td>
<td>0.25-0.50</td>
</tr>
<tr>
<td>Number of data collection periods</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>Duration of each data collection period (h)</td>
<td>1-72</td>
<td>Jan-72</td>
</tr>
<tr>
<td>Main results and observed events</td>
<td>Effects of gas flow, possible leakage through the sealing materials, possible seepage paths in sides, temperatures below 0°C indicating possibility for frost and functioning problems in the mineral sealing</td>
<td>One corner of one cell was wet, otherwise small temperature differences throughout waste, low ambient temperatures kept the test cells cool</td>
</tr>
<tr>
<td>Capital costs of sensor system with installation costs</td>
<td>US$35,000</td>
<td>US$3,500</td>
</tr>
<tr>
<td>Man hours per test/ data collection periods</td>
<td>4-21</td>
<td>4-10</td>
</tr>
</tbody>
</table>
An example of **temperature surface maps** (about 200m x 100m area) measured by the fiber optic sensor cable network installed in the surface-sealing layer at the Ämmässuo landfill site. The locations of the fiber optic sensor cables (thin black lines) and gas collection pipes (blue lines) are also seen in the maps.
## Summary

<table>
<thead>
<tr>
<th>Measurement Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Neutron Probe         | • Moisture content can be measured regardless of its physical state in soils or waste  
                        • Offers large radius of influence, between 150 mm in wet soil and 700 mm in dry soil | • Moisture Measurement of absolute moisture content is difficult  
                        • Presence of non-water bound hydrogen interferes with the measurement  
                        • Some elements other than hydrogen have a propensity to absorb high-energy neutrons  
                        • Changes in density affect the results  
                        • The radioactive source of neutron probe is a highly regulated material  
                        • Automation is not |
# Summary

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</tr>
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</table>
| **Electrical Resistance/Impedance Sensors** | • Sensors are relatively inexpensive  
• Sensor installation is easy  
• Automated measurement is possible  
• Can be produced inexpensively  
• Density does not affect readings  
• Fast response to leachate front arrival | • Sensors suffer from hysteresis at low moisture contents  
• Results affected by changes in electrical conductivity and temperature  
• Once wet the sensors do not drain quickly  
• Sensor must be calibrated using extracted waste |
<table>
<thead>
<tr>
<th>Measurement Technique</th>
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<th>Disadvantages</th>
</tr>
</thead>
</table>
| Electromagnetic Techniques (Time Domain Reflectometry/Transmissometry) | • Sensors are relatively inexpensive  
• Results are reproducible  
• Automated measurement is possible  
• Fast response to leachate front arrival | • Results affected by changes in electrical conductivity  
• Local heterogeneity of material properties affects the results  
• Sensor must be calibrated using extracted waste |
<table>
<thead>
<tr>
<th>Measurement Technique</th>
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<th>Disadvantages</th>
</tr>
</thead>
</table>
| Electrical Resistivity Tomography | • Non-intrusive technique  
• A two-dimensional evolution of a leachate injection plume can be obtained  
• Fast response to leachate front arrival | • Requires the knowledge of leachate electrical conductivity  
• Needs measurement of in situ temperatures from additional temperature sensors  
• Expensive instrumentation costs  
• Technique not evaluated for moisture content measurement |
## Summary

<table>
<thead>
<tr>
<th>Measurement Technique</th>
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</tr>
</thead>
</table>
| PGTT                  | • Provides reasonably accurate assessment of moisture content  
• Measurement accuracy is unaffected by the measurement volume  
• Relatively inexpensive field setup is required  
• Tracer gases can be injected through existing injection wells of a landfill | • Gas sample collection and laboratory analysis pose difficulty for automation  
• Needs measurement of in situ temperatures from additional temperature sensors  
• On larger scale provides assessment of average conditions and may not identify relatively wet spots |
## Summary

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<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Fiber</td>
<td>• Provides data measurements at high spatial resolution</td>
<td>• Technique not evaluated for moisture content measurement</td>
</tr>
<tr>
<td></td>
<td>• Ease of installation and automation</td>
<td>• Interference from preferential high gas flows in measurements</td>
</tr>
<tr>
<td></td>
<td>• Fast response to leachate front arrival</td>
<td></td>
</tr>
</tbody>
</table>
Cost Analysis

Sampling Volume = 200 m³

Sampling Volume = 20 m³

- Electrical Resistance
- Partitioning Gas Tracers
- Time Domain Reflectometry
- Neutron Probe
- Electrical Resistivity Tomography
- Fiber Optic

Total Sampling Cost - US Dollars

Frequency of Measurement

Daily, Weekly, Biweekly, Monthly
Discussion

• Several criteria to evaluate the methods
  – Accuracy of measurement
  – Water saturation or volumetric water content; ability to track infiltration fronts in refuse; reliability in the landfill environment; and cost (covered earlier)

• Accuracy of measurement
  – PGTT successful but at low to intermediate moisture contents
  – Electric resistance and TDR sensors resulted in biased estimates
  – Neutron probe helpful in determining volumetric water content
  – Results from ERT and fiber optic sensors not compared
Discussion

• Tracking infiltration fronts
  – Electric resistance, TDR and ERT successful
  – PGTT method not appropriate because of long time duration involved.
  – Neutron probe and fiber optics not tested in field

• Instrument reliability
  – ERS gave the best results
  – Sufficient record not available for other methods
Conclusions

• For accurate measurement of moisture content in refuse, PGTT method should be preferred

• To track infiltration fronts
  – Electrical Resistance Sensors
  – Time Domain reflectometry
  – Electrical Resistivity Tomography

• For frequent measurements
  – An automated method would be best
  – Still to be researched
thank you!
In-Situ Moisture Measurement Results at NRRL

• Recall from an earlier presentation that two types of moisture sensors were installed in NRRL
  → Resistivity Sensors → TDR Sensors
Typical Response-MTG sensor

![Graph showing the response of MTG sensor over time with different resistance levels labeled as Lower, Middle, and Upper. The x-axis represents days (Day 1 = 01/01/03), and the y-axis represents resistance (KOHMS) ranging from 0.001 to 100. The graph highlights the start of recirculation.]
Simulated Waste
Calibration Process
Calibration Curves

\[ MC = \frac{a}{1 - b \times e^{-cR}} \]
Sensor Performance

- MTG
  - 133 out of 135 provided output in expected range of 0.005 kΩ to 466.7 kΩ.
  - 107 sensors registered a drop in resistance in response to leachate recirculation.
  - 18 sensors had resistance reading of less than 0.05 kΩ, which is indicative of saturation. These sensors did not register any change in response to leachate recirculation.
Sensor Performance

• More than 95% of the moisture sensors located 25-30 ft away from the wells registered an increase in moisture content.
• 30% of the sensors respond to the drying cycle.
Moisture Content-MTG sensor

Days (Day 1 = 01/01/03)
Response of TDR

Apparent length on screen

\[ \varepsilon = \left( \frac{L_2}{L} \right)^2 \quad \varepsilon' = \left( \frac{L'_2}{L} \right)^2 \quad \varepsilon' > \varepsilon \]
Sensor Performance

• TDR
  – 9 out of 12 sensors generated a waveform
  – All 9 TDR probes registered a change
  – Currently 3 sensors are reflecting the waveform
Comparison of TDR and MTG

Time (in Days)
(Day 1 = 01/01/03)

Moisture Content (% w/w)

TDR sensor
MTG sensor
Moisture Distribution

Before recirculation (Day 150)

After recirculation (3,200 m³) (Day 318)

After recirculation (10,000 m³) (Day 491)

After recirculation (14,700 m³) (Day 578)
Estimated Moisture Content

Days (Day 1 = 01/01/03)

Moisture Content (% w/w)

Based on mass balance
Based on conductivity = 8 mS/cm
Based on conductivity = 16 mS/cm
Limitations of Sensors

• Estimated moisture content is much greater than anticipated based on mass balance, potentially because of
  – Preferential flow of leachate
  – Higher conductivity of leachate than calibration solutions
Monitoring Issue

• Temperature

• In-situ waste temperature measurements can help assess degree of biological activity

• It is also very critical to measure temperature when adding air
Thermocouples

- Technology most frequently applied to landfills
- Thermocouples are pairs of dissimilar metal wires joined at one end.
- Thermocouples tend to be more rugged and less expensive than thermistors, however they are slightly less accurate.
- Type J thermocouples are most commonly used in landfills.
- Damage to the sensor wiring cable is one of the most common causes of sensor failure.
Thermistors

- Measure temperature as a function of the change in electrical resistance of materials.
- Composed of inexpensive semiconductor materials.
- They are accurate over a smaller range than thermocouples.
- They are quite stable and accurate over temperature ranges expected in bioreactor landfills.
Monitoring Issue

Head on the Liner

- LCRS should be designed to maintain less than 1 ft of head on the liner.
- Some bioreactor landfills are required to monitor leachate head.
Measuring Head on the Liner

- Measuring water level in the sump or lift station
- Issues:
  - Can give an idea what a minimum level might be, but not a maximum

In this example, the head in the sump has no relationship with the head on the liner system
Measuring Head on the Liner

- Piezometer buried within the waste
- Issues:
  - Installation
  - Preferential channeling?
  - Changes flow pattern in LCRS?
  - How representative?

Device for Measuring liquid level must be lowered into the pipe
Measuring Head on the Liner

- Placement of a device (e.g., a transducer) in the LCRS on top of the liner for direct measurement
- Issues:
  - Installation
  - Long-term performance?
  - Impact of gas pressure?
  - How representative?
Measuring Head on the Liner at NRRL
Transducer Installation

LCS Surface

Drainage Layer

Geomembrane

Geofabric

Pressure Transducer
Monitoring Issues

• Measuring Pressures in the Landfills

• Different locations where pressure measurements are useful
  – Depth of water (e.g., head on the liner)
  – Weight of landfill
  – Pore water pressure
Pressure Measurement

- Instruments utilize an electrical transducer, the output (current, voltage, frequency) of which changes as a function of the applied pressure.
- Different configurations allow different types of pressures to be utilized.
Water Level Transducers

- Transducers can be lowered in water as a tool to measure the depth of standing water above the transducer.
Total Earth Pressure Cells

Used for measuring the pressure of material above a particular location (the load)

- Welded steel plates for pressure measurement
- Vibrating wire transducer
Earth Pressure Cells at NRRL

Cell 3
Earth Pressure Cell Installation

- Excavate Cell Location
- Place and Test Cell
- Backfill and Compact
- Re-test Cell

June – August 2000
Data Collection
Results: Pressure Cell Output

Pressure Cell R (TO6)

Overburden Pressure

Landfill Depth
Pore Water Pressure Transducers

• Measure the fluid pressure surrounding the sensor.
• Similar to transducers used for water level measurements, but design to be buried.
• Pore water pressure is important because of stability concerns.
Injection line Cross-Section

Vibrating Wire Piezometer Grid
Data logger for transducers installed in the summer
Pore Water Pressure Evaluation at NRRL (vertical wells)

• Goals
  – Measure water movement through municipal solid waste utilizing vertical injection wells
  – Slope stability implications
Test Site – New River
Regional Landfill – Raiford, FL

Bioreactor Area

Cell 3 Project Area
Injection Well/Instrument Layout

Well #1

Well #2

Injection Wells

10'

5'

25' Between Wells

VW Piezometer Well

Current Bioreactor
Injection Well/Instrument Vertical Layout

Injection Well #1

Data Station

Injection Well #2

Cover Soil

MSW

VW piezometers

Data Station

Injection Well/Instrument Vertical Layout

Injection Well #1

Data Station

Injection Well #2

Cover Soil

MSW

VW piezometers
Vibrating Wire Piezometers

- Multilevel Housing
- 5 per instrument borehole
- 10’ increments

*Diagrams: www.slopeindicator.com
Drill Borehole
Insert Instruments connected via PVC
Pump Grout Through Pipe Into Borehole
Connect Instruments, Inject Leachate, Measure Pressure/Water Front
Insert Instruments connected via PVC
Cover Soil
Injection Well
MSW
Monitoring Issues

• Displacement Measurements
  – Settlement of the landfill surface
  – Settlement of layers within or underneath the landfill
  – Lateral movement of the waste mass
Settlement

- Surveys/Photogrammetry/LiDAR
  - Overall settlement
- Static settlement sensors
  - Single point settlement data
- Mobile settlement profilers
  - Line settlement data
Settlement Plates

Allow waste layers within the landfill to be measured for elevation depth over time.
Settlement Sensors

Model 4650 installation for the remote measurement of subsurface settlement beneath a large embankment.

(Geokon.com)
Settlement Profiler

Model 4651 installation used to measure and monitor embankment settlement. As an alternative installation, the empty manhole (shown above at left) and open-ended pipe may be replaced by a capped pipe with a pulley and return cable to pull and position the torpedo from the reel end of the pipe (shown above at right).
Settlement Profiler Dead End Pull

- Water Level Control
- Water Level Sight Tube
- Readout Box
- Desiccant Chamber
- Reservoir
- Shaft
- Graduated Liquid Tube and Sensor Cable
- Reel
- Spacer
- Sensor
- Reference Station
- Pedestal
- Pull-in Cable
- Buried Pipe
Settlement Profiler

- Measure temporal and spatial settlement at different depths within the landfill
Measuring Settlement
Measuring Settlement
Slope Inclinometers

- Another method to measure settlement in a horizontal profiler is to measure the slope change using an inclinometers.
Horizontal Inclinometers

slopeindicator.com
Vertical Inclinometers

• Can be used to measure slope changes. This may thus be a method of monitoring for side slope stability.

Vertical Inclinometers

Inclinometer Casing

Landfill Slope
Vertical Inclinometers

Inclinometer Casing

Landfill Slope
Example of Instrumentation Application at Landfill

• The Polk County Phase III landfill cell has been designed as a bioreactor landfill.
• It has also been designed as a very deep landfill.
• An issue with all landfills, especially deeper facilities, is “to what extent will the subsurface settle?”
Phase III
Phase III
Project Description

• Install settlement cells and earth pressure cells underneath the Phase III liner

• Measure settlement and overburden pressure over the life of the landfill
Research Objectives

• Measure overburden pressure atop settlement cells with earth pressure cells
• Correlate settlement with overburden pressure
• Compare actual settlement with predicted settlement based on Cone Penetration Tests
  – Differential settlement
Phase III
16 Settlement Cells

Model 4650 installation for the remote measurement of subsurface settlement beneath a large embankment.

(Geokon.com)
Phase III Site

Cell 2

Cell 1

Berm

Box

Looking
Wrap Up of Day 1

- Bioreactor basics and activity in Florida
- Regulations pertaining to bioreactors
- Considerations for bioreactor feasibility
  - Regulatory, technical and site factors
  - Economics
- Instrumentation and monitoring of bioreactor landfills
Preview of Day 2

• Tour of Polk County North Central Landfill in the morning

• Afternoon:
  – Bioreactor design and operation strategies
  – Aerobic bioreactor landfills