Bioreactor Design & Operation; Demonstration Projects, Results & Future Directions

Debra Reinhart, PhD, PE, DEE
University of Central Florida
Presentation Overview

- Florida bioreactor landfill demonstration project
  - Overview
  - Results
  - Economics
  - Methane generation by wet cell landfills
- Future directions of bioreactor landfills
Florida Bioreactor Landfill Demonstration Project
To design, construct, operate and monitor a full-scale landfill bioreactor in Florida in a manner that permits a complete and fair evaluation of this technology as a method of solid waste management in Florida, with appropriate consideration of science, engineering, environmental and economic issues.
Florida Bioreactor Demonstration Project
Goals and Objectives

The objectives of the landfill bioreactor demonstration are to:

- Design and operate the bioreactor technology using innovative techniques and concepts.
- Control and measure all major inputs and outputs.
- Develop standardized design and operation procedures for this technology.
- Further define and quantify the true costs and benefits of landfill bioreactors.
Florida Bioreactor Demonstration Project
Goals and Objectives

- Evaluate the use of aerobic bioreactor landfill technology
- Compare the aerobic approach to the use of anaerobic bioreactor technology.
- Instrument the landfills to permit *in-situ* monitoring of bioreactor activity
- Monitor the landfills in a manner to measure the impact of bioreactor activities
New River Regional Landfill

- Located in Union County Florida
- Manages waste from several North Florida Counties (approximately 800 tons per day)
- Retrofit Bioreactor
Project History

- Project Development & Design
- Permit Application Submitted (1998)
- Well Field Installation (1999)
- Permit Awarded (2000)
- Construction Initiated (2001)
- Leachate Recirculation Initiated (2002)
- Air Injection Initiated (2003)
- Permit Awarded (2005)
- Project Complete (2006)
Bioreactor Features

- Leachate recirculation system
- Air injection system
- Exposed geomembrane cap (EGC)
- Gas collection system
- In-situ instrumentation
- Segregated leachate collection system
New River Regional Landfill
NRRL Bioreactor Construction Aerials – View to North

June 24, 2002
Top of Landfill

Installation of Vertical Wells

Top of Sand Drainage Blanket

10 ft
In addition to leachate/air injection wells, the researchers will also be installing instrumentation within the landfill to measure Moisture, Temperature and Gas composition. Future updates will discuss the operation of these MTG sensors in more detail. In short, these gravel-packed slotted PVC cylinders contain a device for sensing the degree of moisture present, as well as a temperature thermocouple and a tube for collecting gas samples.
Vertical Injection Well Clusters

Instrumentation Cluster
Toe Drain

Toe Drain Under Construction
Gas is collected from the horizontal trenches underneath the exposed geomembrane cap.
Candle-Stick Flare

Two Positive Displacement Air Blowers

Three Centrifugal Gas Extractors
Moisture Distribution

Before recirculation (Day 150)

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

Higher moisture content

Lower moisture content

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

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

- Based on mass balance
- Based on conductivity = 8 mS/cm
- Based on conductivity = 16 mS/cm
Settlement Around a Vertical Well

![Graph showing settlement around a vertical well with radial distance from the well cluster on the x-axis and settlement on the y-axis.](image-url)
Settlement and Moisture Addition

![Graph showing the relationship between settlement (in feet) and moisture added (in gallons). The graph displays a positive correlation, with settlement increasing as moisture added increases.](image-url)
The Presence of Moisture can Greatly Impact Air Permeability
The hydraulic conductivity of waste ($K_s$) was determined by conducting borehole permeameter tests. These tests involve measuring the steady-state pressure at the bottom of the well for a constant flow rate.
Hydraulic Conductivity

<table>
<thead>
<tr>
<th>Depth Layer</th>
<th>Number of Locations</th>
<th>Field saturated hydraulic conductivity, $K_s$ ($\times 10^{-6}$ cm/sec) AM±SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Layer (3-6 m deep)</td>
<td>8</td>
<td>2.41±1.89</td>
</tr>
<tr>
<td>Middle Layer (6-12 m deep)</td>
<td>10</td>
<td>1.22±0.58</td>
</tr>
<tr>
<td>Deep Layer (12-18 m deep)</td>
<td>5</td>
<td>1.19±0.50</td>
</tr>
</tbody>
</table>
Florida bioreactor project has met its objectives to develop design and operating criteria, if not to achieve bioreactor status.

Multiple publications, theses, and dissertations have been published.

Bioreactor continues to be operated with leachate and air injection.

Data compilation and release will occur over the next year.
Florida Bioreactor Landfill Demonstration project was funded by the Hinkley Center for Solid and Hazardous Waste Management.
Objectives:

- Evaluate the economic feasibility of aerobic and anaerobic bioreactor landfills, comparing their costs to conventional landfills
## Total Present Worth Cost Comparison

<table>
<thead>
<tr>
<th>Type</th>
<th>Settlement (%)</th>
<th>Gas recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Retrofit bioreactor (anaerobic)</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>As built bioreactor (anaerobic)</td>
<td>25</td>
<td>50</td>
</tr>
</tbody>
</table>

*Air space recovery is assumed to be utilized at the end of the retrofit bioreactor life and as it occurs in the as-built bioreactor.
Post Closure Savings

- 30 yrs Traditional
- 30 yrs Bioreactor
- 25 yrs Bioreactor
- 20 yrs Bioreactor
- 15 yrs Bioreactor
- 10 yrs Bioreactor

Post-Closure Cost (Million $)
PW Cost of a Hybrid Landfill as a Function of Duration of Air Addition

With Gas Recovery

<table>
<thead>
<tr>
<th>Air addition (years)</th>
<th>Present Worth (Million $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>1</td>
<td>51</td>
</tr>
<tr>
<td>2</td>
<td>52</td>
</tr>
<tr>
<td>3</td>
<td>53</td>
</tr>
<tr>
<td>4</td>
<td>54</td>
</tr>
<tr>
<td>5</td>
<td>55</td>
</tr>
</tbody>
</table>

- **Retrofit** (blue bars)
- **As-Built** (red bars)
PW Cost of a Hybrid Landfill as a Function of Duration of Air Addition

No Gas Recovery

Present Worth (Million $)

Air addition (years)

retrofit
As-built
Conclusions

- Without advantages associated with reduced PCC, retrofit bioreactor and traditional landfill PW costs are extremely close.
- As-built bioreactor landfills have lower costs than traditional and retrofit bioreactor landfills, mainly because of air space recovery and leachate treatment.
- Utilization time of recovered air space is important. If utilized at the end of a bioreactor it is not nearly as profitable as if utilized as it is occurring.
- Cost of aerobic landfills is greater than anaerobic when gas recovery and use is possible. The difference reduces when no gas recovery is planned or where leachate treatment costs are high.
- Inefficient gas collection during active phase reduces the benefit of enhanced gas production.
Design Implications

- **Location of injection**
  - Sufficient distance from side slopes (50-100 ft)
  - Sufficient waste above (~ 20 ft)
  - Spacing of 50 ft common

Horizontal Injection Spacing

Vertical Injection Spacing
Liquid introduction rates
  - Horizontal injection (0.15 - 0.30 gpm/ft trench)
  - Vertical injection
    - Injection rates of 0.5-2.5 gpm
    - Well specific capacity $10^{-6}$ to $10^{-7}$ m$^3$/sec/m of screen length

Maximize flexibility with multiple sources and systems

Avoid impermeable daily cover

Allow for settlement using flexible hose connections

Provide cleanout
Design Implications – Cont’d

- Materials of construction – usually HDPE
- Pipe diameter 3-4 in
- Trench width 3-5 ft
- Perforation size 3/8 to ¾ in
- Bedding materials
  - Chipped tires
  - Stone/gravel
  - Crushed glass
Wet Cell Gas Generation

Year

LFG Flow Rate (m³/Yr)

k = 0.5
k = 0.2
k = 0.04
Data Collection

- Sites with continuous flow data, waste placed at one time: Yolo Co. Test Cells and Full Scale Cells (NE and WS), DSWA Test Cells, Brogborough Test Cells, and GIT

- Sites with continuous flow data, waste placed over multiple years: Southern Solid Waste Management Center (Delaware), Central Solid Waste Management Center (Delaware), and Landfill A

- Sites with single data points (16) - multiple full-scale wet landfills where data were not collected over a long period of time
Selected Single Points

Selected Single Points Best Fit Curve

- Wijster BR, Netherlands
- Alachua Co, FL
- Middle Peninsula, VA
- Spruce Ridge, MN
- Crow Wing, MN
- Sorab Test Cells
- Salem Co., NJ
<table>
<thead>
<tr>
<th>Method</th>
<th>$k$ (yrs$^{-1}$)</th>
<th>$L_0$ (m$^3$/Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single Placement Sites</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brogborough Wet</td>
<td>0.39</td>
<td>73</td>
</tr>
<tr>
<td>Yolo Full-scale NE</td>
<td>0.20</td>
<td>83</td>
</tr>
<tr>
<td>Yolo Pilot Wet</td>
<td>0.23</td>
<td>88</td>
</tr>
<tr>
<td><strong>Multiple Placement Sites</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SSWMC</td>
<td>0.21</td>
<td>115</td>
</tr>
<tr>
<td>Landfill A</td>
<td>0.11</td>
<td>95</td>
</tr>
<tr>
<td>CSWMC</td>
<td>0.12</td>
<td>87</td>
</tr>
<tr>
<td><strong>Mixed-effects Model</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.28</td>
<td>76</td>
</tr>
<tr>
<td>Upper 95%</td>
<td>0.28</td>
<td>96</td>
</tr>
<tr>
<td>Lower 95%</td>
<td>0.28</td>
<td>54</td>
</tr>
</tbody>
</table>
Study Recommendations

- $k = 0.3 \text{ year}^{-1}$
- Lo of 100 m$^3$/Mg
Future Directions

■ Role of aerobic bioreactor landfilling
■ In situ nitrification/denitrification
■ Pump and treat aerobic flushing bioreactor landfill
Aerobic Landfills
Advantages

- Enhance waste degradation
- Mitigate odor and methane emissions
- Increase settlement/airspace recovery
- Reduce leachate management liability and costs
- Removal of anaerobically recalcitrant compounds (i.e. ammonia-nitrogen)
- Reduce environmental risk
Challenges Associated with Aerobic Operation

- Distribution and control of air and liquids
  - Horizontal liquid application may
  - In aerobic systems, waste settlement is more rapid and pronounced, thus horizontal leachate application may not be appropriate
  - Control of temperature
- Changes in waste characteristics may be beneficial to air distribution, as changes in air flow patterns may result potentially maximizing the air and liquids coverage area
Challenges Associated with Aerobic Operation

- In-situ monitoring of conditions to ensure that air and liquids follow similar flow patterns
- Determining the amount of air required (the rate of mass transfer of oxygen from the gas phase to the liquid is unknown)
Challenges Associated with Aerobic Operation

- **Economics**
  - Aerobic operation costs more than anaerobic
  - Additional capital cost, electricity
  - Reduced leachate management

- **Unknown emissions**
  - Gaseous (nitrous oxide, volatile organics)
  - Metal migration
  - Collection system clogging (CO₂)
Future of US Aerobic Landfills

- Air injection will more likely be used periodically
  - Initiate biological reactions early in the landfill life
  - Remediate old landfills
  - Polish leachate quality (remove ammonia-nitrogen) and anaerobically recalcitrant waste (air addition at end of landfill life)
  - Hybrid bioreactor landfills with either short term cycling of air injection into the landfill or sequencing of aerobic and anaerobic conditions
In Situ Nitrification/Denitrification

![Graph showing Ammonium-Nitrogen Concentrations (mg/L) over Landfill Age (Years) from 0 to 12 years. The graph illustrates an increasing trend in Ammonium-Nitrogen concentrations with increasing landfill age.](image-url)
Why Remove Ammonia?

- Toxicity
- Oxygen demand
- Impact on post-closure
Ammonia readily and rapidly disappears at all oxygen levels and can occur at temperatures as high as 45°C.
Field-Scale Implementation Plan

Nitrogen Removal Zone

- Apply in old waste environments
- Apply to smaller areas of the landfill (dedicated treatment zones)
- Oxygen must be present, the higher the faster the rate
- pH should be near neutral
Economics of Process

- Equipment needed:
  - Air blower
  - Air injection piping

- Costs taken into account:
  - Air blowers (capital and operating costs)
  - Leachate injection operation cost
  - Air piping cost
  - Maintenance and landfill personnel time
## Economics of Process

<table>
<thead>
<tr>
<th>Leachate Injection Rate (L/m²-day)</th>
<th>Total Process Cost in Present Value ($)</th>
<th>Volume Leachate Treated (gal)</th>
<th>$/gal of Leachate Treated</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>75,000</td>
<td>$3.86 \times 10^6$</td>
<td>0.019</td>
</tr>
<tr>
<td>15</td>
<td>68,800</td>
<td>$2.89 \times 10^6$</td>
<td>0.024</td>
</tr>
<tr>
<td>8</td>
<td>64,700</td>
<td>$1.45 \times 10^6$</td>
<td>0.045</td>
</tr>
</tbody>
</table>

On-site leachate treatment ranges from $0.004 – 0.18/gal

Off-site leachate treatment ranges from $0.06 – 0.40/gal
Objectives of a Sustainable Landfill

- Landfill emissions must be controlled to ensure minimal environmental impacts.
- The residues left in landfills should not pose unacceptable risk to the environment and the need for post-closure care should not be passed to the next generation.
Beyond the Bioreactor Landfill

The Pump and Treat Aerobic Flushing Bioreactor Landfill

Complete Stabilization of Solid Waste Cells
Questions?