Organic Waste Stability – Fundamentals and State-of-the-Practice

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EREF
Lighting a path to sustainable waste management practices

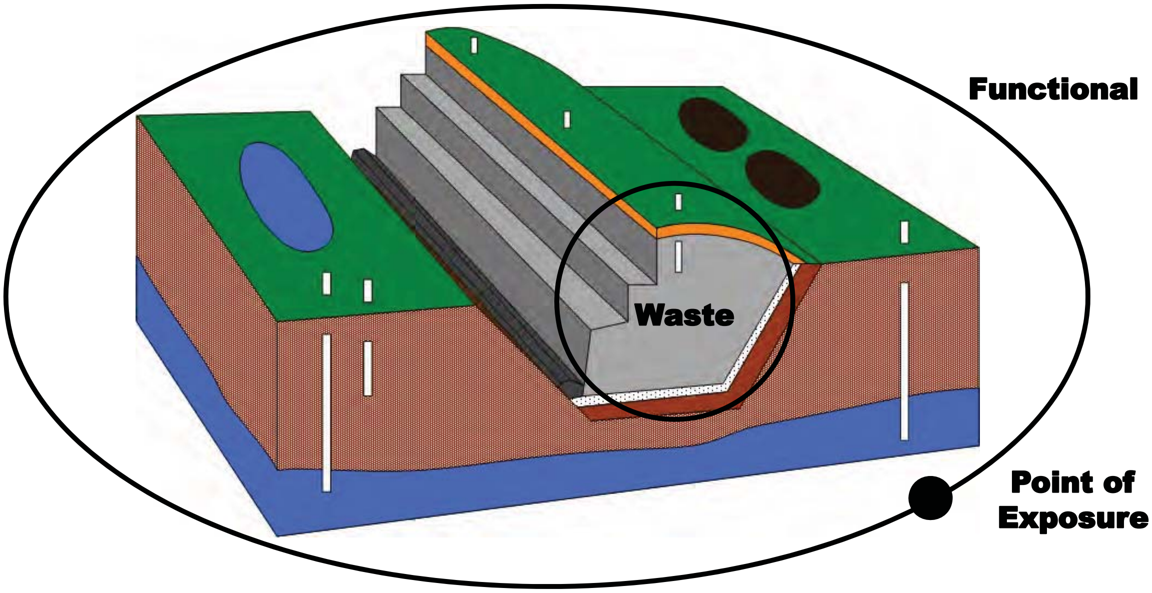
Colorado State University

Presentation Outline

- What is organic stability?
- Landfill applications to promote organic stability
- Fundamentals of anaerobic biodegradation
  - – Coupled biological-chemical-physical behavior of solid waste as observed in laboratory- and field-scale experiments and full-scale landfills
- Organic stability review – State of Wisconsin

What is Organic Waste Stability?

Waste Stability & Functional Stability



- Post-closure care (**PCC**) – ensure proper site management following closure such that landfill “does not pose a threat” to human health and the environment

Waste Stability

Initial State:
Fresh / Undecomposed / Organic

Final State:
Stable / Decomposed / Inert

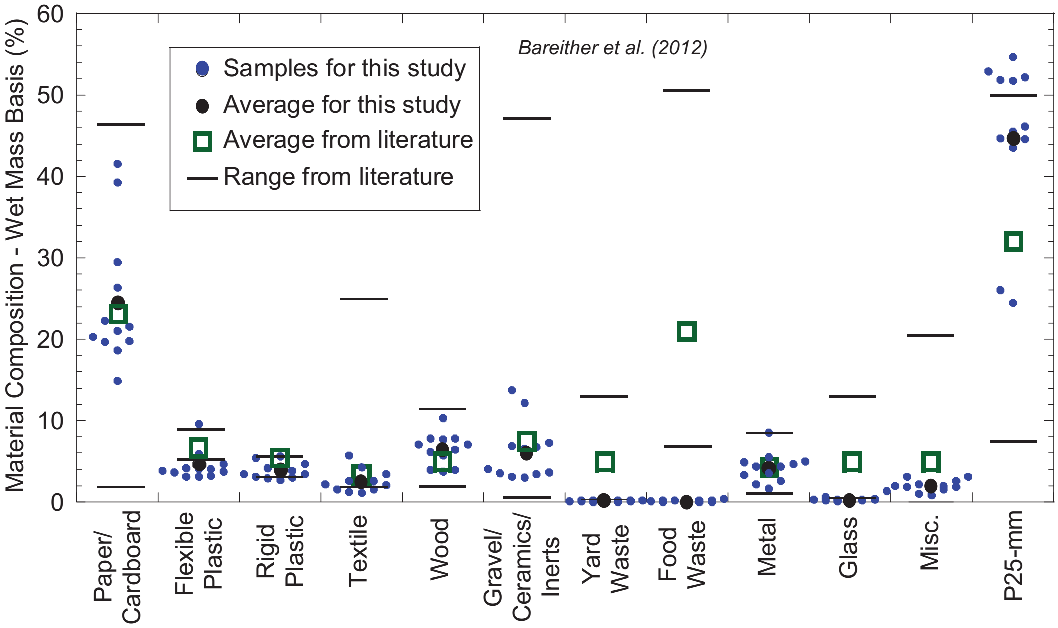
- Stable (*adj*) – good state or condition, not easily change
- Waste Stability = Organic Stability = Inorganic Stability
  - Exhausted gas generation; CH_4 main concern as GHG
  - (i) Low moisture condition, negligible leachate generation concern; (ii) High moisture condition, leachate collection and treatment
  - Reduced potential settlement; exhausted biocompression

Waste Stability

- Near complete decomposition of organic waste constituents
  - Reduce human health, environmental, and financial risks associated with undecomposed solid waste
- Short- and long-term risks:
  - Gaseous emissions
  - Release of contaminants in leachate to the environment
  - Waste settlement to extent that final cover and/or gas collection system are damaged

Waste Characteristics

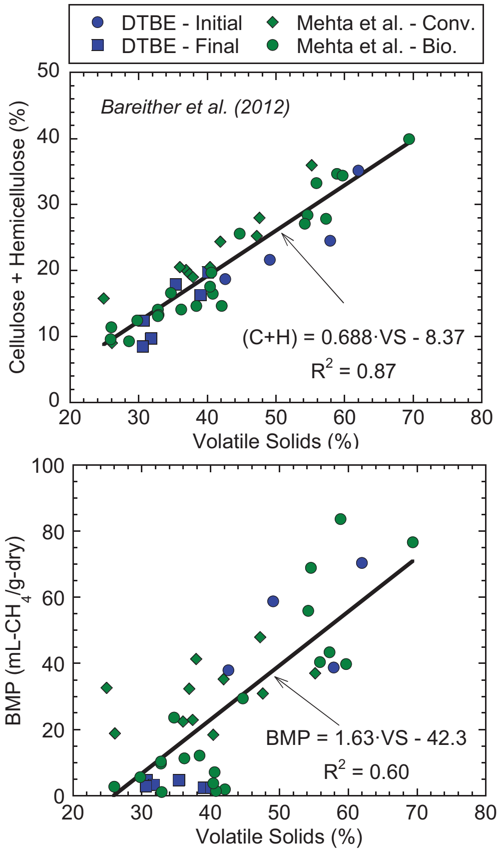
- Geotechnical characterization
  - Waste composition – categorical data
  - Particle size and distribution
  - Soil content
  - Moisture content
- Environmental characterization
  - Volatile solids
  - Biochemical methane potential
  - Organic polymers: cellulose, hemicellulose, and lignin



- Methane recovery = paper/cardboard, food waste, yard waste, wood, textile
- Compost potential = yard waste, food waste, paper/cardboard; wood
- High BTU for WTE : plastic + CH_4 potential wastes

Organic Waste Characteristics

- Volatile solids (VS) = mass loss due to incineration, temperature range 440-750 °C
- Cellulose, hemicellulose, and lignin contents = primary organic constituents; C+H ≈ CH_4 yield
- Biochemical methane potential (BMP) = volume of CH_4 per mass of waste (*dry mass basis*)
- Correlations between VS; C, H, and L; and BMP – also with MSW parameters (density; strength; compressibility; permeability)
- Avoid correlations to waste age; unique for a given landfill



Organic Stability – Operations and Evaluation

Wisconsin Dept. of Nat. Resources OSR

- Wisconsin organic stability rule (OSR)
  - Requires owners / operators to …“incorporate landfill organic stability strategies into the plans of operation for their facilities.”
  - Plan for … “significantly reducing the amount of degradable organic material remaining after site closing in order to materially reduce the amount of time the landfill will take to achieve landfill organic stability.”
- Organic Stability
  - Near complete decomposition of organic waste constituents = human health, environmental, and financial risks associated with undecomposed waste are reduced
  - Risks: gaseous emissions, potential release of contaminants in leachate to the environment, and waste settlement to extent that final cover and/or gas collection system are damaged

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Possible Operations

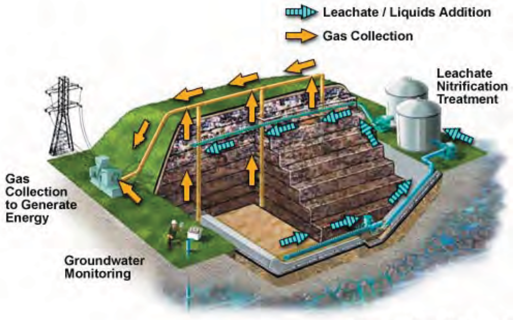
Potential waste management strategies to promote organic waste stability = landfill / owner specific

- Diversion of biodegradable organics
- Mechanical or biological treatment prior to disposal

Waste Pre-treatment

- Compositing
- Anaerobic digestion
- Combustion

- In-situ landfill treatment
  - Liquid addition and/or leachate recirculation
  - In-situ aeration
  - Combination



Courtesy of Waste Management

Bioreactor Landfills

- SWANA definition: a bioreactor landfill is a controlled landfill where liquid & gas conditions are actively managed in order to accelerate or enhance bio**stabilization** of the waste
- **Anaerobic bioreactor** – biodegradation without oxygen
  - Enhance biodegradation via moisture enhancement
  - Generate landfill gas (CH_4 & CO_2) → capture to minimize greenhouse gas emissions and to generate energy
- **Aerobic bioreactor** – biodegradation with oxygen
  - Inject air & liquid into waste using vertical or horizontal wells
  - More rapid compared to anaerobic; no CH_4 generation
- **Hybrid bioreactor**
  - Sequential anaerobic-aerobic treatment to realize benefits of both biodegradation pathways

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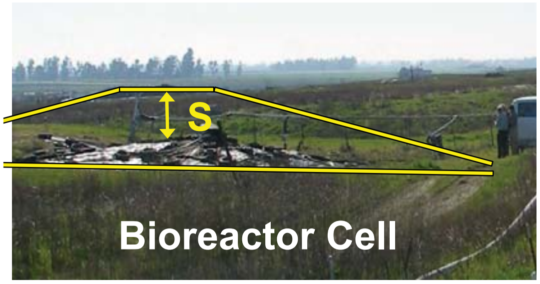
Bioreactor Benefits

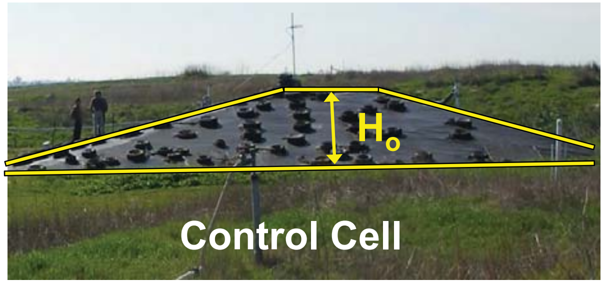
- Increase waste settlement
  - Airspace recovery
- Enhance organic waste decomposition
  - Accelerate biogas production
  - In-situ leachate treatment

Reduce post-closure care

<u>Yolo County Pilot Project</u>

Settlement in bioreactor ≈ 100% ↑



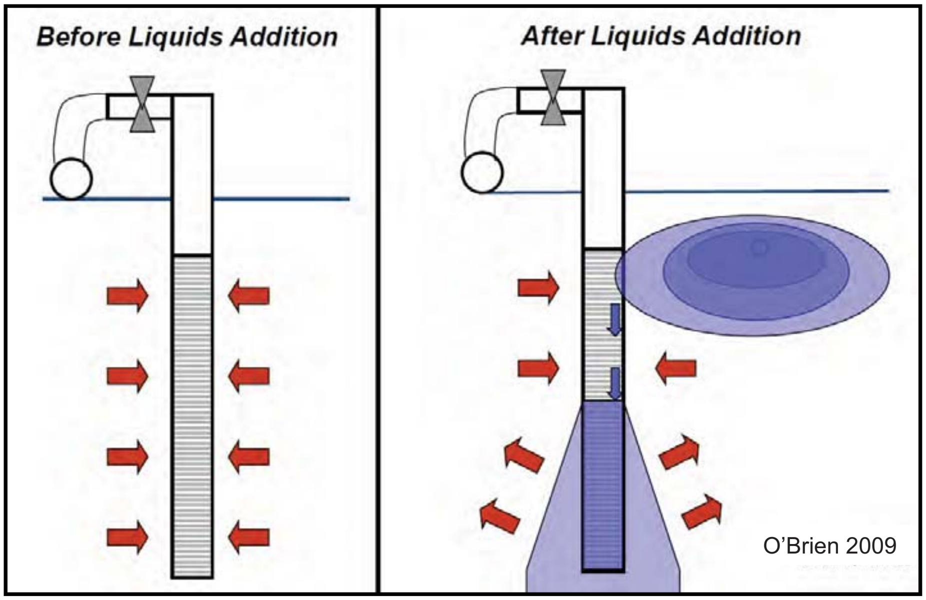


Bioreactor Concerns

- Leachate seeps
  - Develop due to pressurized liquid injection + solid waste above moisture holding capacity
- Landfill slope stability
  - Concerns due to increased pore water pressure + decreased waste strength following decomposition
- Gas emissions and odor control
- Elevated temperatures, fire, and explosions
  - Increased waste temperature during biological and/or chemical reactions
  - Explosions concerns with mixed CH_4 and O_2 gas

Bioreactor Concerns

- Watering out of gas wells and/or decreased gas collection due to addition / recirculation and subsequent retention of too much liquid within the wells or waste mass



O’Brien 2009

Leachate Recirculation Methods

- Surface infiltration pits and surface spray application

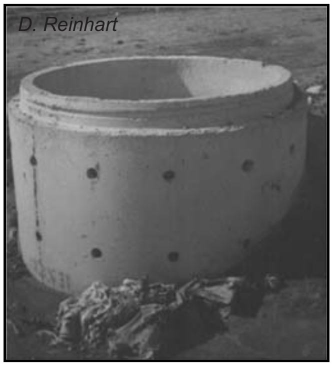

University of Southampton


D. Reinhart


Waste360

Leachate Recirculation Methods

- Vertical wells and horizontal recirculation trenches


D. Reinhart


University of Southampton


Waste360

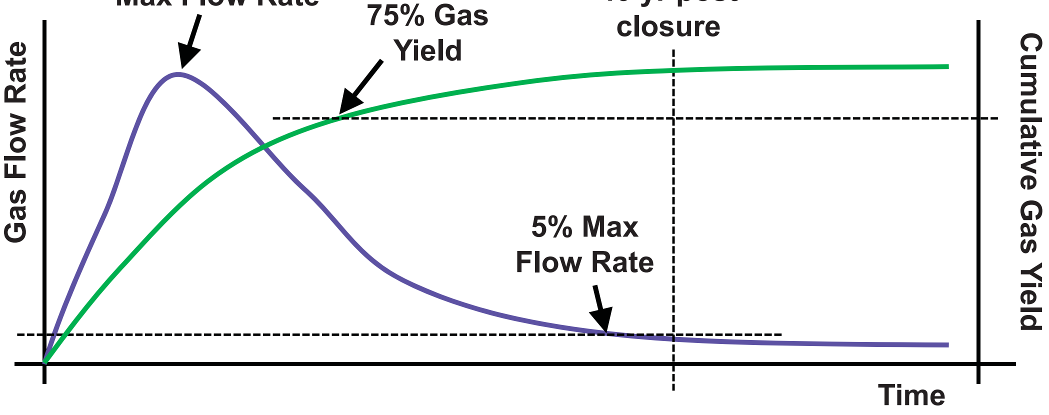
Leachate Recirculation Methods

- Leachate infiltration blanket or pad

www.cimagazine.net

Organic Stability Goals

1) Monthly average gas ($CH_4 + CO_2$) flow rate ≤ 5% average maximum monthly gas flow rate observed during the life of the facility, or ≤ 7.5 ft^3-gas/yd^3-waste/yr
2) Cumulative gas ($CH_4 + CO_2$) yield ≥ 75% of projected total gas yield
3) Steady downward trend in rate of total gas production ($CH_4 + CO_2$)
4) Time required to achieve landfill organic stability ≤ 40 yr post-closure



Gas Modeling via LandGEM

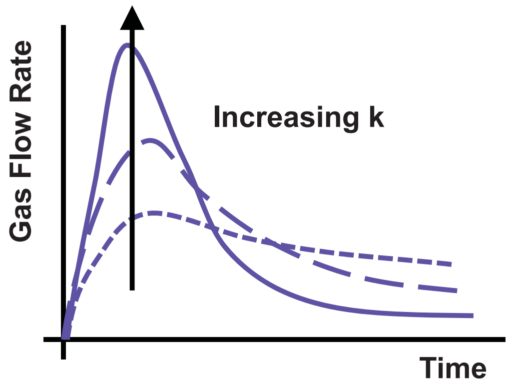
- LandGEM = methane generation model

USEPA (2005)

$$Q_n = \left(k \cdot L_o\right) \sum_{i=0}^{n} \sum_{j=0.0}^{0.9} \frac{M_i}{10} e^{-k \cdot t_{i,j}}$$

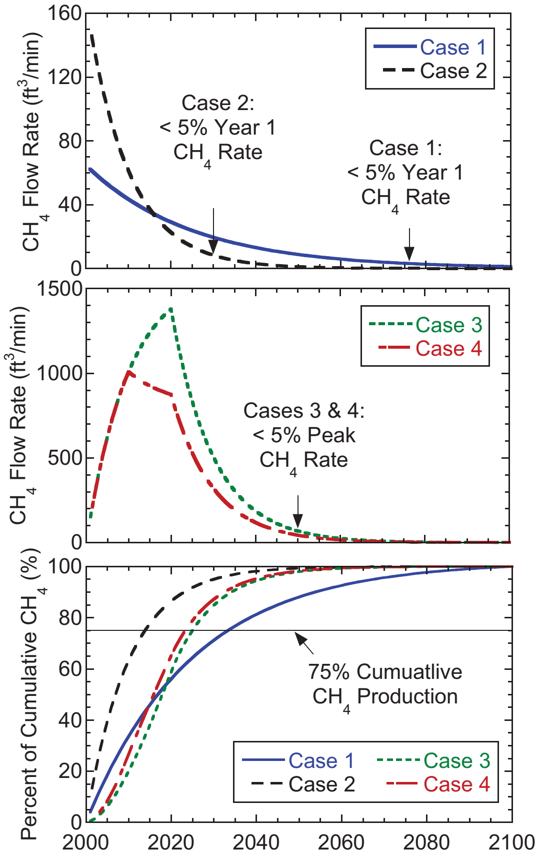
- Q_n = CH_4 generation year n (m^3-CH_4/yr)
- k = first-order decay rate (1/yr)
- L_o = ultimate CH_4 yield (m^3-CH_4 / Mg-wet MSW)
- M_i = mass of waste accepted in year i
- j = deci-time increment
- t = time (yr)

Influence of k on CH_4 generation



OS Assessment

- Case 1: 260,000 tons MSW Yr 1
  - **k = 0.04 1/yr**
    L_0 = 100 m^3-CH_4/Mg
- Case 2: 260,000 tons MSW Yr 1
  - **k = 0.10 1/yr**
    L_0 = 100 m^3-CH_4/Mg
- Case 3: 260,000 tons/yr MSW disposed in Yr 1-20
  - **k = 0.10 1/yr**
    L_0 = 100 m^3-CH_4/Mg
- Case 4: 260,000 tons/yr MSW in Yr 1-10; 130,000 tons/yr MSW in Yr 11-20
  - **k = 0.10 1/yr**
    L_0 = 100 m^3-CH_4/Mg



Bareither et al. (2014)

Coupled Physical, Chemical, and Biological Behavior During Anaerobic Biodegradation

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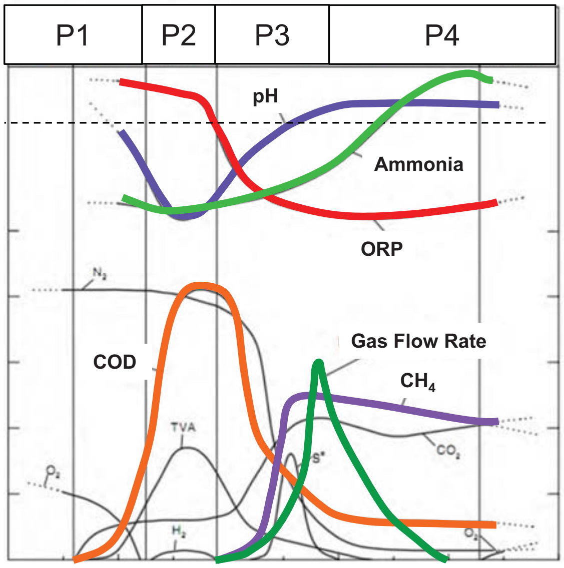
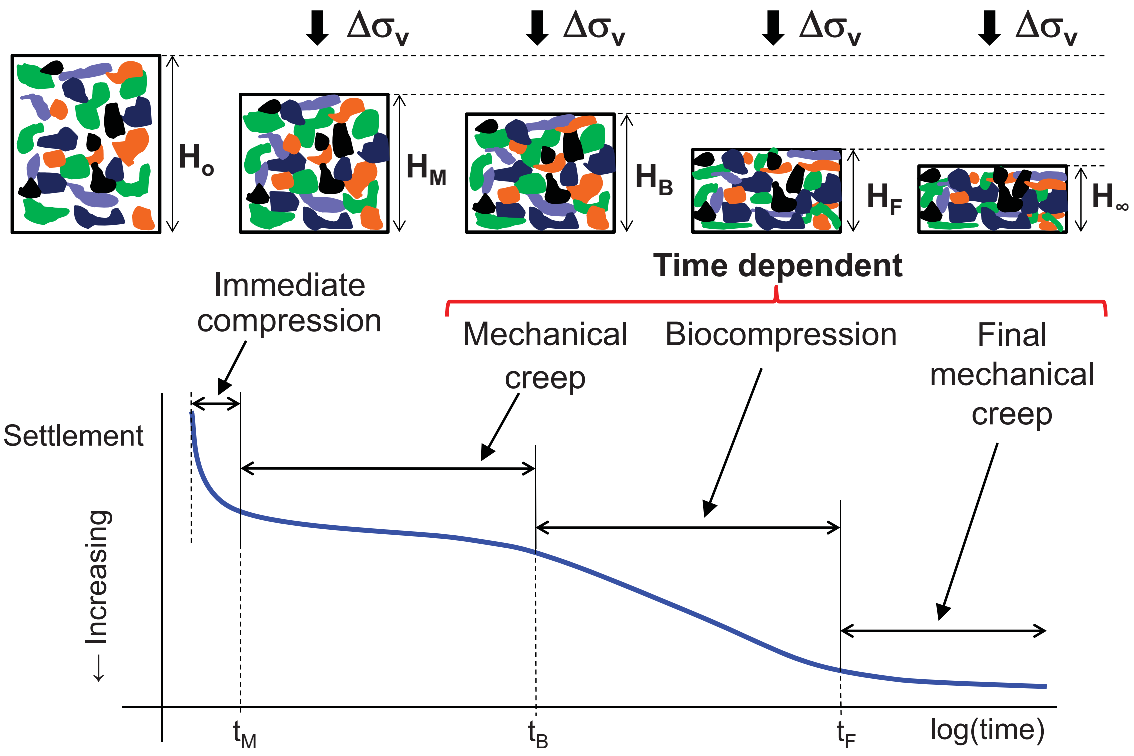
Coupled Leachate & Gas Behavior

- Leachate chemistry
  - pH, oxidation-reduction potential (ORP), chemical oxygen demand (COD), biochemical oxygen demand (BOD), and ammonia-nitrogen (NH_4-N)
- Biogas
  - Composition (CH_4:CO_2)
  - Production
- Phases of biodegradation
  - P1. Aerobic Phase
  - P2. Acid Formation – Acidogenesis
  - P3. Accelerated CH_4 Phase
  - P4. Decelerated CH_4 Phase

Kim and Pohland (2003)



Conceptual Settlement Model

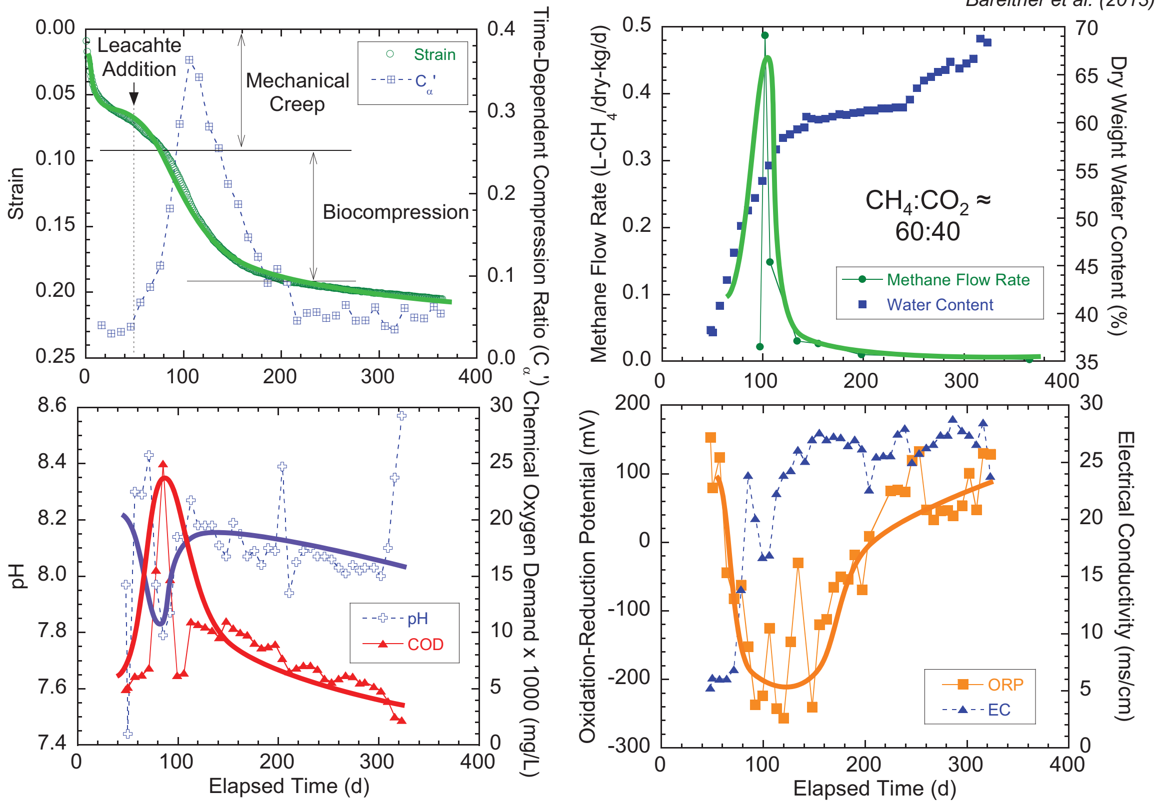


Laboratory Experiments

- Advantages
  - Controlled conditions (initial & boundary)
  - Precise measurement
  - Target test variables
- Challenges
  - Scaling data to field conditions
  - Specialized equipment for handling waste, leachate, and gas

MSW, 1-ft diameter, 1340 psf

Bareither et al. (2013)

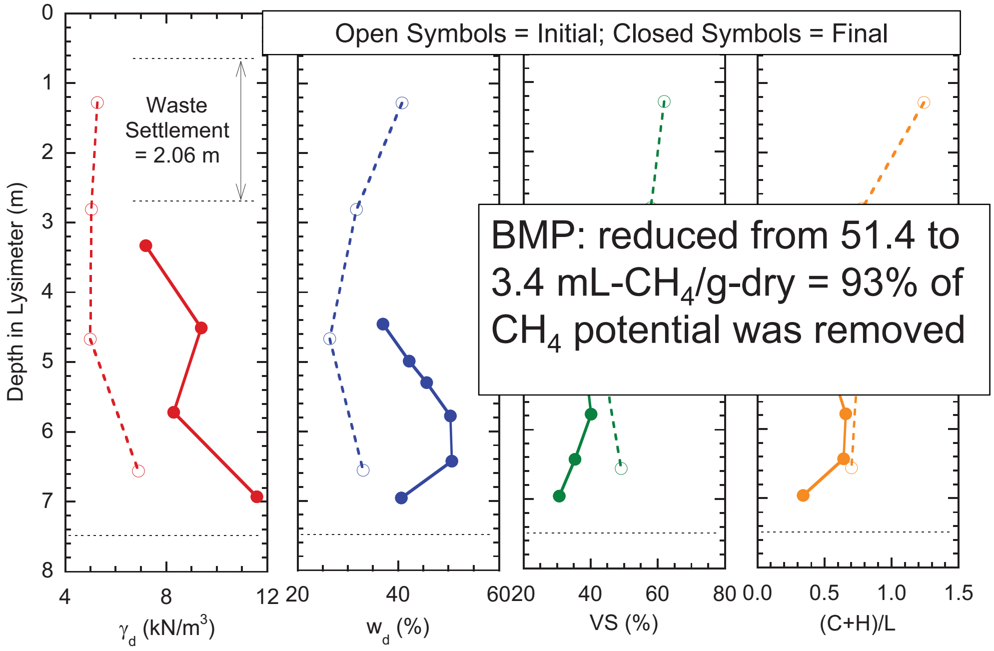


Deer Track Bioreactor Experiment (DTBE)

- Waste age ~ 3-4 months old
- Waste thickness = 6.9 m
- Operated for 1067 d
- Leachate dosing

Waste Properties

Bareither et al. (2012)



BMP: reduced from 51.4 to 3.4 mL-CH_4/g-dry = 93% of CH_4 potential was removed

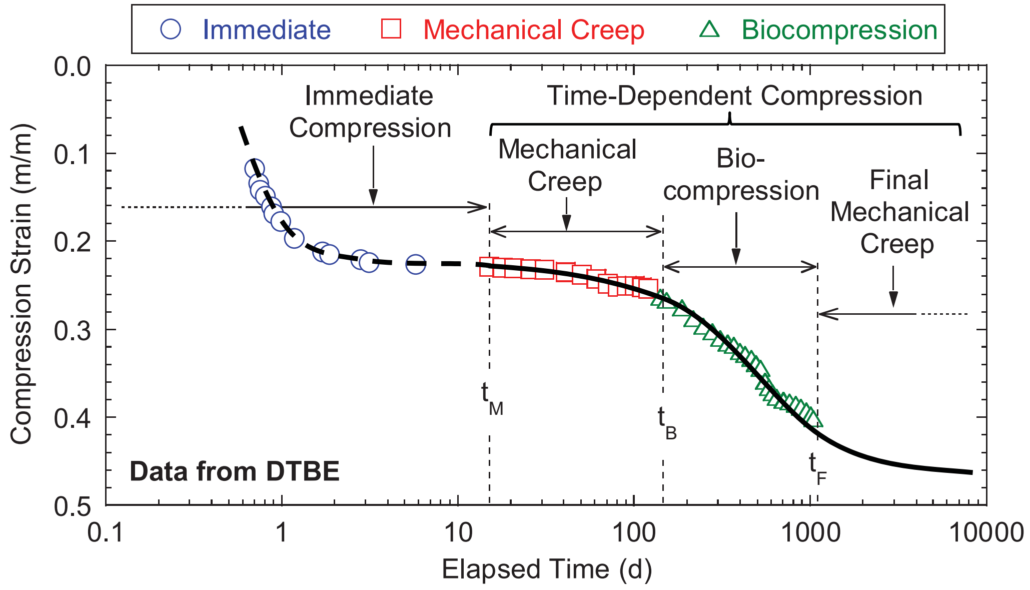
Dry unit weight	Water content	Volatile solids	(C+H)/L
⇧ 71%	⇧ 11%	⇩ 18%	⇩ 0.87 → 0.49

Settlement Behavior

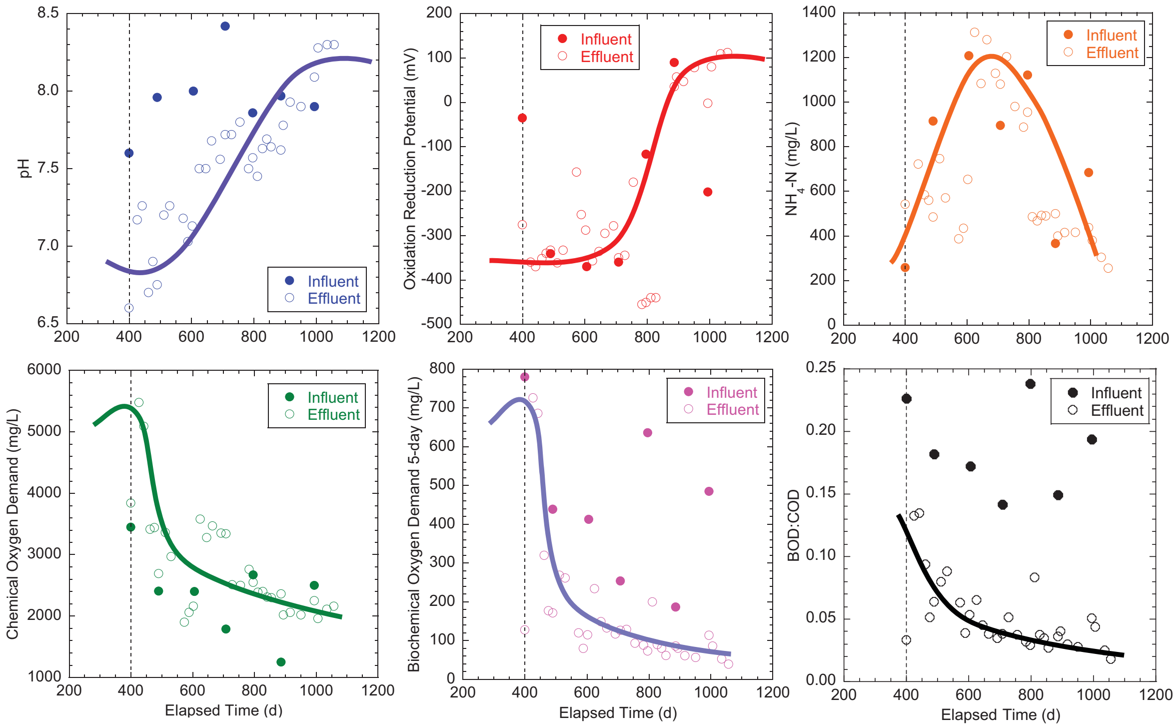
Observation: duration of compression phases longer than lab

- t_M = 15-20 d, t_B = 130 d, $t_F \approx$ 1000 d

Bareither et al. (2012)



Leachate Chemistry

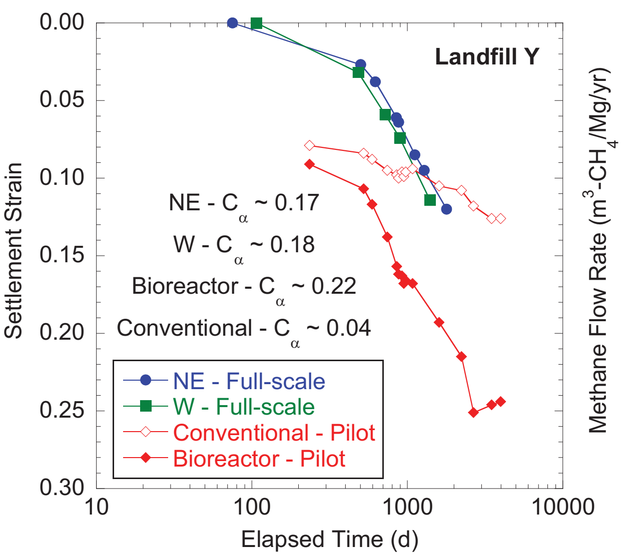


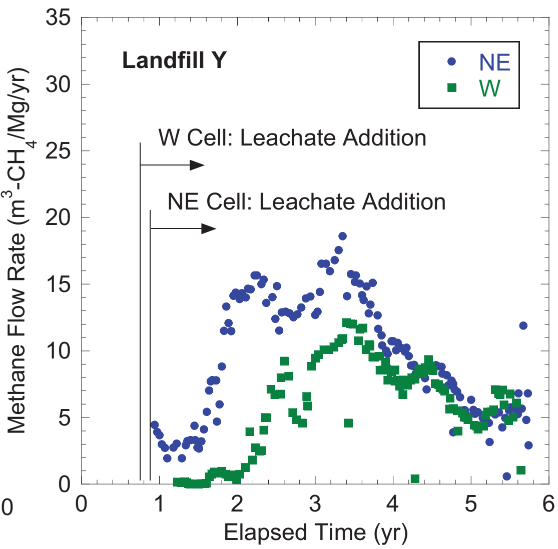
Bareither et al. (2012)

Full-Scale Landfill Evaluation

- Landfill gas: gas well or area specific data = direct assessment of localized waste stability; site-specific data to assess overall landfill stability
- Leachate chemistry: often commingled and relevant to storage tank = no information on localized waste stability; sump-specific data = more valuable (*still homogenized*)
- Settlement: in-situ plates or surface monuments = best assessment for localized waste stability; areal surveys = limited utility due to elapsed time between surveys

Full-Scale Settlement & Gas



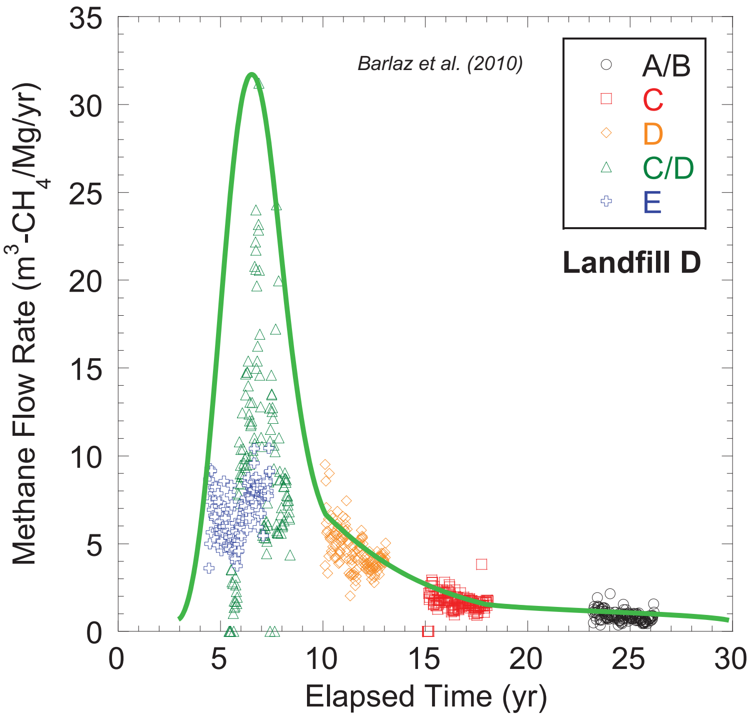


Bareither et al. (2010) and Barlaz et al. (2010)

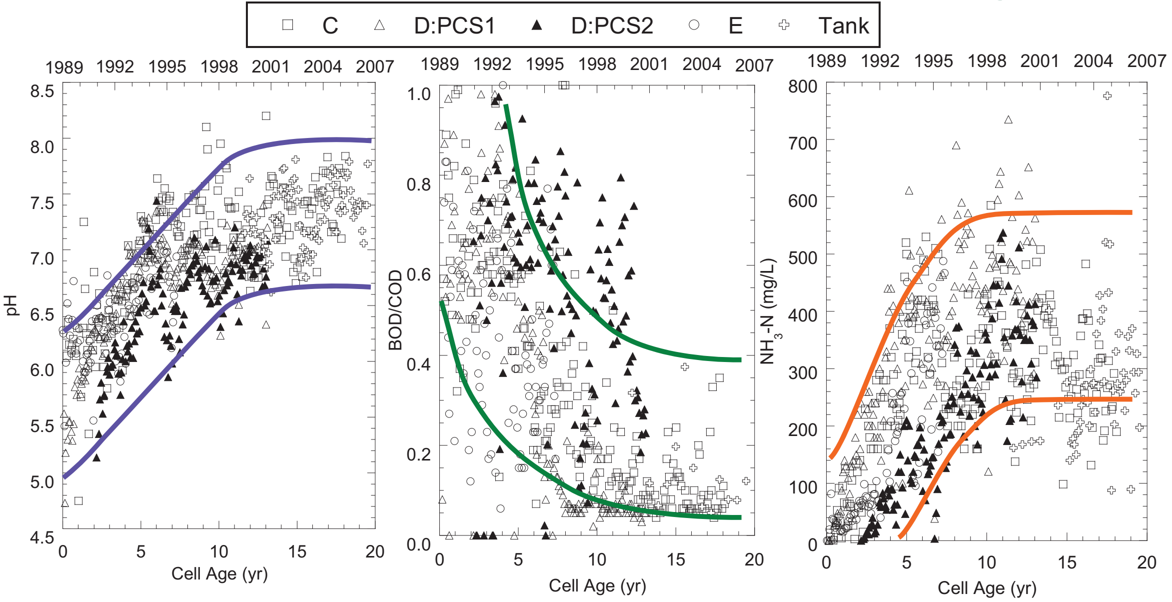
- Elapsed time for biocompression ~ 500 d (1.4 yr); approximately coincides with CH_4 generation
- Lag time between leachate addition & biodegradation

Full-Scale CH_4 Generation

- Landfill D Cells: different age of waste at different states of decomposition
- Combined data = exhibits typical first-order decay curve for CH_4 generation (e.g., LandGEM)
- Stabilized waste should have low CH_4 potential



Full-Scale Leachate Chemistry



- Overall, see general trends in leachate sump & tank data

Barlaz et al. (2010)

  - Increasing pH ~ 7.0 to 8.0; decreasing BOD/COD ratio; stabilizing and possibly reducing NH_3-N

Waste Stability – Coupled Behavior

- Response to initial liquid addition / leachate recirculation
  - Stimulate hydrolysis = ⇩ pH due to ⇧ production & accumulation of organic acids (COD, BOD, VFA)
  - Settlement rate increases due to moisture-induced softening
- Methane generation
  - Methanogens use available, soluble substrate = ⇧ pH due to ⇩ in concentration of organic acids
  - High settlement rates coincide with net reduction in solid mass
- Stabilized waste
  - pH stabilized ~ 7 to 8; COD, BOD, and COD/BOD all decrease and stabilize
  - Methane is exhausted = lower VS, BMP, C+H relative to initial
  - Reduced potential for biocompression & differential settlement

Organic Stability Rule – Review of Current Practice

Organic Stability Evaluation

Objective: assess the impact and effectiveness of the organic stability rule (OSR) five years following implementation

OSR: achieve organic stability ≤ 40 yr post-closure, defined as:

1) Monthly average gas (CH_4 + CO_2) production rate ≤ 5% of average maximum monthly gas production rate observed during the life of the facility, or ≤ 7.5 ft^3-gas/yd^3-waste/yr
2) Cumulative gas (CH_4 + CO_2) yield ≥ 75% of projected total gas production from landfilled waste

Potential waste management strategies

- Diversion of biodegradable organic material
- Mechanical or biological treatment prior to disposal
- In-situ landfill treatment (e.g., liquid addition, leachate recirculation, or in-situ aeration, alone or in combination)

Landfills Studied

Bareither et al. (2014)

Site ID	Owner	Initiation of OSR Compliance	Organic Stability Actions [a]	Tipping Rate (tons/d)[b]	Year Liquid/ Leachate Addition Initiated	RD&D Permit [c]
A	Private	2007	**LR**	1180 (810-1780)	**2013**	—
D	Private	2007	**LR; LWA;** OD	1210 (1100-1400)	**2001**	**2007**
E	Private	2011	**LR; LWA;** OD	1470 (1300-2000)	**1998**	**2007**
F	Public	June 2012	OD; **LR**	210 (180-230)	**2012**	—
G	Private	Dec. 2008	**LR; LWA**	3030 (2700-4100)	**2006**	**2007**
I	Private	2007	**LR; LWA**	810 (700-900)	**2002**	**2007**
J	Private	2007	**LR; LWA;** DFC	700 (620-740)	**Not Available**	**2008**
K	Private	2007	**LR; LWA;** DFC	1110 (960-1350)	**2002**	**2009**
L	Private	May 2007	**LR; LWA;** OD	1040 (900-1100)	**1999**	**2007**
M	Private	2012	**LR; LWA;** DFC	360 (230-570)	**2001**	**2010**

[a] LR = leachate recirculation; LWA = liquid waste addition; OD = organics diversion; DFC = delay final cover (allow additional infiltration)

[b] Average listed and range in parentheses for 2007-2012.

[c] Year permit approved if applicable; otherwise not applicable (—)

Liquid Waste Addition & RD&D

- RCRA Subtitle D Research, Development, and Demonstration (RD&D) Permit
  - Can reduce run-on surface water control
  - Add supplemental liquids other than leachate
  - Use alternative final cover designs to enhance waste moisture content
- Most common action at landfills in this study = acceptance of external commercial liquid wastes, with disposal by direct application into the landfill waste mass

New Highlight

Revision to the Research, Development and Demonstration (RD&D) Permits Rule for Municipal Solid Waste Landfills

On May 10, 2016, a final rule was published in the *Federal Register* revising the maximum permit term for Municipal Solid Waste Landfill (MSWLF) units operating under RD&D permits.

This final rule allows RD&D permits for municipal solid waste landfill bioreactors to be extended from 12 to up to 21 years. The rule allows directors of EPA approved state waste programs to increase the number of renewals for such permits from three to six.

Waste Diversion & Composting

- Reported at 4 of 10 sites
- Sites D, E, and L = on-site composting facilities
  - All initiated for yard waste management, with subsequent efforts to accept source-separated food waste
  - Site D: 1:1 yard-to-food waste mix; mature compost sold for landscaping or used on-site as top soil
  - Sites E & L: considering farm crop residue, manure, and other non-food organic waste
- Site F = diverts waste to local refuse-derived fuel facility operated by electrical utility
  - Approximately 57 % of MSW in Site F region processed at RDF
  - Low BTU MSW fraction and ash disposed at Site F

Leachate and Liquid Management

Site ID	Leachate Gen. (Million gal/yr)	Leachate Recirc./ Gen. (%)	Liquid Waste Fraction of Total Liquid (%)	Types of Commercial Liquid
A	7.95	0	**0**	—
D	7.14	95.3 (82.7-100)	**4.3 (1.1-7.1)**	Cleaning water from glue & paint facilities; corn syrup
E	12.54	18.7 (6.0-56)	**22 (1.3-59)**	General commercial wastes; haul vehicle cleanout water; storm water; gas condensate; dredged materials;
F	8.94	5.4	**0**	Does not accept third-party liquids
G	15.81	40.7 (21.6-60)	**68 (0-100)**	Soap residual; food waste residues; general commercial wastes
I	5.79	16.8 (0.0-43.1)	**0 or 100**	Automobile wash water; industrial process sludge
J	3.83	3.8 (0.0-8.0)	**NA**	General commercial wastes
K	16.19	1.1	**82 (26-100)**	Liquid-containing food wastes; industrial wastes; sludge
L	7.74	67.7 (36.5-92.0)	**8.9 (4.0-19)**	POTW sludge; industrial wastewater; hydrovac loads from hydro-excavations
M	6.60	10.4 (0.0-27.4)	**0 or 100**	Horizontal injection; surface application

Bareither et al. (2014)

Leachate and Liquid Management

- Balance of liquid waste & leachate recirculation is dependent on (1) off-site leachate treatment costs and (2) other factors, e.g., MSW available to absorb liquid
- **Sites D and L** = high off-site leachate treatment cost
  - Smallest % liquid waste addition for active RD&D permits
  - Largest % of generated leachate that was recirculated
- **Sites G and I** = lower off-site leachate treatment costs
  - Report 100% liquid addition in a given year

Site ID	Off-Site Treatment ($/gal)	Liquid Waste Fraction of Total Liquid (%)
A	**0.02**	**0**
D	**0.04**	**4.3 (1.1-7.1)**
E	**—**	**22 (1.3-59)**
F	**0.002**	**0**
G	**0.02**	**68 (0-100)**
I	**0.009**	**0 or 100**
J	**0.027**	**NA**
K	**—**	**82 (26-100)**
L	**0.05**	**8.9 (4.0-19)**
M	**—**	**0 or 100**

Bareither et al. (2014)

Gas Generation & Use

Bareither et al. (2014)

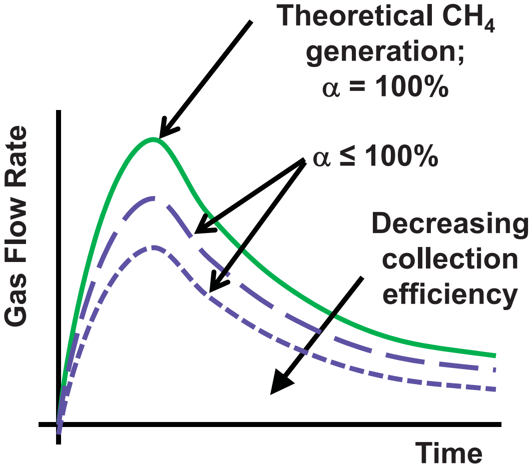
Site ID	Annual Ave. Flow (ft^3/d)	Percent Flared (%)	Gas Utilization Summary
D	1,647	56	Approximately 33% sold to 3rd party contractor for electricity generation; **3 on-site engines** that are all old and need maintenance
E	2,033	97	**Transported via pipeline to local POTW for energy source** in treatment operations
F	227	0	**Transported via pipeline to commercial energy provider**
G	3,678	16	**Gas turbines** (4 x 36.8 m^3/min); 42.5 m^3/min flare
I	1,561	NA	**Sell gas to neighboring rendering plant**; collaboration between landfill, plant owner, and power company to install 3 landfill-owned engines at rendering plant
J	330	NA	Implemented **4-engine gas plant in 2002**; permit for additional 6-engines = 10-engine plant; relocated two engines to other sites due to decrease in gas collection
K	1,930	NA	**Two on-site turbines** installed in 1985 and 4 additional engines installed in 1986
L	1,573	66	**Two on-site engines** (~10 m^3/min combined); **sell gas to energy company** to operate two microturbines (2.8-3.5 m^3/min); flare (25.5 m^3/min)
M	1,578	7.1	**Four engines in 2006**; added 3 engines in 2007; excess flared. Currently, 4 engines remain with 3 operating; other 3 engines were removed due to declining gas

Modified LandGEM

- Modified model to (i) incorporate monthly waste disposal and predict methane flow rates on a monthly basis and (ii) incorporate gas collection efficiency

$$Q_j = \frac{kL_o}{12}\sum_{i=1}^{j}\alpha_{ji}M_i e^{-k\left(\frac{j-i}{12}\right)}$$

- Q_j = CH_4 collection rate in month j (volume/month)
- α_{ji} = monthly gas collection efficiency associated with mass of waste placed in month i and collected in month j
- M_i = mass of waste placed in month i



Wang et al. (2013)

Collection Efficiency

- Influencing factors on gas collection efficiency
  - Cover type; presence of gas wells; functioning of vacuum system to extract gas
- Lower bound = 0% = no gas collection system installed
- Upper bound = 90-100% = collection system in-place and active + geomembrane final cover

Landfill & gas collection system description	Ave. Collection Efficiency (%)
Active landfill, vertical well gas collection, and daily cover only	67
Active landfill, vertical well gas collection, and intermediate cover	75
Active landfill, vertical well gas collection, and final soil cover or combined vertical well and horizontal trench gas collection and intermediate cover	87
Active landfill, gas collection, and geomembrane, subtitle D, or equivalent cover	90

Amini et al. (2013)

Organic Stability Assessment

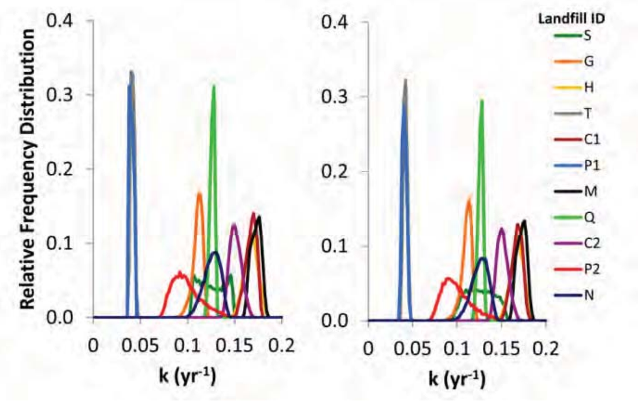
- Most LandGEM analyses conducted with L_0 = 100 m^3-CH$_4$/Mg
  - AP-42 default for predictions of landfill gas generation
- Common decay rates used:
  - *k* = 0.04 1/yr → AP-42 default)
  - *k* = 0.08 1/yr → recommended by Reinhart et al. (2005) for gas generation in wet landfills
- In general, gas modeling at all sites supports meeting OSR benchmarks within a post closure period of 40 yr

Site ID	Assumed L_0 (m^3/Mg-MSW)	Assumed *k* (1/yr)
A	100	0.05, 0.08
D	100	0.04, 0.08
E	80, 100	0.04, 0.08
F	80	0.08
G	NA	NA
I	100	0.027, 0.15
J	100	0.088
K	100	0.068
L	80, 100	0.04, 0.08
M	100	0.062, 0.050

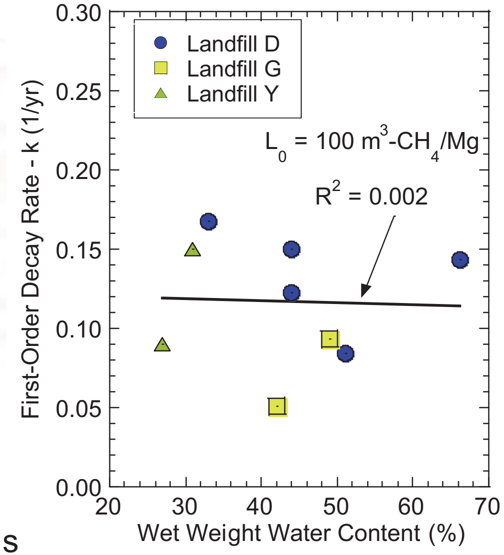
Bareither et al. (2014)

First-Order Decay Rates

Wang et al. (2015)



Barlaz et al. (2010)



- Barlaz et al. (2010)
  - Optimized *k* via LandGEM; 3 landfills
  - No relationship between k and waste water content
- Wang et al. (2015)
  - Optimal k for 11 landfills via Monte Carlo simulations = 0.07-0.19 1/yr

Organic Stability Assessment

- Strategy 1: site-wide basis with single L_0 and k
  - Easy, but does not allow assessment of enhanced degradation
- Strategy 2: specific L_0 and k values defined areas where organic degradation is enhanced
  - More challenging and requires separation of waste mass and gas collection data based on landfill areas
  - Ideal to evaluate the performance of organic stability plans
- Strategy 3: temporally and spatially varying L_0 and k values
  - Merit in this approach, but transition analysis from a check on organic stability performance to curve-fitting of gas collection curves

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OSR Recommendations

Recommendations for landfill policies that incorporate organic stability actions:

1) Use of life cycle analysis to assess organic stability strategies
2) Incorporate provisions of liquid waste addition into RCRA Subtitle D
3) Develop guidance on biochemical compatibility of liquid waste disposal in landfills
4) Clarify requirements of early and aggressive gas collection
5) Promote beneficial use of landfill gas
6) Develop a standardized gas analysis procedure to assess OSR goals
7) Consider metrics to aid transition from an active to passive long-term landfill gas emissions system.

Summary

- Organic stability
  - – Near complete decomposition of organic waste that minimizes future risks
- Potential operations
  - – Organic waste diversion; pre-treatment; in-situ waste treatment
- Solid, liquid, and gas metrics
  - – Solids: composition, VS, BMP, (C+H)/L
  - – Liquid: leachate chemistry (pH, COD, BOD)
  - – Gas: methane flow rate and yield

Summary

- Current practice to achieve organic stability = primarily in-situ anaerobic waste treatment
  - – Liquid waste addition under US EPA RD&D permits
  - – Caution to not over-add liquid and water-out gas wells or inhibit gas permeability and gas collection
  - – Wisconsin landfills = effectively meeting gas metric goals stipulated in the organic stability rule
- Current practice in gas modeling
  - – Assume L_0 = 100 and either (i) optimize *k* for entire site or (ii) assume lower *k* for older waste / conventional ops and higher *k* for younger waste / bioreactor ops
  - – Need to account for gas collection efficiency

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