Overview of Bioreactor Landfill Technology: Benefits and Obstacles

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Bioreactor Landfills

- A bioreactor landfill is designed and operates to accelerate decomposition of the waste mass
  - Leachate recirculation is most common implementation
    - Permitted under Subtitle D
    - Increase mixing
    - Reduce time in acid phase
    - More efficient reaction

SWANA Definition

"……a sanitary landfill operated for the purpose of transforming and stabilizing the readily and moderately decomposable organic waste constituents within five to ten years following closure by purposeful control to enhance microbiological processes. The bioreactor landfill significantly increases the extent of waste decomposition, conversion rates and process effectiveness over what would otherwise occur within the landfill."

Bioreactor Landfill Definition
(EPA NESHAP Rule)

"MSW landfill or portion of a MSW landfill where any liquid other than leachate …is added in a controlled fashion into the waste mass (often in combination with recirculating leachate) to reach a minimum average moisture content of a least 40 % by weight to accelerate or enhance the anaerobic …biodegradation of the waste…"

Accelerating Waste Decomposition in Bioreactor Landfills

- The primary mechanism for increasing the rate of waste decomposition is the increase in moisture content of the solid waste.
- This can be accomplished by:
  - Recirculation of leachate
  - Addition of water
  - Addition of other bulk liquids

Accelerating Waste Decomposition in Bioreactor Landfills

- Air addition has also been proposed to accelerate waste decomposition
- Other factors that have an impact:
  - Temperature
  - pH
  - Nutrient content
  - Presence of microorganisms

Categorizing Bioreactor Landfills

- Categorize by how much moisture and how much control
  - Bioreactors
  - Leachate recirculation only landfills
- Categorize by the biological
  - Anaerobic
  - Aerobic
  - Phased aerobic/anaerobic

Moisture Management at Bioreactor Landfills

- How do you get the liquids in?

- Leachate recirculation systems
  - Surface Systems *vs* Subsurface Systems
  - Retrofit *vs* As-built

Methods of Recirculation

- Surface methods
  - Pre-cap
  - Post-cap

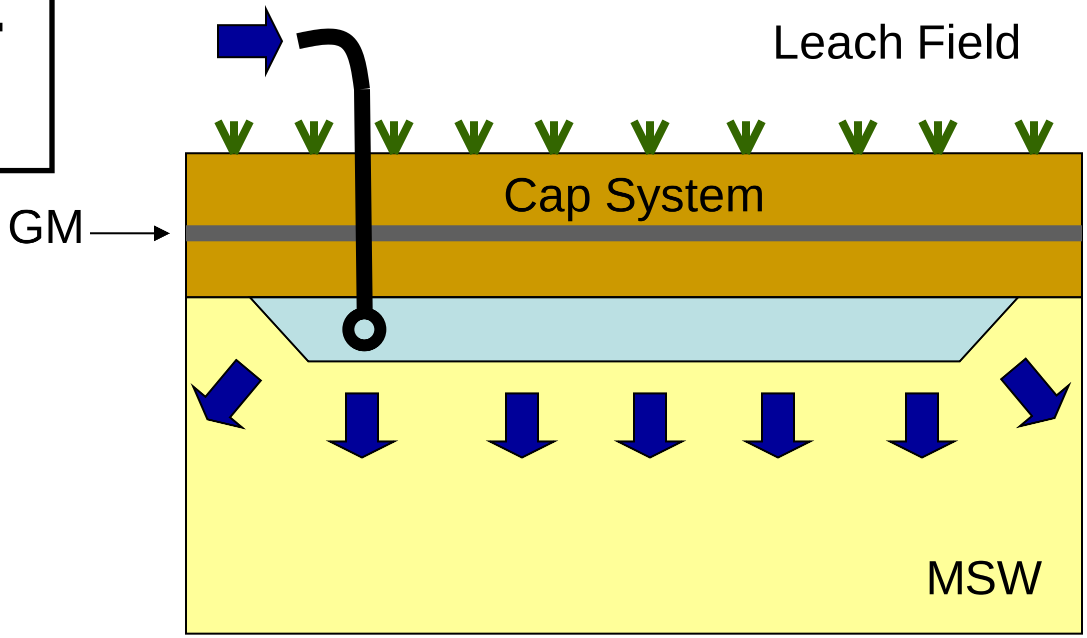
- Subsurface methods

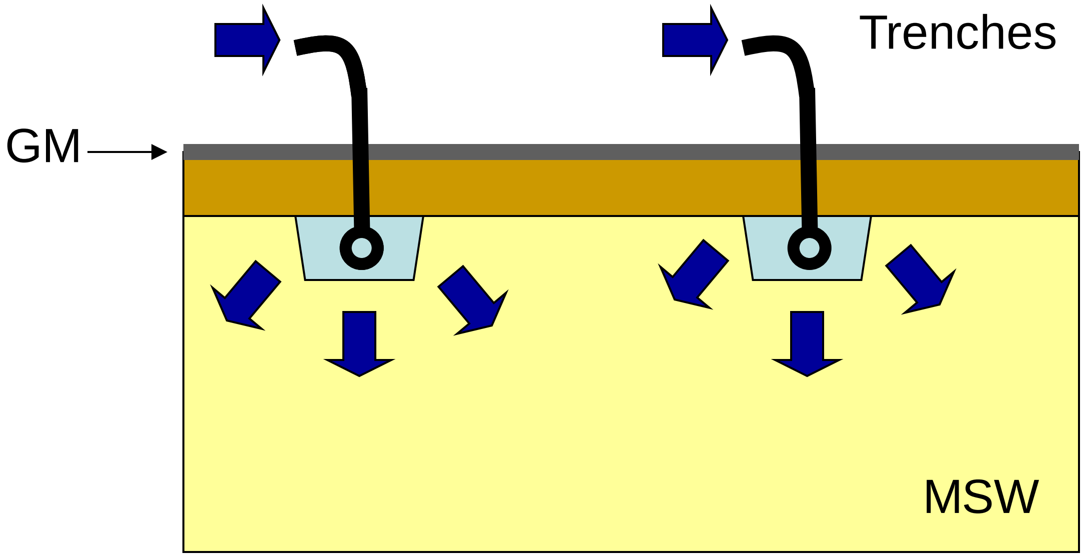
Surface Methods: Pre-Cap

- Spray Irrigation
- Drip Irrigation
- Tanker Truck Application
- Infiltration Ponds

Surface Methods: Post-Cap

- Leach Field
- Trenches
- Drip Irrigation





Subsurface Methods

- Vertical Injection Wells
- Horizontal Trenches
- Buried Infiltration Galleries

Supplemental Liquid Addition

- many landfills say they need more water: gal/ton
- currently prohibited under Subtitle D (RDD permits)
- potential sources include:
  - addition of river water or groundwater
  - non-hazardous liquid wastes such as tank washdown water
    - Compatibility with landfill microbiology (e.g., tank washings, high BOD wastewater)

Bioreactors are Controlled Systems

- Operating a bioreactor involves more than simply increasing moisture content
  - Moisture addition needs to be performed in a safe manner
  - Gas should be controlled
  - The degree of monitoring and inspection increases greatly

Bioreactor Landfill Benefits

1. Reduced leachate strength & in-situ leachate treatment
2. Enhanced settlement
   - Final cap maintenance reduced
   - Airspace recovery due to higher densities
3. Methane is a greenhouse gas and a "CO_2 neutral" energy source. More gas faster improves economics of energy recovery.
4. Post-closure monitoring period may be reduced?

Areas of Concern

- Despite the many advantages bioreactor landfills provide, if operated incorrectly, these systems can present an environmental and safety risk.
- Uncontrolled liquids addition
  - Head on liner
  - Seeps
- Slope stability
- Gas emissions

Gas Production

- More gas faster – challenge is to collect it early
- Horizontal or dual purpose trenches
- Odor management

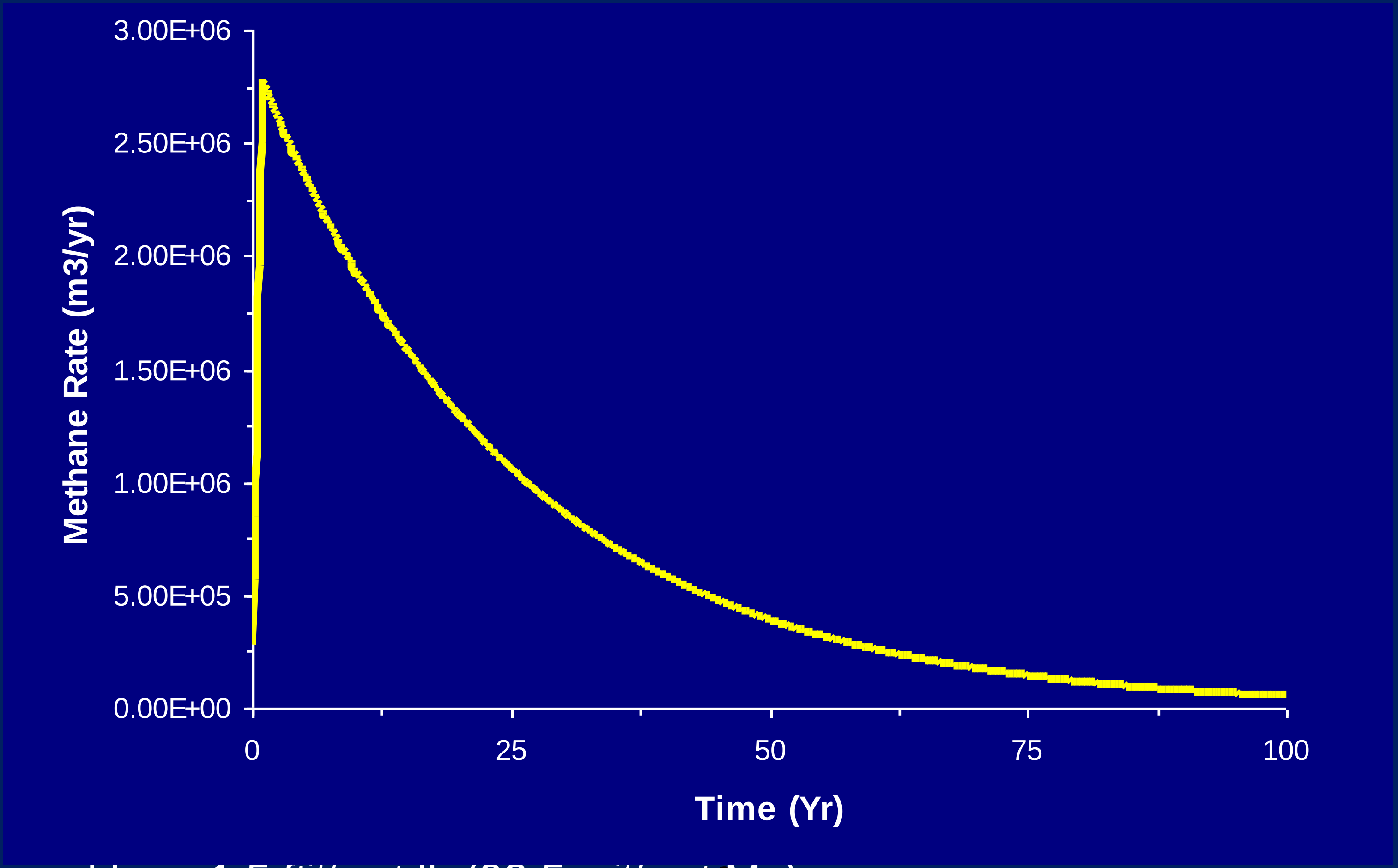
Landfill Gas Modeling

$$Q_n = k \cdot L_0 \cdot \sum_{i=0}^{n} \sum_{j=0.0}^{0.9} \frac{M_i}{10} \cdot e^{-k \cdot t_{i,j}}$$

- Q_n is annual methane generation for a specific year t (m^3 CH_4/yr);
- k is first order decay rate constant (1/yr)
- L_0 is total methane potential (m^3 CH_4/ton of waste);
- M_i is the annual burial rate (tons)
- t is time after initial waste placement (yr);
- J is the deci-year time increment

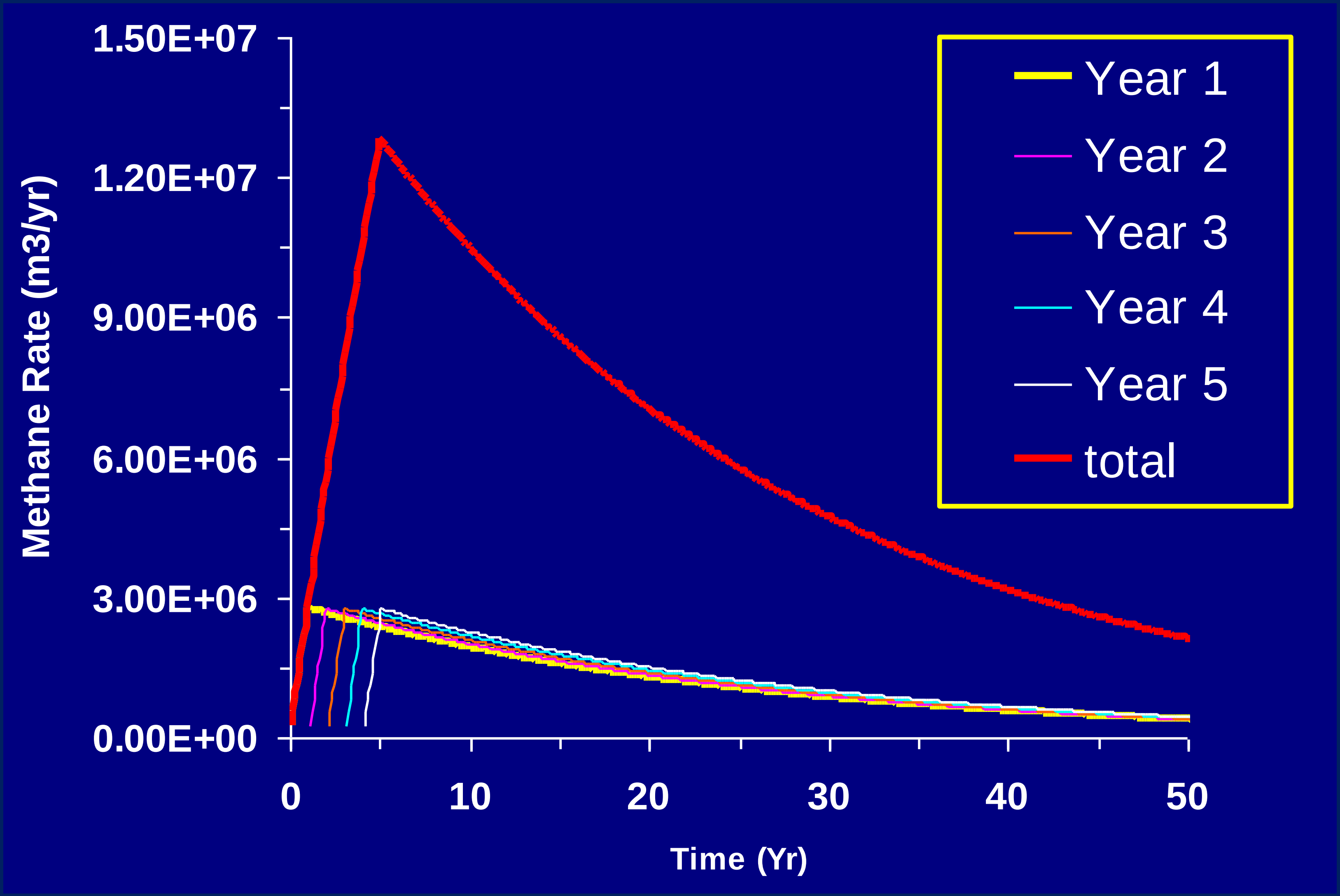
Landfill Gas Emissions Model (LandGem)
http://www.epa.gov/ttn/catc/products.html#software

Methane Production Rate Curve for One Years Waste

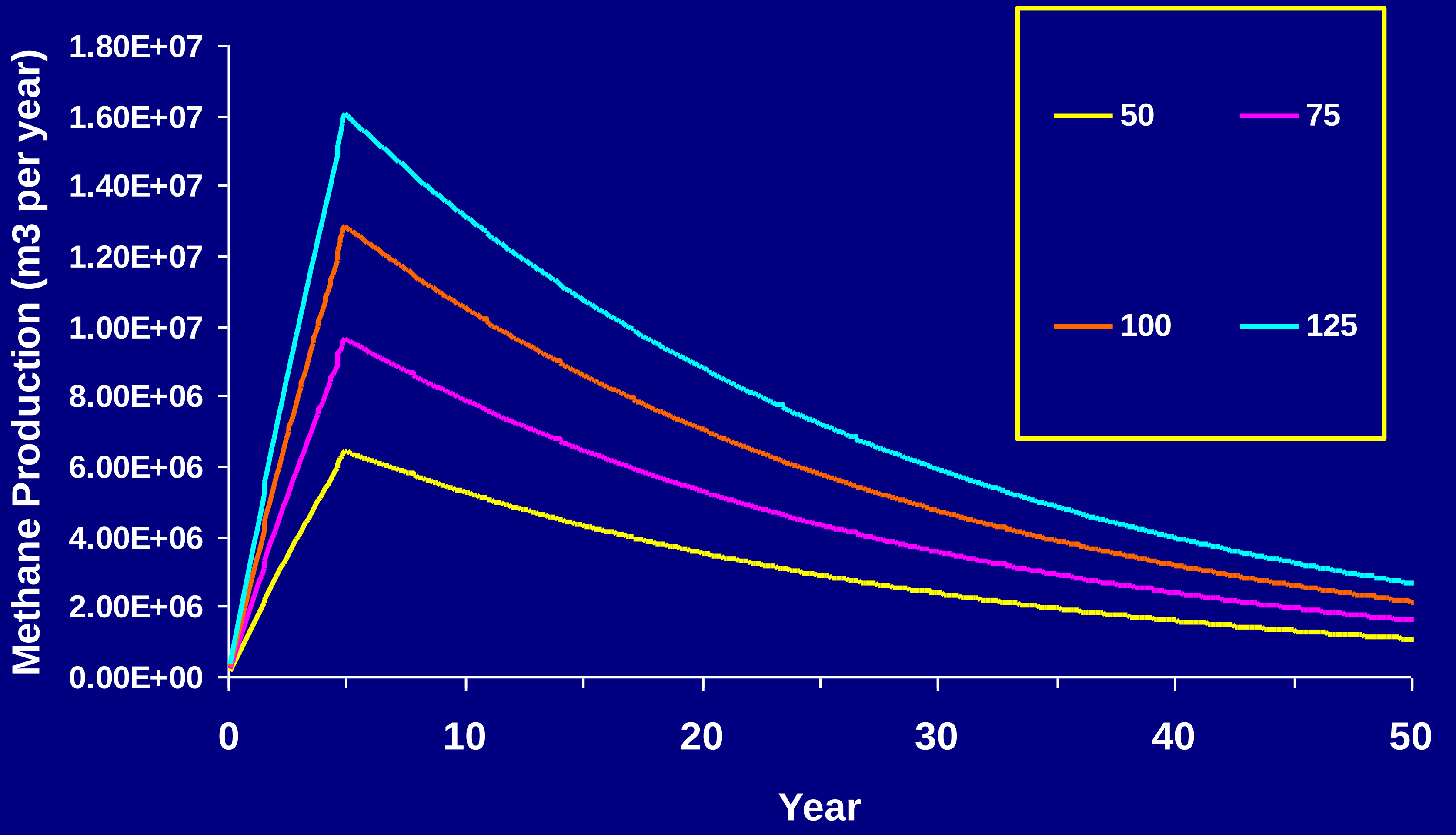


and Lo = 1.5 ft^3/wet lb (93.5 m^3/wet Mg)

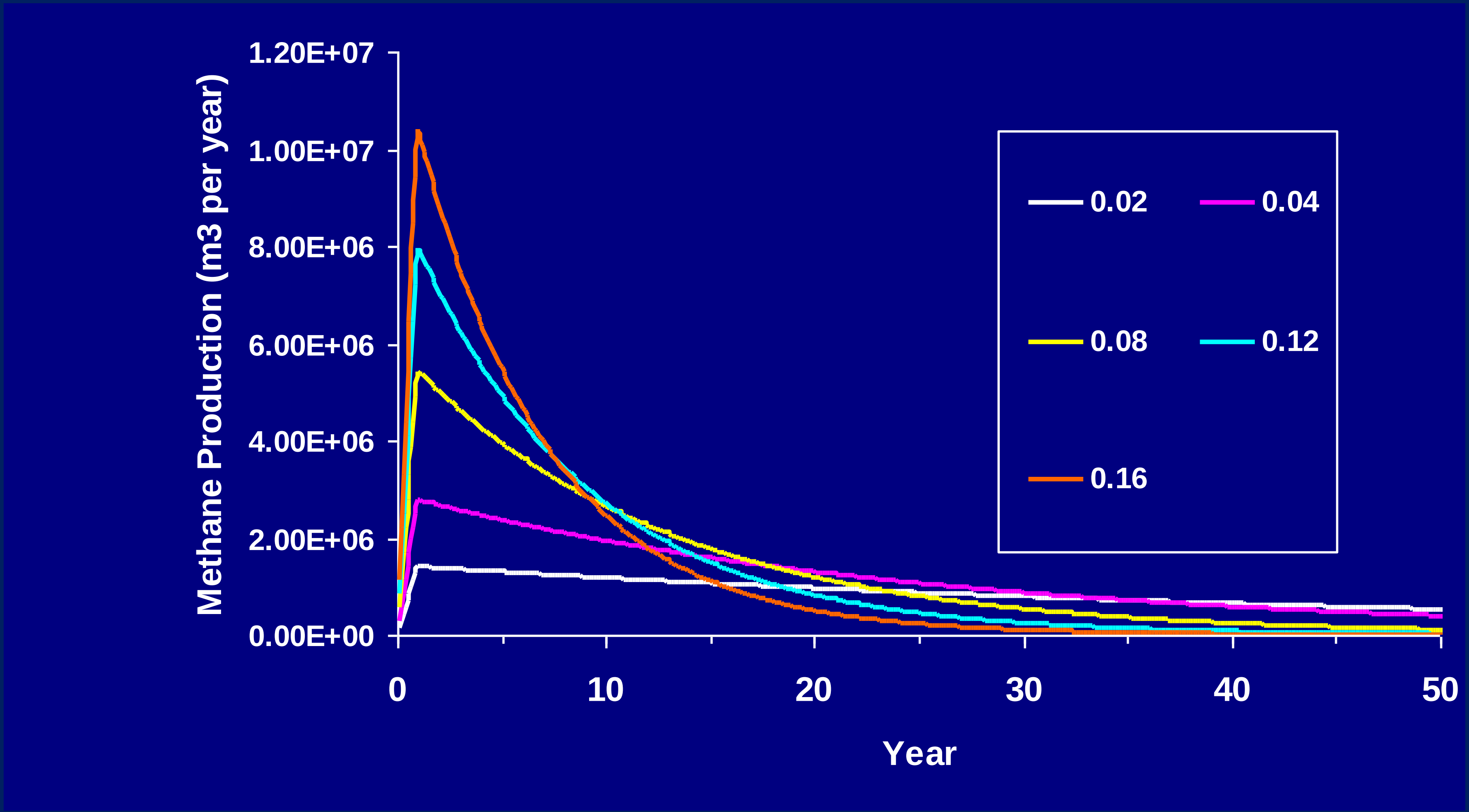
Methane Production Rate Curve for Five Years Waste



Effect of L_0 on Methane Production



Effect of Decay Rate (k) on Methane Production



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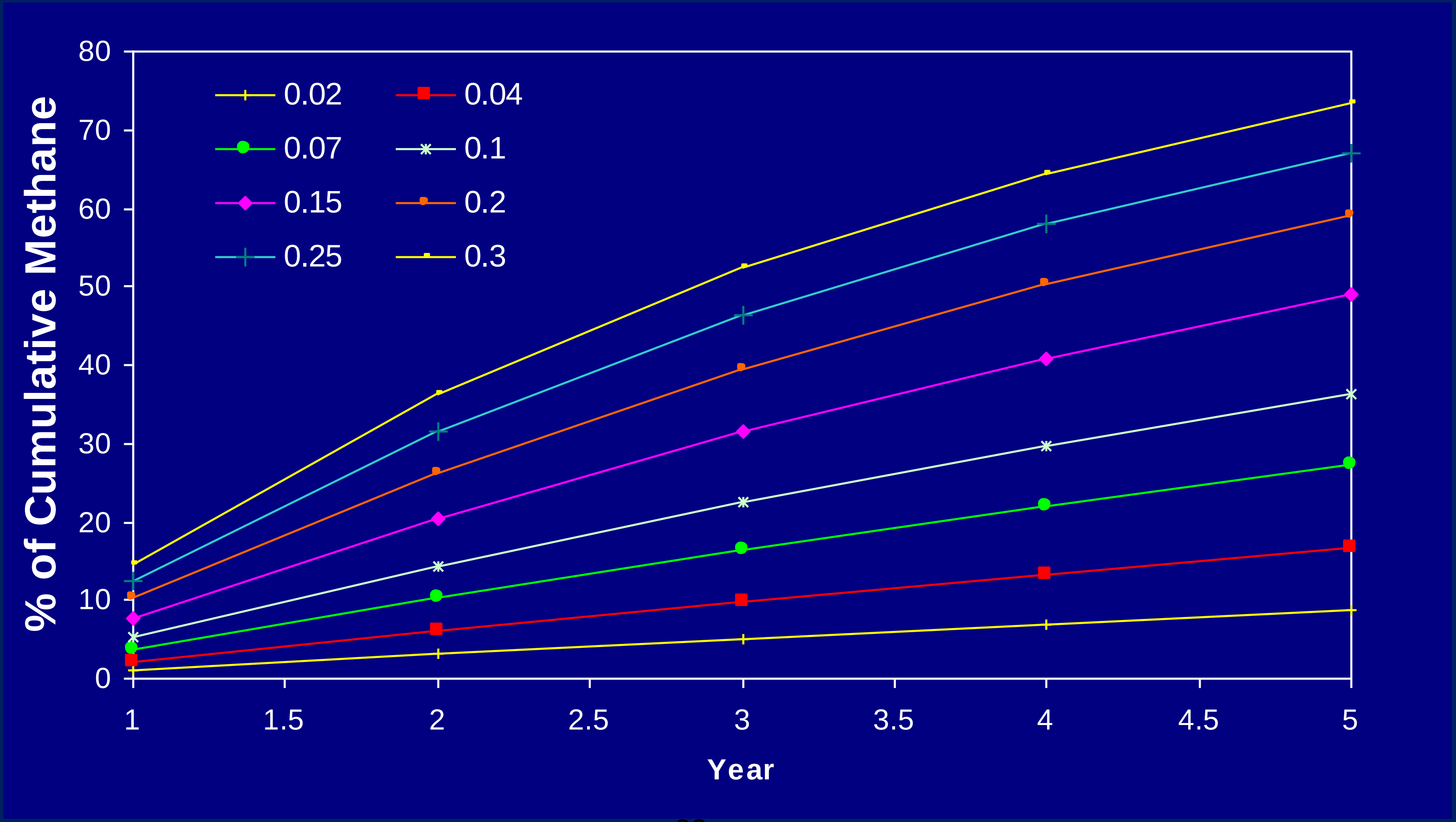

Aerobic Bioreactors

- Air injection
- Claim is no methane production which has advantages and disadvantages
- Enhanced and more rapid solids decomposition?
- Need to provide moisture due to evaporative losses
- Typically no gas control
- Role in stabilization of older landfills (Germany)

Design, Permitting and Operations Challenges

- Effective moisture distribution and control
- Gas collection
- Monitoring
- Controlling side seeps and breakouts
- Slope stability
- Effective use of increased airspace
- Appropriate use of air addition
- Long term management and closure

Effective Moisture Distribution and Control

- Types of devices
- Number and spacing of devices
- How much liquid do you (can you) add?
- Do you operate under pressure?
- Head on the liner

Monitoring

- Liquids
- Gas
- Solids
- Settlement
- In-situ properties

Gas Collection

- The addition of water complicates gas extraction
- Approaches
  - Combined devices
  - LCRS
  - Strategic phasing of collection
  - Surface collection

Controlling Side Slopes and Breakouts

- Design and operate to minimize seep formation
- Need to plan on seeps occurring

Slope Stability

- Waste characteristics change with time
- Elevated liquids levels decrease waste strength
- Challenge as part of the permitting process
- Function LCRS is critical

Design, Permitting and Operations Challenges

- Effective use of increased airspace
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(EPA NESHAP Rule)

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Performance of North American Bioreactor Landfills: Leachate Hydrology & Waste Settlement

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Research Associate
Geological Engineering
University of Wisconsin-Madison

28 April 2011

Environmental Research and Education Foundation
Regional Summit 2011

THE UNIVERSITY of WISCONSIN MADISON

Bioreactor Partnership
An Industry-Academia Partnership

NSF

State-of-the-Practice Papers

ASCE *Journal of Environmental Engineering*, August 2010, Volume 136, No. 8

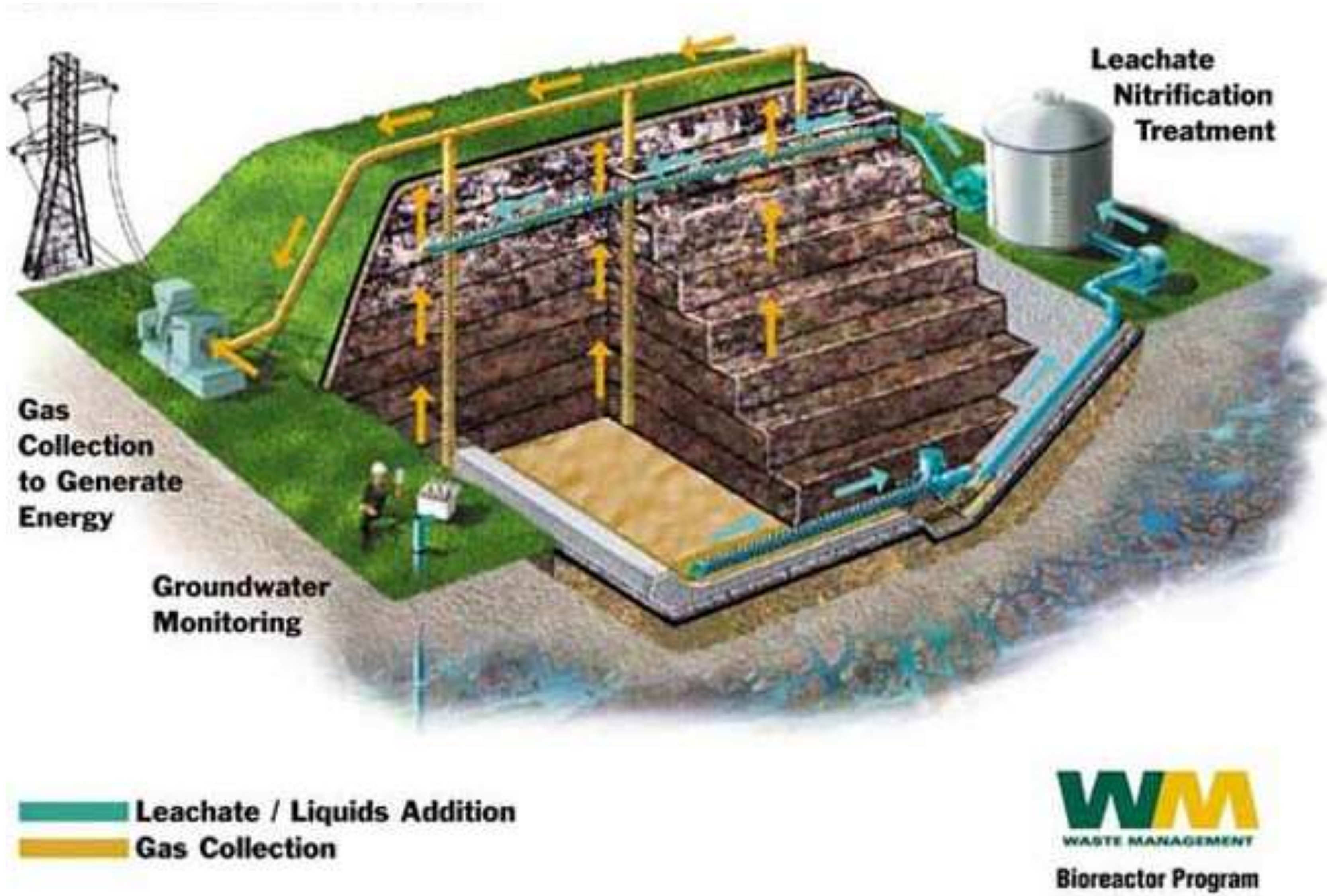
- Performance of North American Bioreactor Landfills. I: Leachate Hydrology and Waste Settlement
  - Christopher A. Bareither, Craig H. Benson, Morton A. Barlaz, Tuncer B. Edil, and Thabet Tolaymat
- Performance of North American Bioreactor Landfills. II: Chemical and Biological Characteristics
  - Morton A. Barlaz, Christopher A. Bareither, Azam Hossain, Jovita Saquing, Isabella Mezzari, Craig H. Benson, Thabet Tolaymat, and Ramin Yazdani

U.S. Waste Management

- 64% of U.S. waste disposed in landfills in 2008
  - 32 of 44 U.S. states are increasing landfill capacity (Arsova et al. 2008)
- Alternative Technologies
  - Waste-to-energy – 7%
  - Recycling and compositing – 29%
  - Mechanical-biological treatment
  - Refuse-derived fuel
  - Anaerobic digestion

How can we make solid waste landfills more sustainable?

Bioreactor Landfill Design



Operate landfill as an anaerobic treatment cell where liquids and gases are actively managed.

Bioreactor Benefits

- Enhanced solids decomposition for stabilization
- Accelerated biogas production for energy recovery (compress gas curve).
- In-situ leachate treatment and storage, reducing long-term risk
- Increased settlement & airspace recovery

State-of-the-Practice – Questions

- Does recirculation adequately moisten waste?
- Are recirculation practices evolving (leachate dose rates and methods)?
- Is recirculation affecting leachate generation rate and leachate management?
- Is recirculation affecting liner leakage?
- Is enhanced settlement/airspace recovery being realized?
- Is gas generation being enhanced and does it relate to water content?
- Is leachate treatment/stabilization being realized?

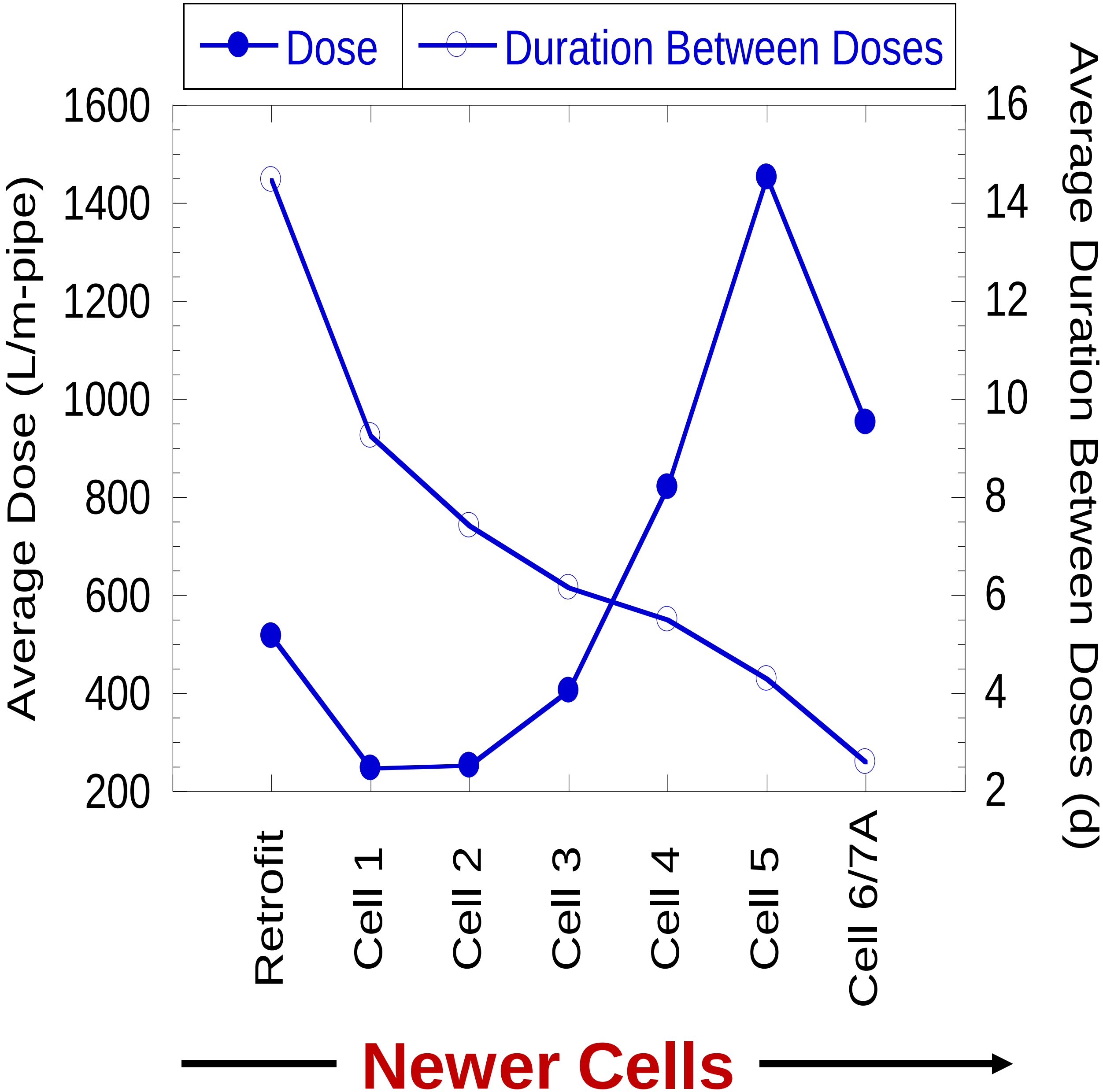
Landfills Studied

Landfill	North American Region	Owner	Avg. Annual Precip. (mm)	Landfill Area or Cell Designation	Year Oper-ational	Area (ha)	Duration of Leachate Recirculation (yr)	Recirculation Method[a]
D	Mid-Atlantic	Public	1096	C	1988	7.9	5	Vertical
				D and C/D Valley	1993	9.1	10	Vertical & horizontal
				E	1999	13.2	3	Horizontal
G	Northeast	Private	1233	Old	1986	2.8	2.6	Horizontal
				Expansion	2000	40.0	1 – 3[b]	Horizontal
L	Northeast	County	1182	—	1997	18.6	6	Horizontal
M	Southeast	Private	1093	Recirculation	1993	10.7	5	Horizontal
				Closed	1995	8.7	—	None – conventional
				Operational	1999	8.0	—	None – conventional
Y	West	County	581	NE	2001	1.4	6	Horizontal
				W	2001	2.4	5	Horizontal

[a]Refers to orientation of injection method – vertical wells or horizontal trenches

[b]Duration of recirculation varies among eight individual cells

Leachate Recirculation



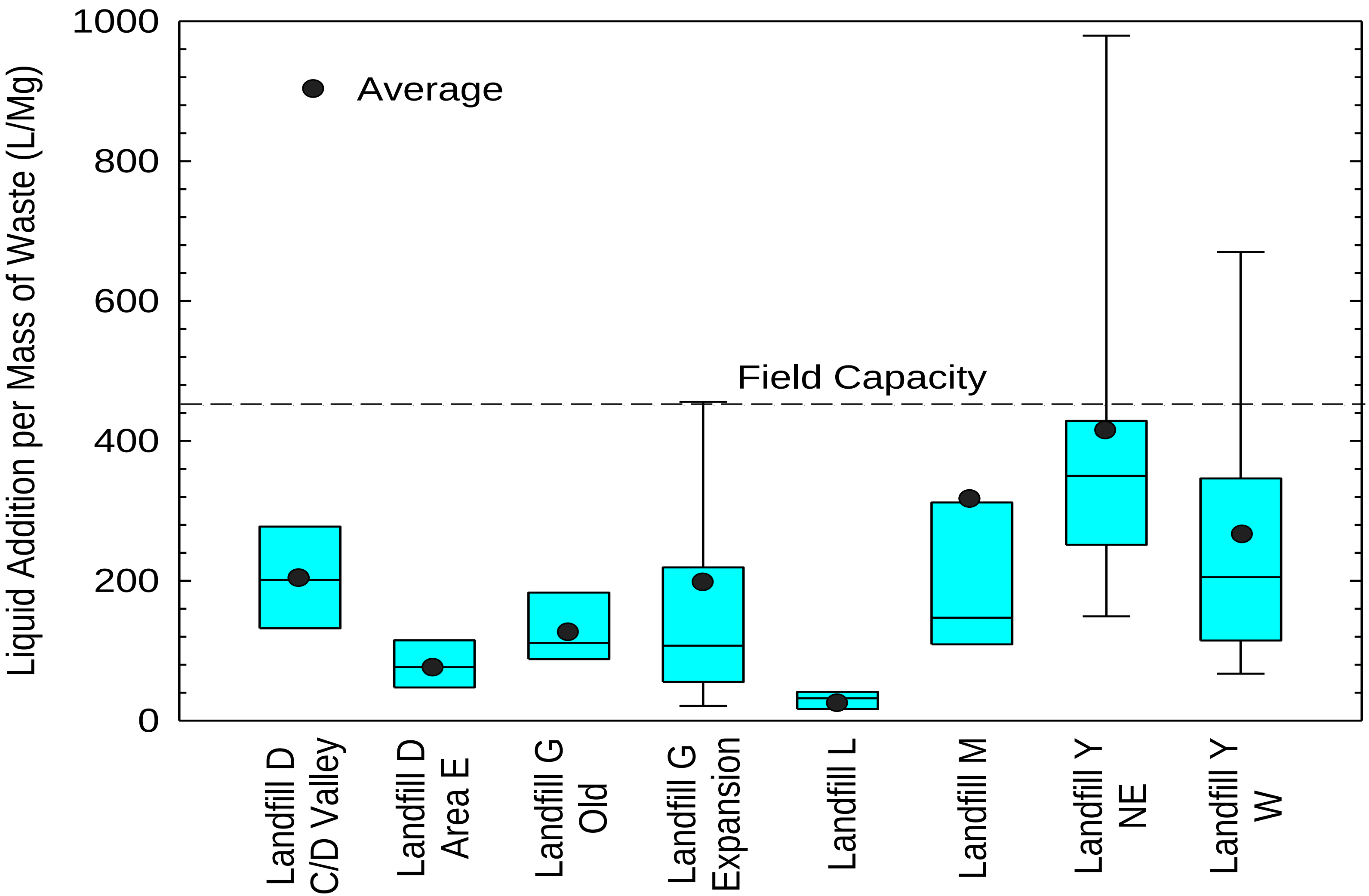
Dose history at Landfill G:

- More leachate recirculated more frequently

Average dose (L/m-pipe)

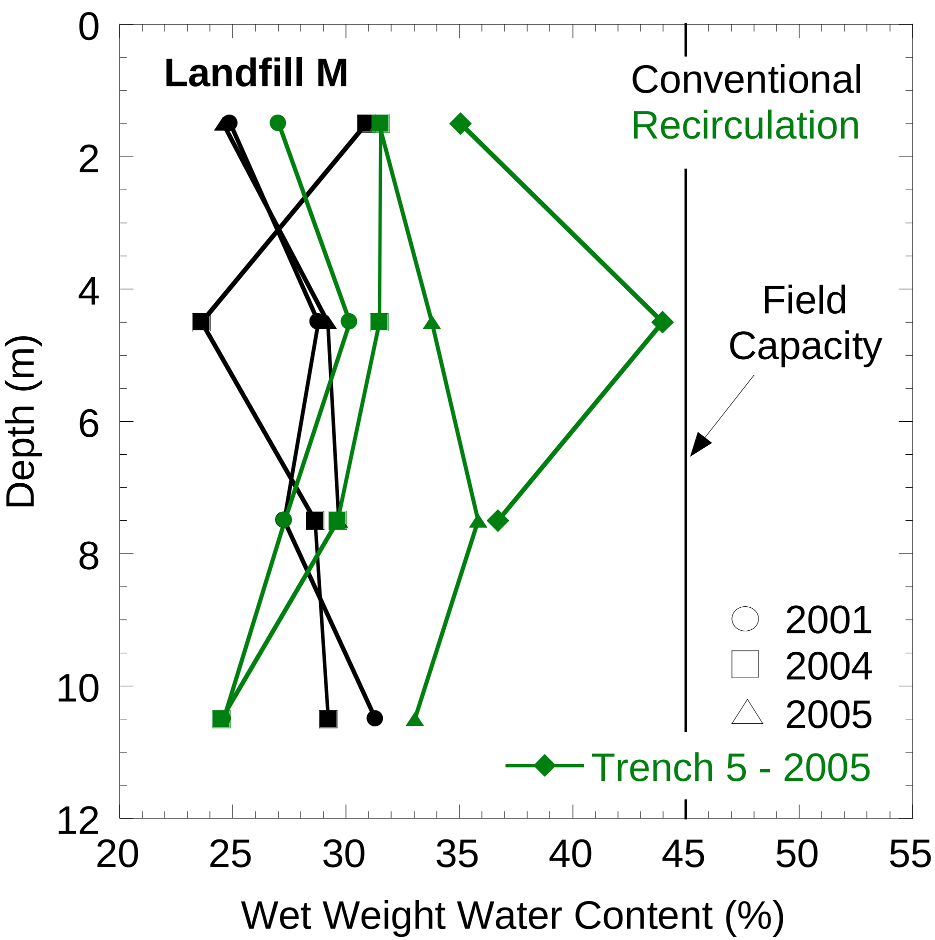
- This study – 180-940
- Benson et al. (2007) – 280-434
- Townsend & Miller (1998) – 950-2100

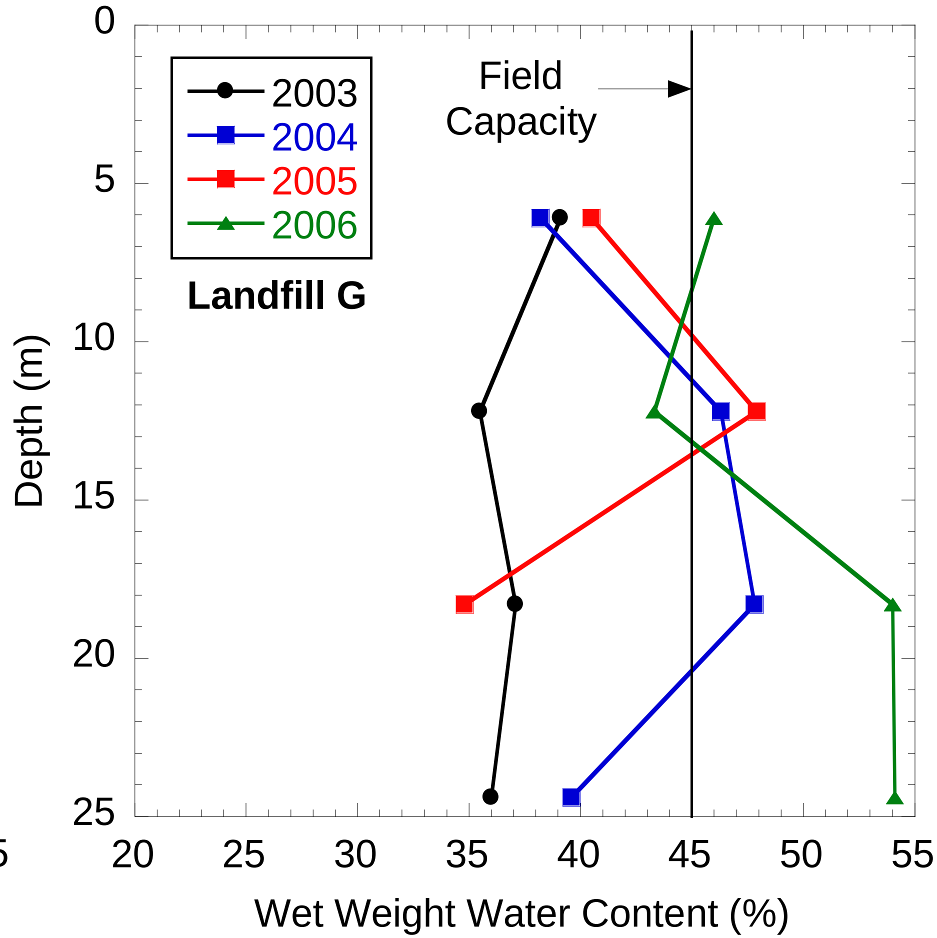
Leachate Recirculation



- Horizontal trench recirculation – normalized to wetted volume of waste
- Assume field capacity = 45% and initial waste moisture content = 20%

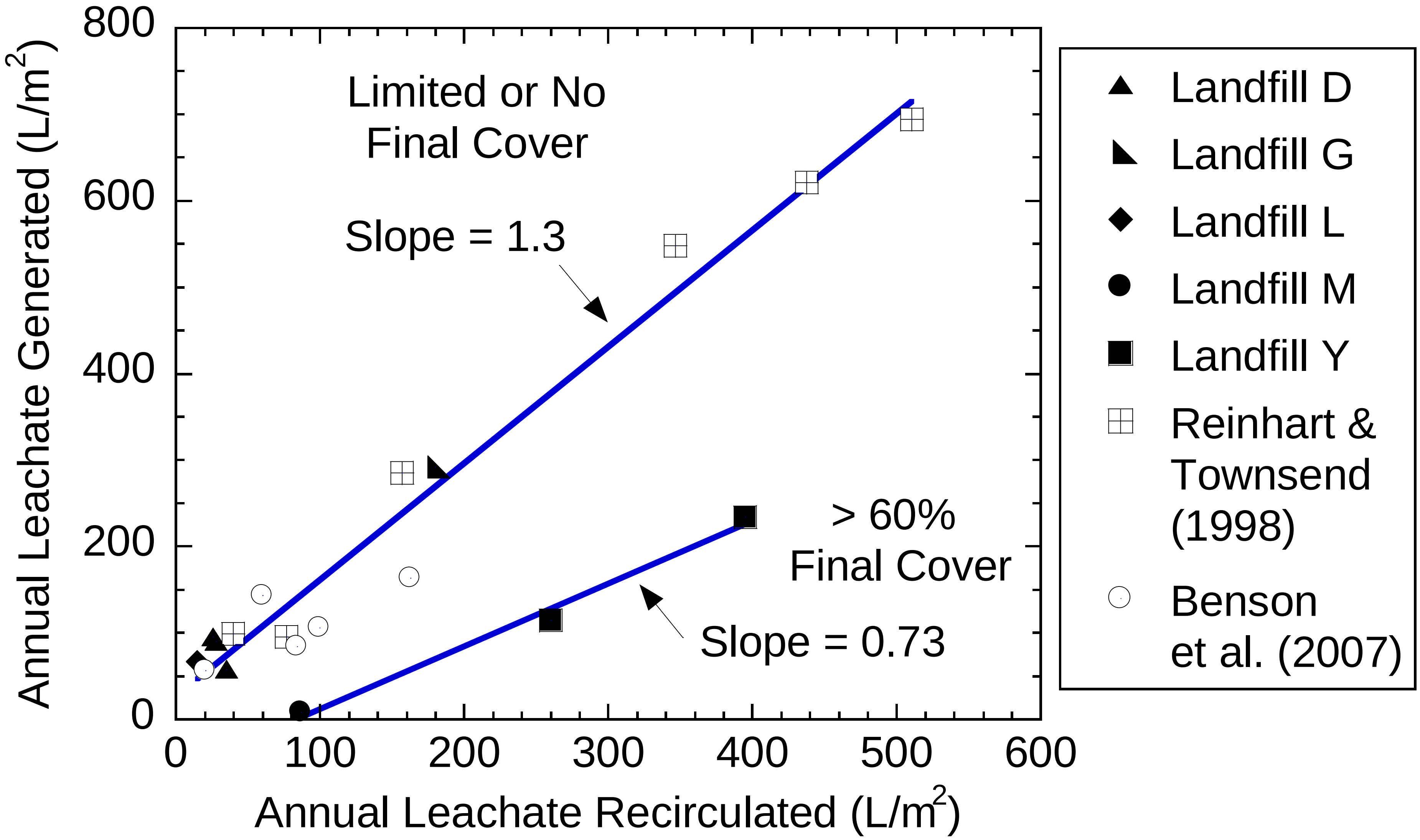
Moisture Content





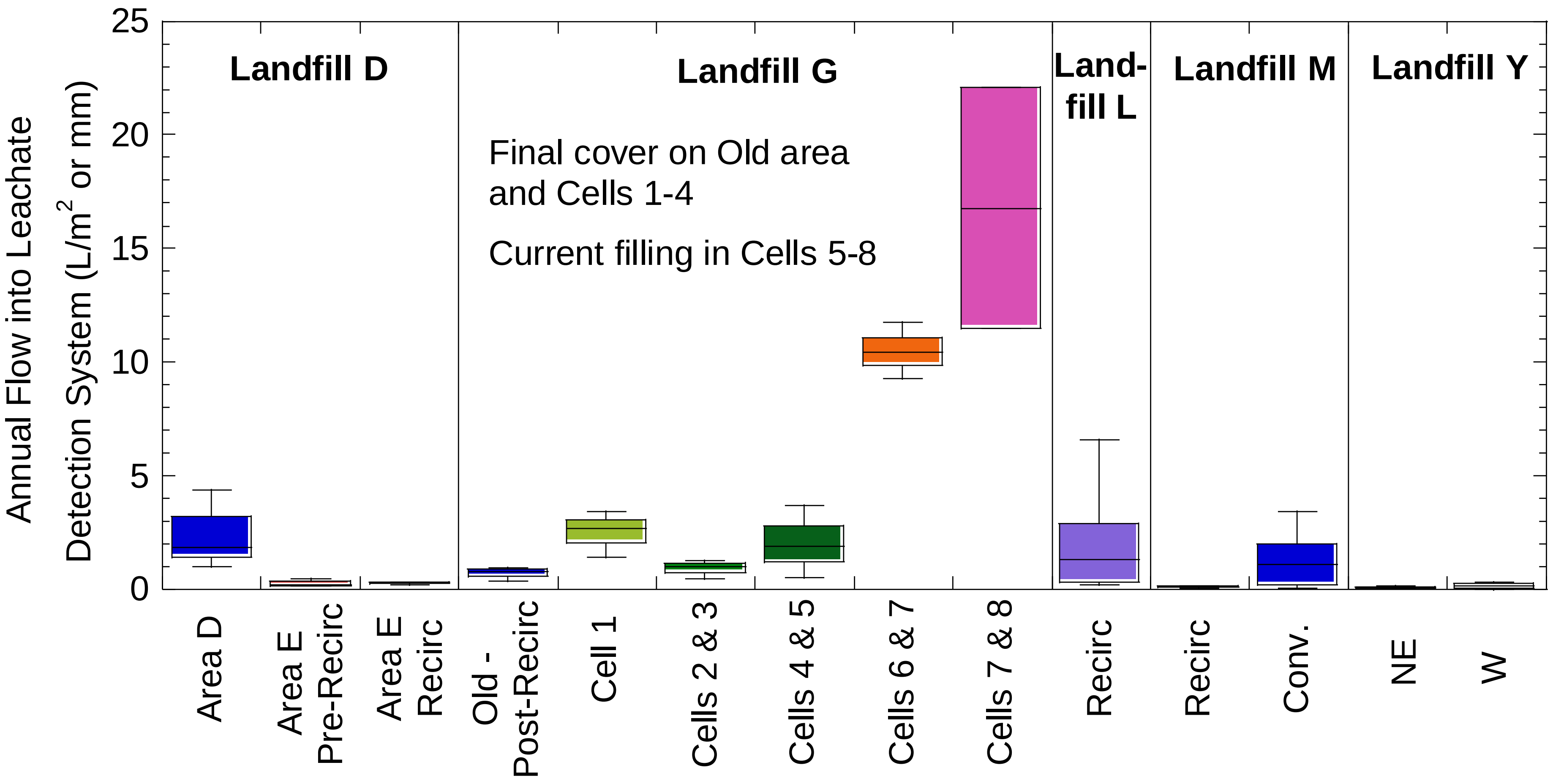
- Landfill M – retrofit; Landfill G – trenches installed with filling
- Trench 5 – received ~ 55% of total leachate recirculated at Landfill M
- Moisture content profiles reflect downward movement of leachate

Leachate Generation



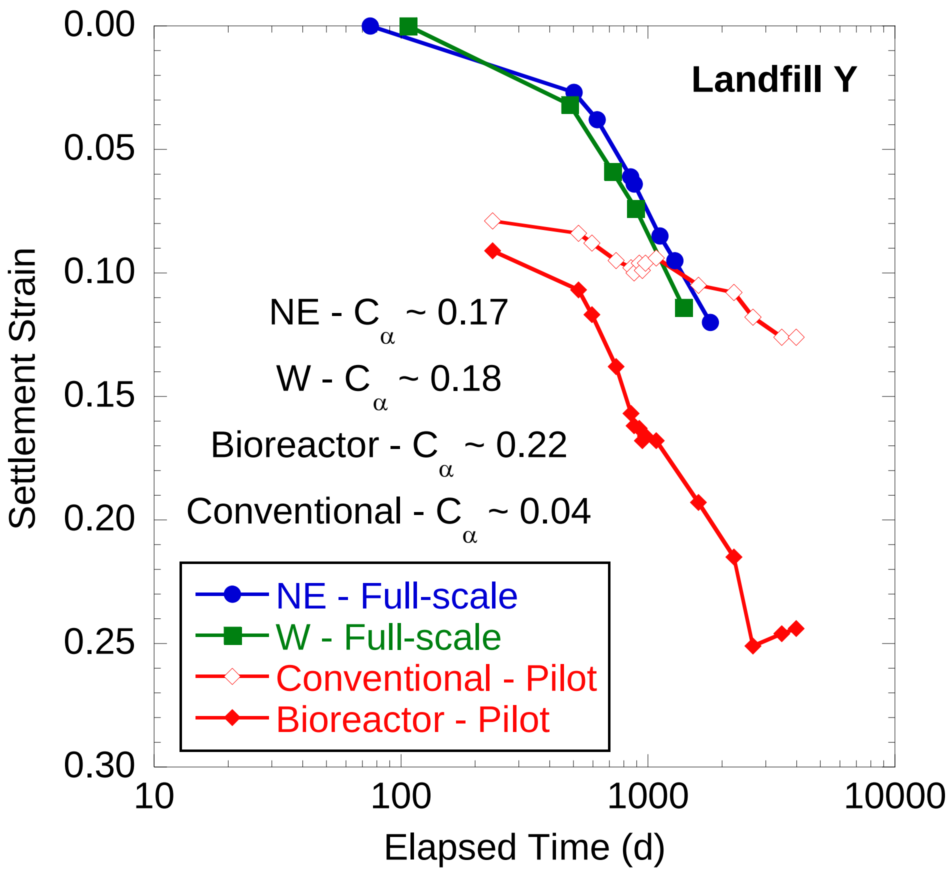
1 L/m^2 = 1 mm

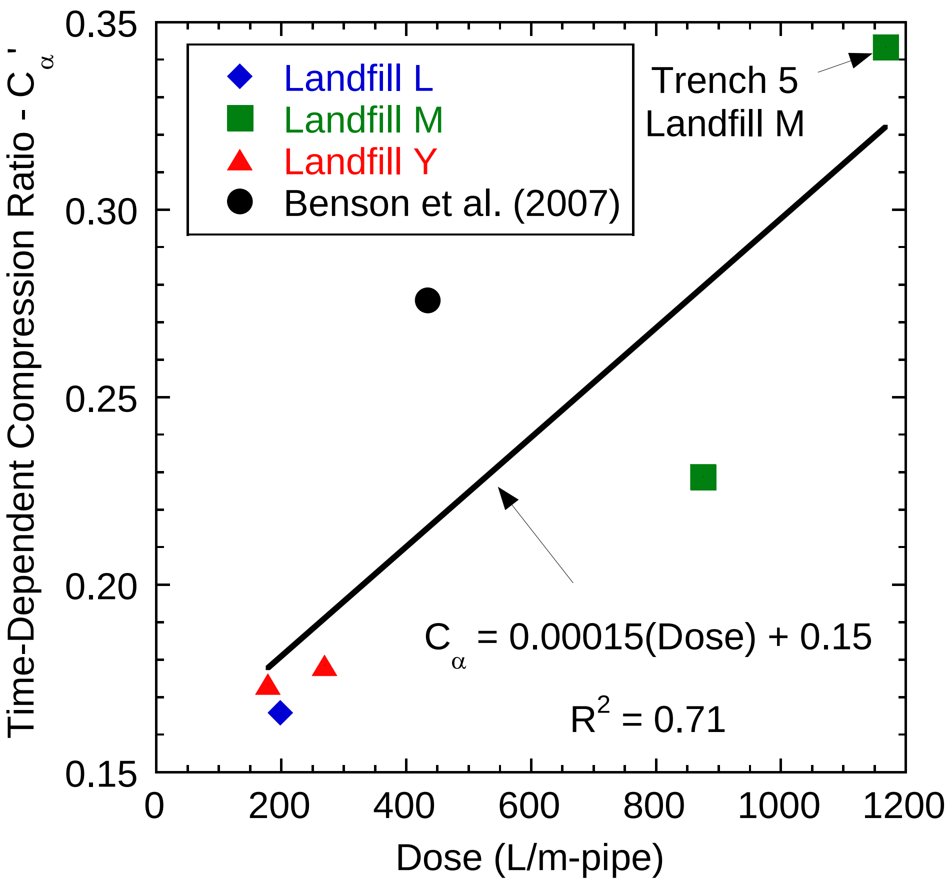
Liner Leakage



- All flows below ALR, agrees with head on liner meeting regulations
- Leachate recirculation did not increase flows into LDS
- Landfill D Area E and Landfill M – GM-GCL composite liner system

Settlement





- C_α' = time-dependent compression coefficient
  - Conventional ~ 0.04, Bioreactor ~ 0.20
- C_α' increases with increase in leachate dose

$$C_\alpha' = \frac{\Delta\varepsilon}{\Delta \log t}$$

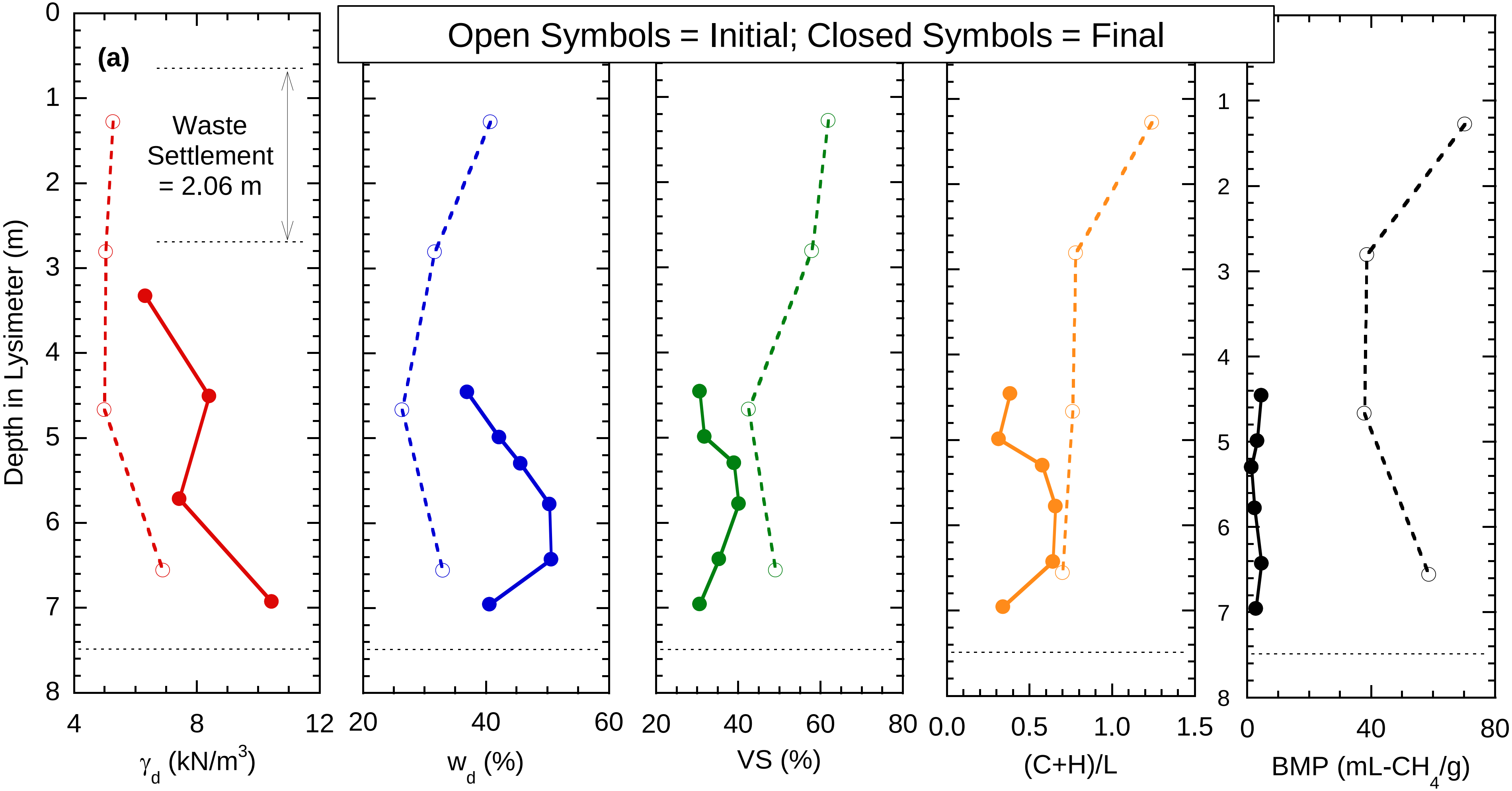
Conclusions

- Leachate generation: rates for bioreactors and conventional landfills are similar
  - Generation rate = function of cover status and recirculation rate
- Recirculation volumes are increasing in recent years
  - Only most aggressive recirculation strategies have achieved moisture contents near field capacity
- Conventional liner systems used for bioreactors are not stressed more than for conventional landfills
  - Similar leak detection flows at bioreactor and conventional sites
- Increased rates of leachate recirculation = increased settlement rates (C_α')

Deer Track Bioreactor Experiment

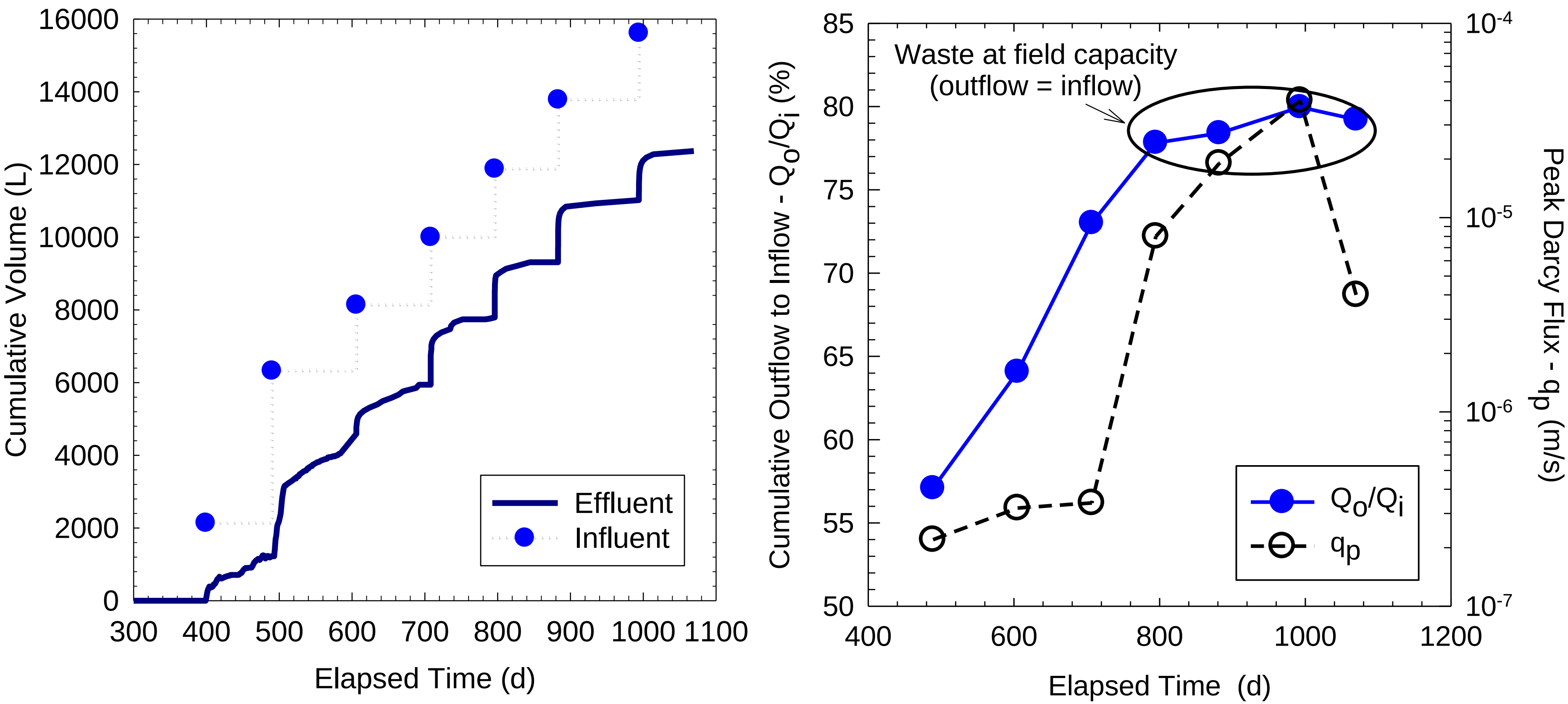
- Create detailed data sets of hydraulic, mechanical, and chemical behavior
- Well-defined boundary conditions and replicate full-scale landfill conditions
- Measure leachate volumes and chemistry, moisture content, pore pressure, solids composition, settlement, and temperature
- Operated for 1067 d, leachate dosing initiated on Day 399
- Quarterly doses with liquid addition approximated current state-of-practice

Waste Properties



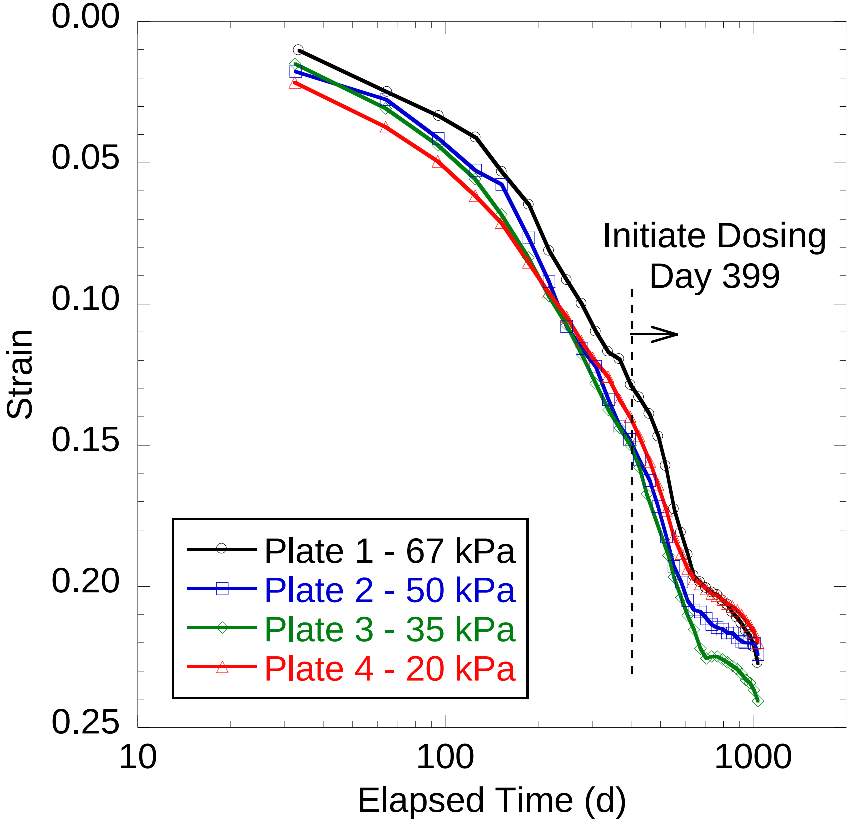
Dry unit weight	Water content	Volatile solids	(C+H)/L	BMP
⇧ 28%	⇧ 11%	⇩ 18%	⇩ 0.87 → 0.49	⇩ 93%

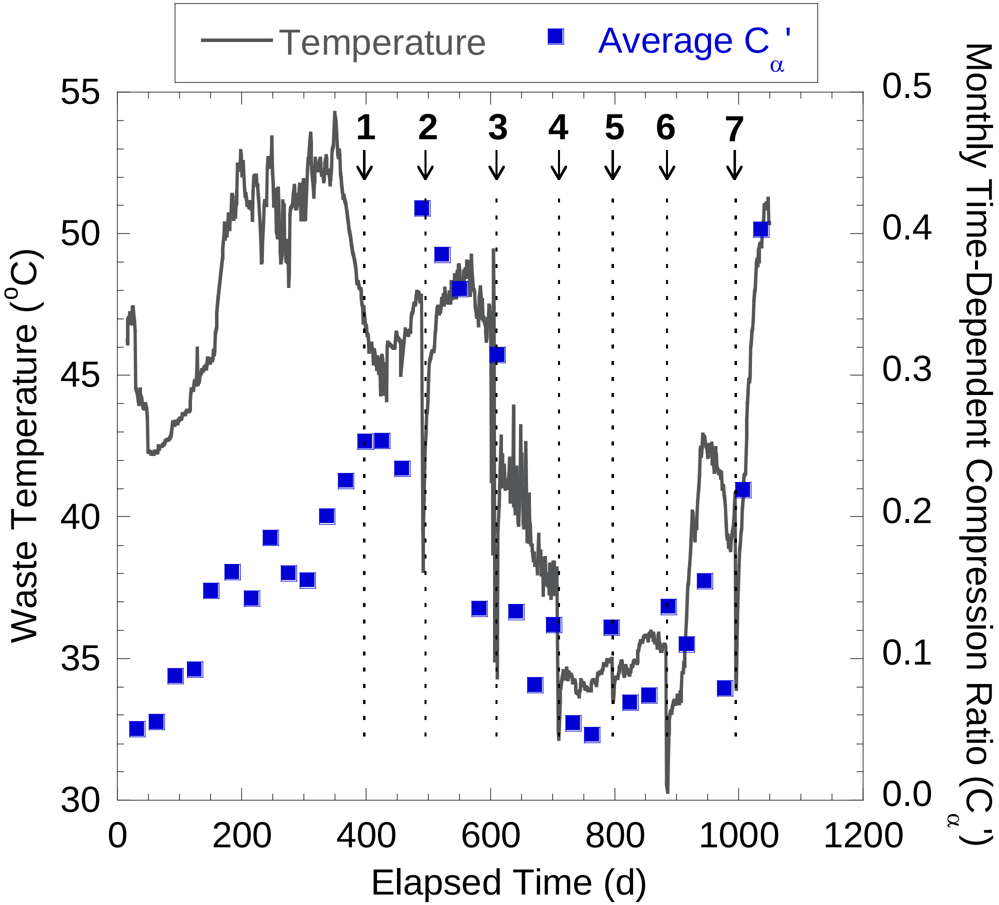
Field Capacity and Leachate Generation



- 15,620 L total leachate added – 2890 L (19%) retained
- Field capacity wet weight water content = 31-32% (dry weight = 44-48%)
- Peak Darcy flux ($2.0\text{x}10^{-7}$ - $4.0\text{x}10^{-5}$ m/s) increased with time and saturation

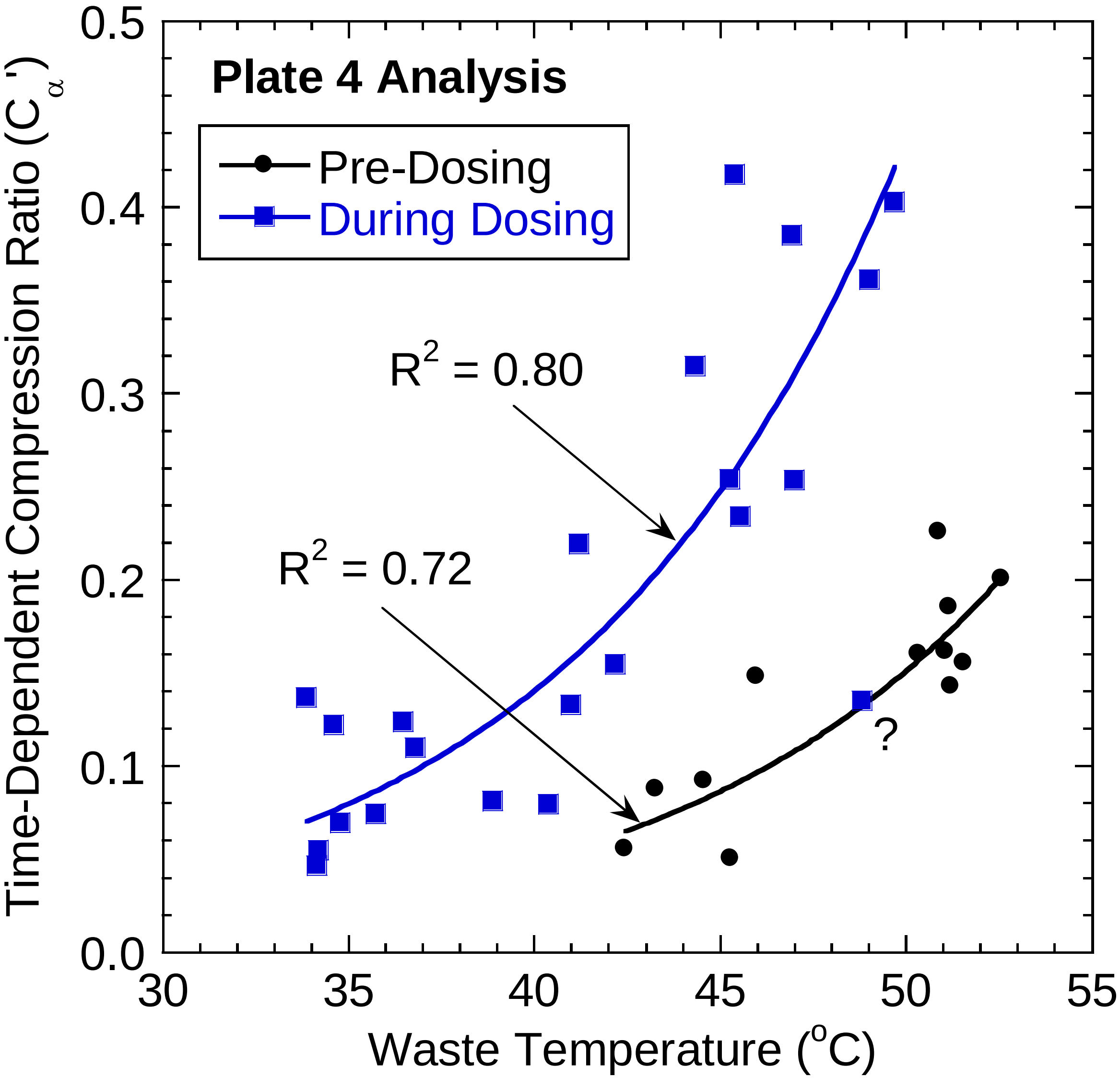
Waste Settlement and Temperature





- No significant difference in strain or C_α' between four settlement plates
- Temperature fluctuations = due to biological activity and leachate dosing
- Variable C_α' due to moisture-induced softening and bioactivity
  - Similar C_α' range to literature and state-of-the-practice

C_α' vs. Temperature



- C_α' fluctuations = due to variations in temperature prior to dosing and during
- C_α' larger during dosing = due to moisture-induced softening and biotic waste decomposition
- Prior to dosing C_α' is lower ~ 0.04 to 0.24
- During dosing C_α' is larger for a given temperature ~ 0.04 to 0.42

DTBE Lessons Learned

- 93% of methane potential removed after 3 yr; only 2 yr of leachate dosing
- Field capacity ranged between 31-32% (wet-weight) or 44-48% (dry weight)
- Peak Darcy flux (q_p) and leachate generation rate increased with dosing
- C_{α}' ranged from 0.04 to 0.42 – is temperature dependent and larger during dosing

Performance of North American Bioreactor Landfills: Leachate Quality and Gas Production

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Landfill Gas Modeling

$$Q_n = k \cdot L_0 \cdot \sum_{i=0}^{n} \sum_{j=0.0}^{0.9} \frac{M_i}{10} \cdot e^{-k \cdot t_{i,j}}$$

- Q_n is annual methane generation for a specific year t (m^3 CH_4/yr);
- k is first order decay rate constant (1/yr)
- L_0 is total methane potential (m^3 CH_4/ton of waste);
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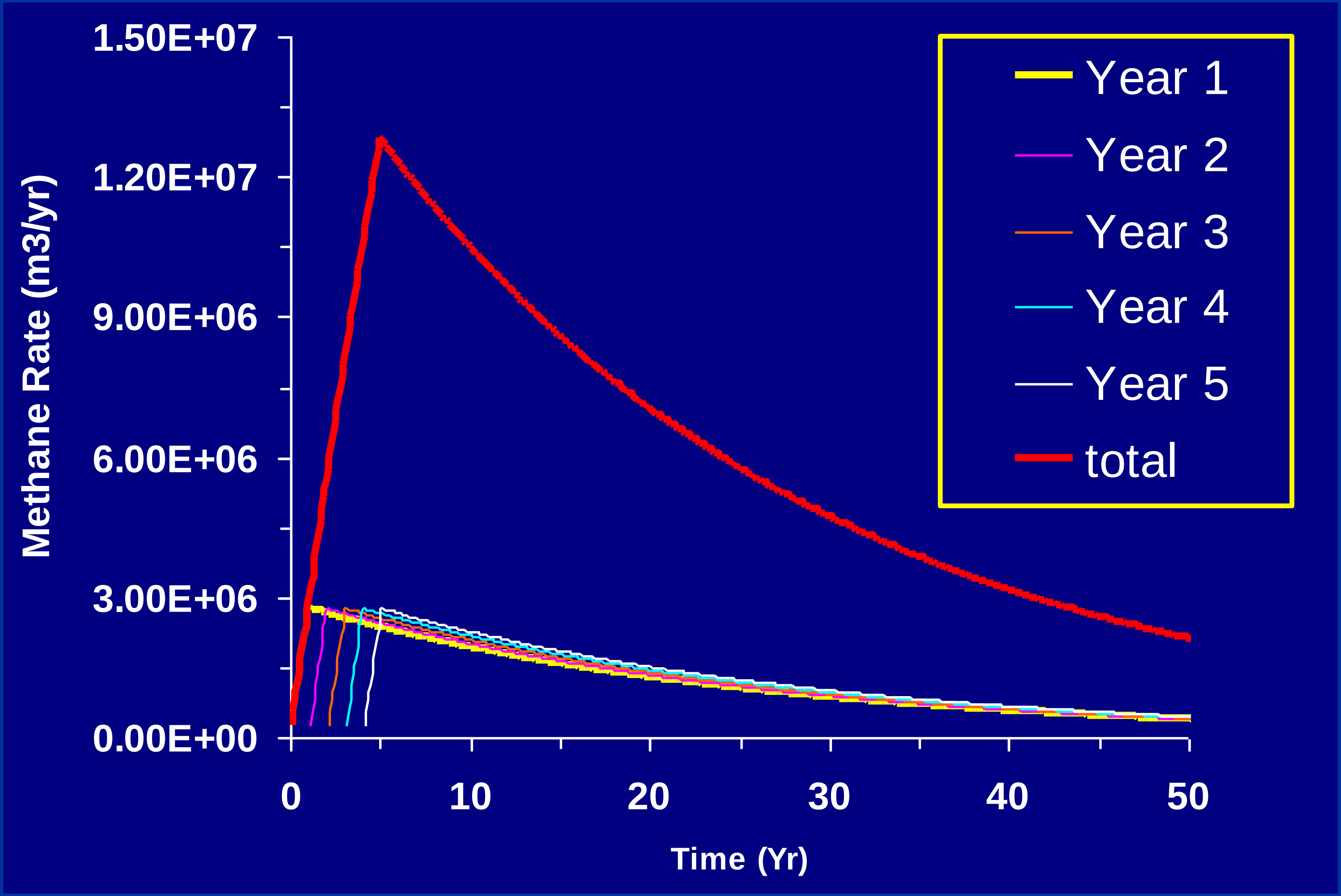
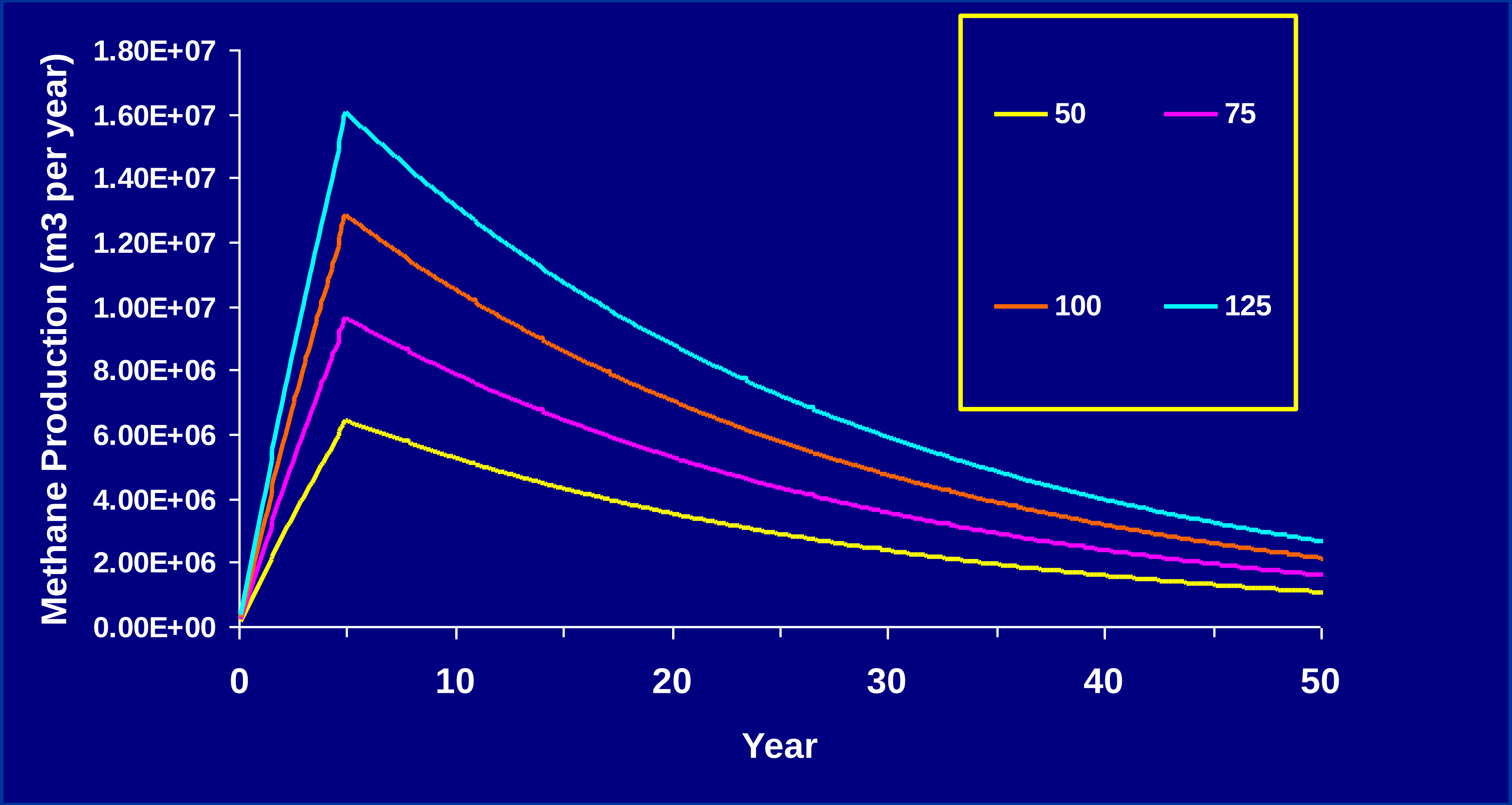
Landfill Gas Emissions Model (LandGem)
http://www.epa.gov/ttn/catc/products.html#software

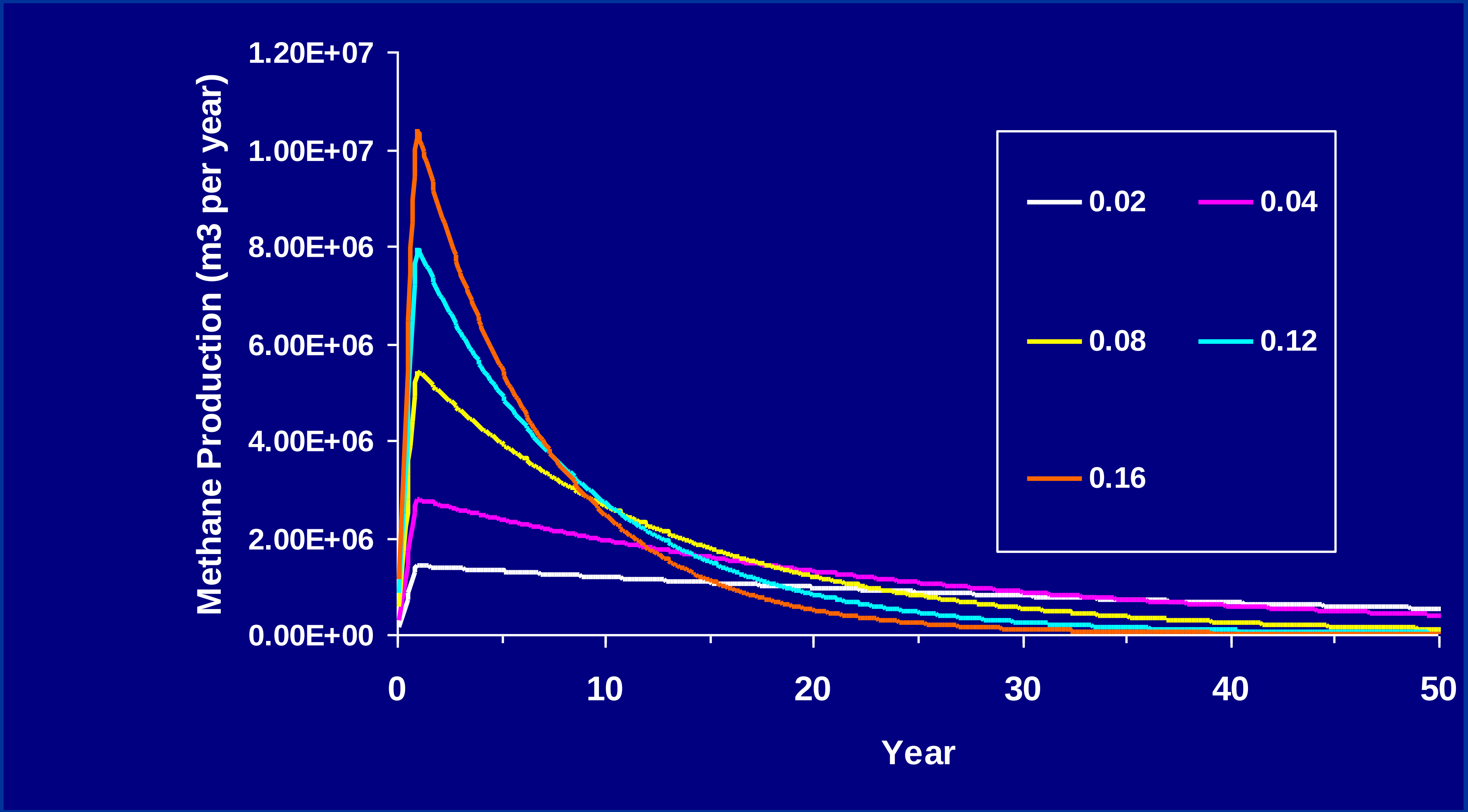
Methane Production Rate Curve for Five Years Waste



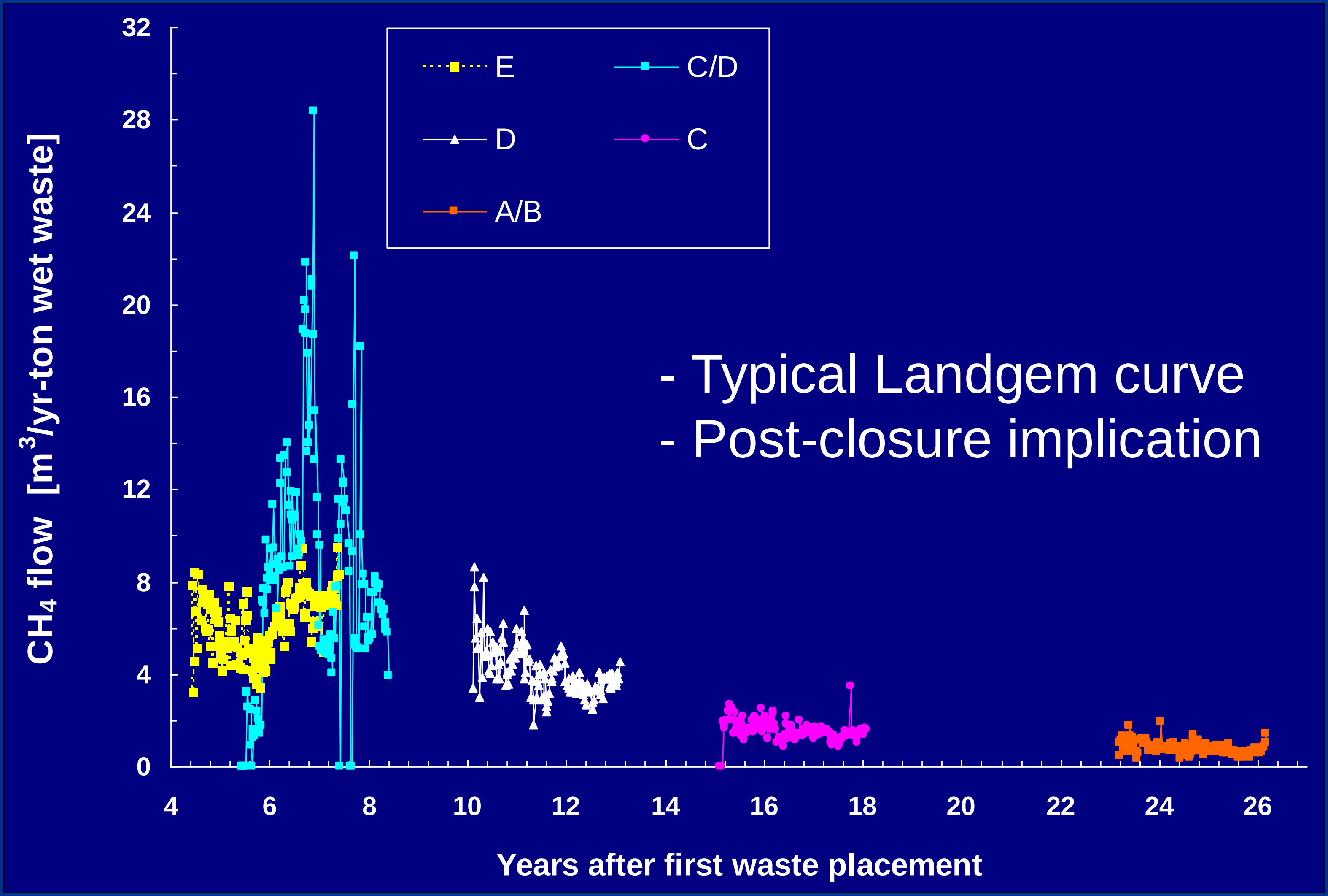
Effect of L_0 on Methane Production



Effect of Decay Rate (k) on Methane Production

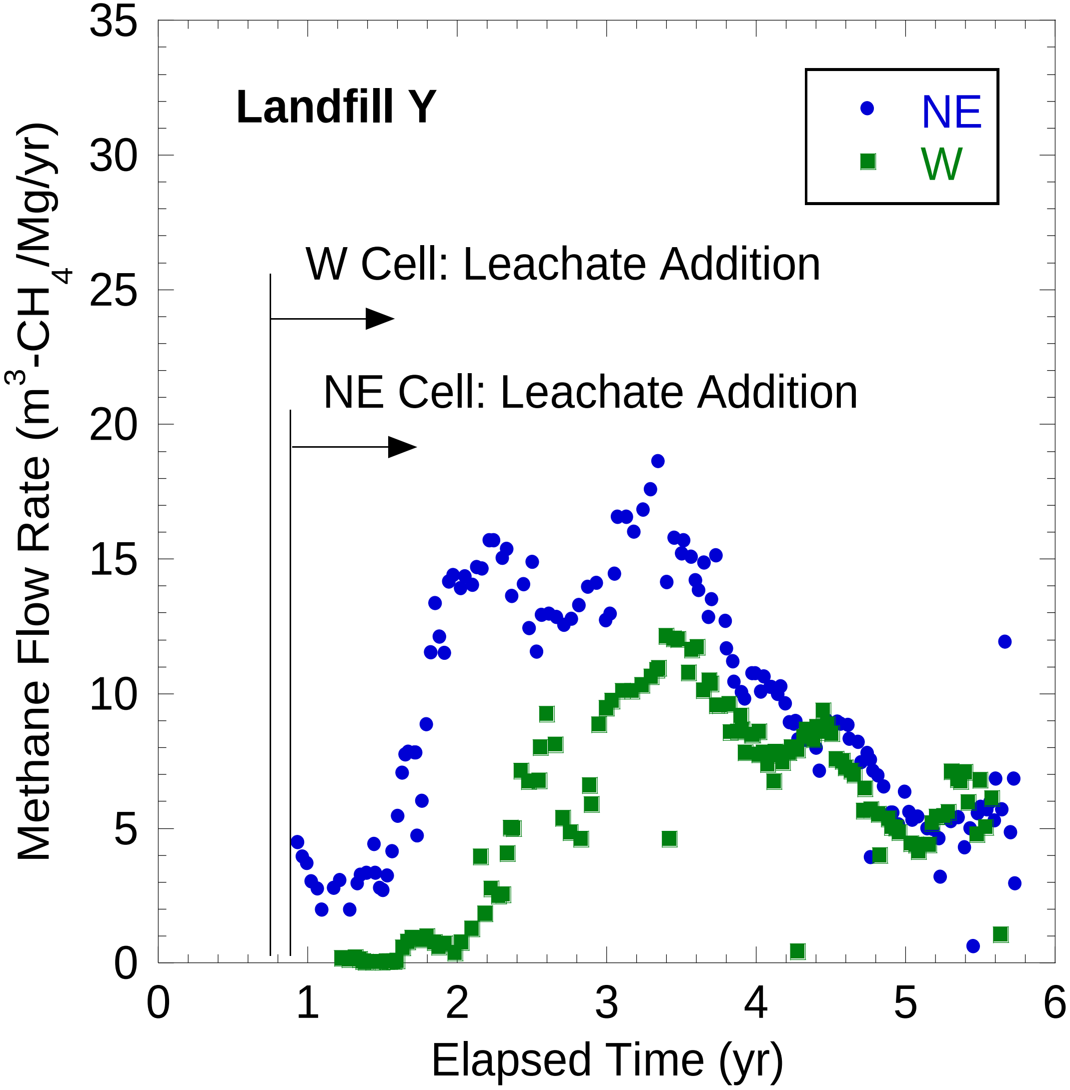


Landfill D Gas Recovery



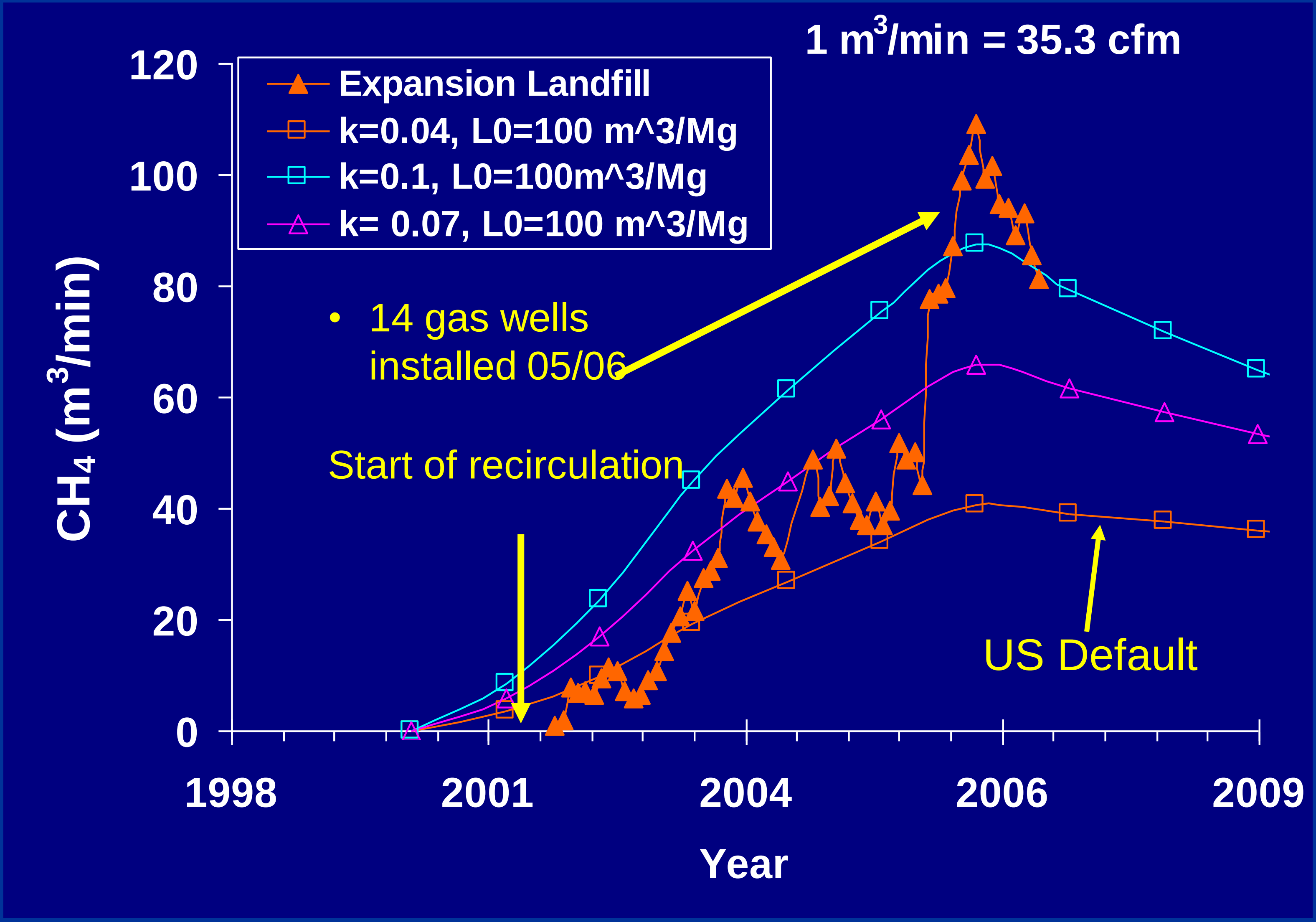
- Typical Landgem curve
- Post-closure implication

Landfill Y Gas Recovery

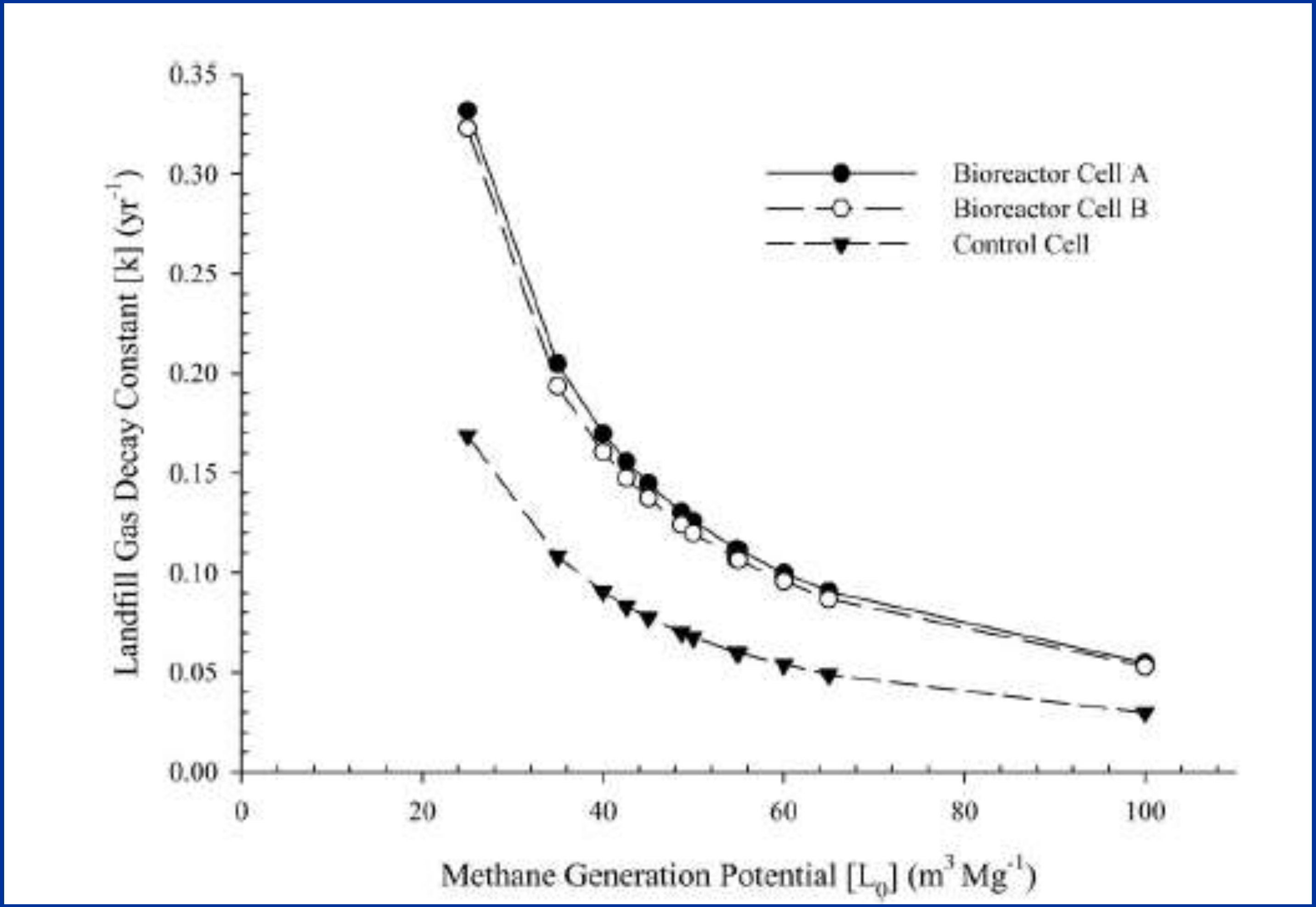


- Unique data set because the large majority of the gas was collected
- Gas collected from both vertical wells and horizontal trenches
- Measured Methane Yield of 86 – 90 Liters/Mg

Landfill G Gas Production



Effect of Assumed L_0 on Decay Rate

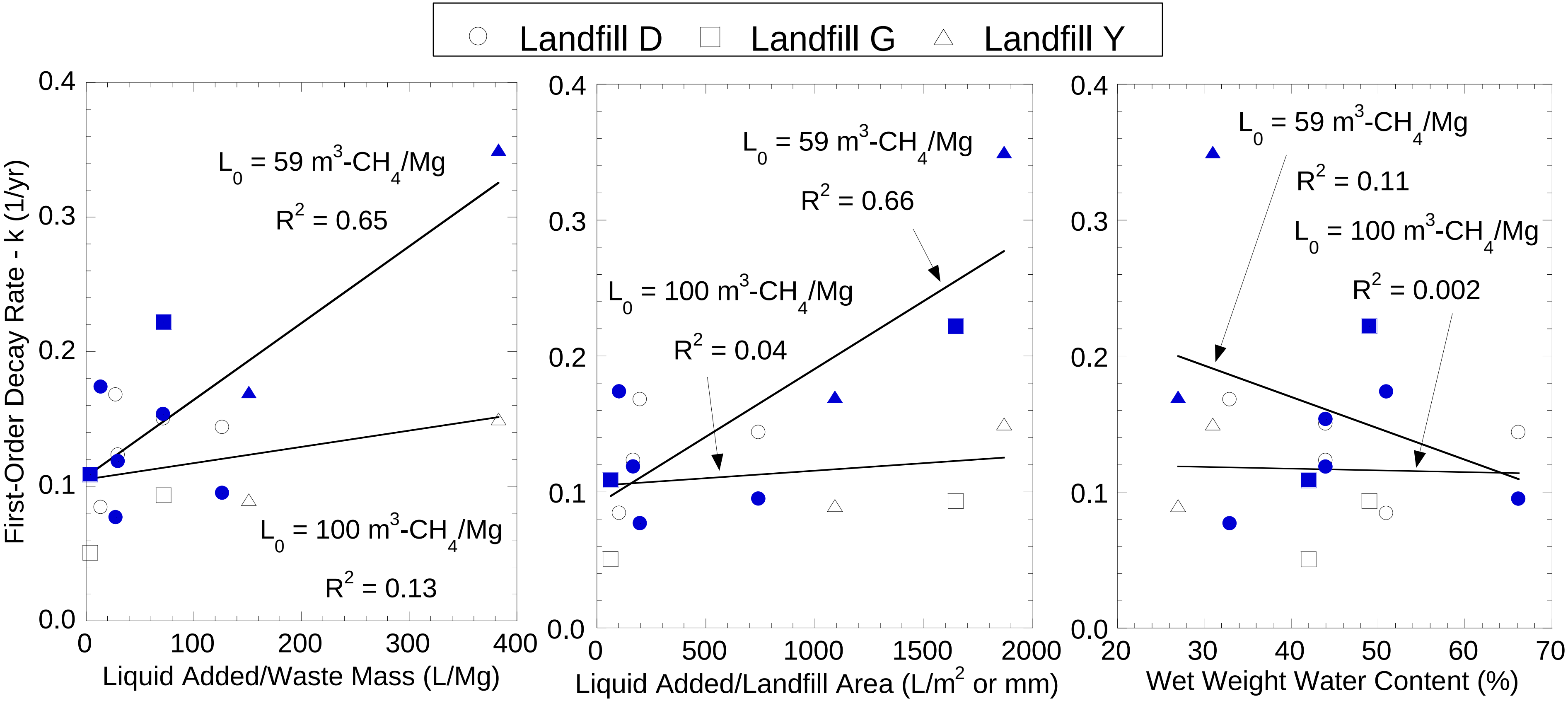


Summary of Landfill Gas Generation Rates

Landfill	Cell	Decay Rate
D	A/B	0.14 (0.09)
	C	0.17 (0.08)
	D	0.12 (0.12)
	C/D	0.15 (0.15)
	E	0.08 (0.17)
G	Original	0.05 (0.11)
	Expansion	0.09 (0.22)
Y	NE	0.15(0.35)
	W	0.09 (0.17)

Values in parentheses assume an Lo of 59 m^3 CH_4/Mg

Methane Generation



- L_0 = 100 m^3-CH_4/Mg is EPA default; 59 m^3-CH_4/Mg from survey
- Production rate increases with liquid added, but not correlated well with water content.

Summary of Gas Data Analysis

- Decay rates of greater than 0.04 are supported by data from multiple landfill cells
- The assumed Lo will have a significant effect on the calculated decay rate
- The methane collection efficiency changes with time which makes it difficult to use filed data for estimation of the decay rate
- In some cases, only part of the landfill is operated with added moisture. As such, when projecting gas production, we should not apply higher decay rates to the entire landfill
- Beneficial use at all landfills
    - Contracts were an issue at every facility

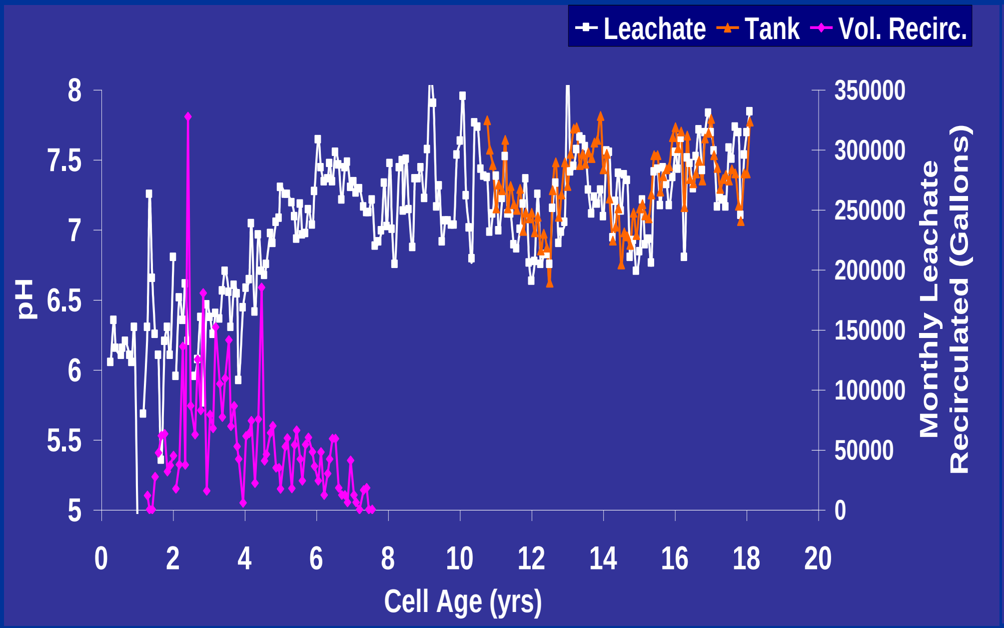
Do Bioreactors Promote Surface Emissions?

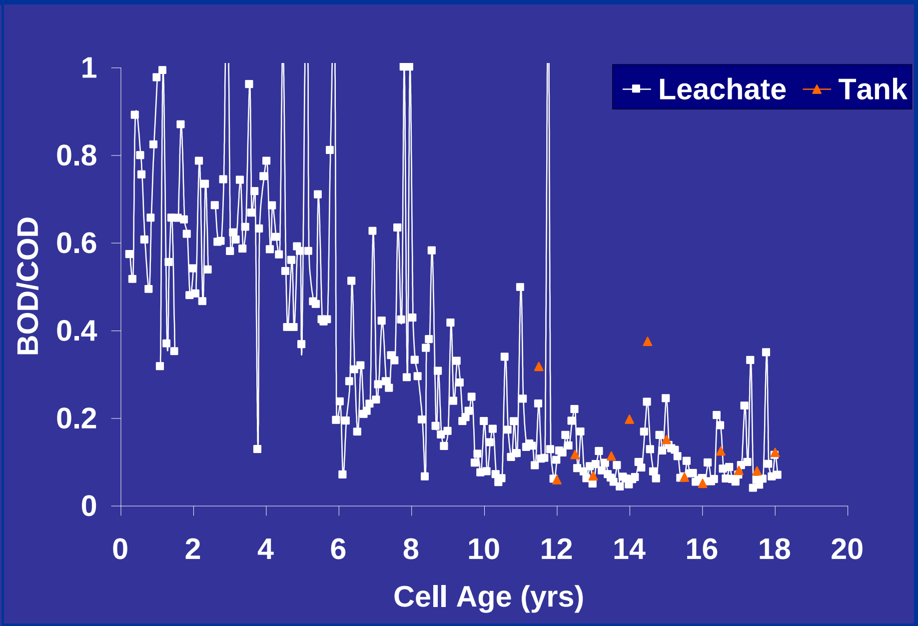
- Landfill M: 61 exceedances between start of leachate addition (Aug., 2002) and March, 2006
  - 4 in control area (all associated with penetrations)
  - 11 in bioreactor area
    - 9 of 11 associated with penetrations (sumps, leachate injection probes, temperature probes)

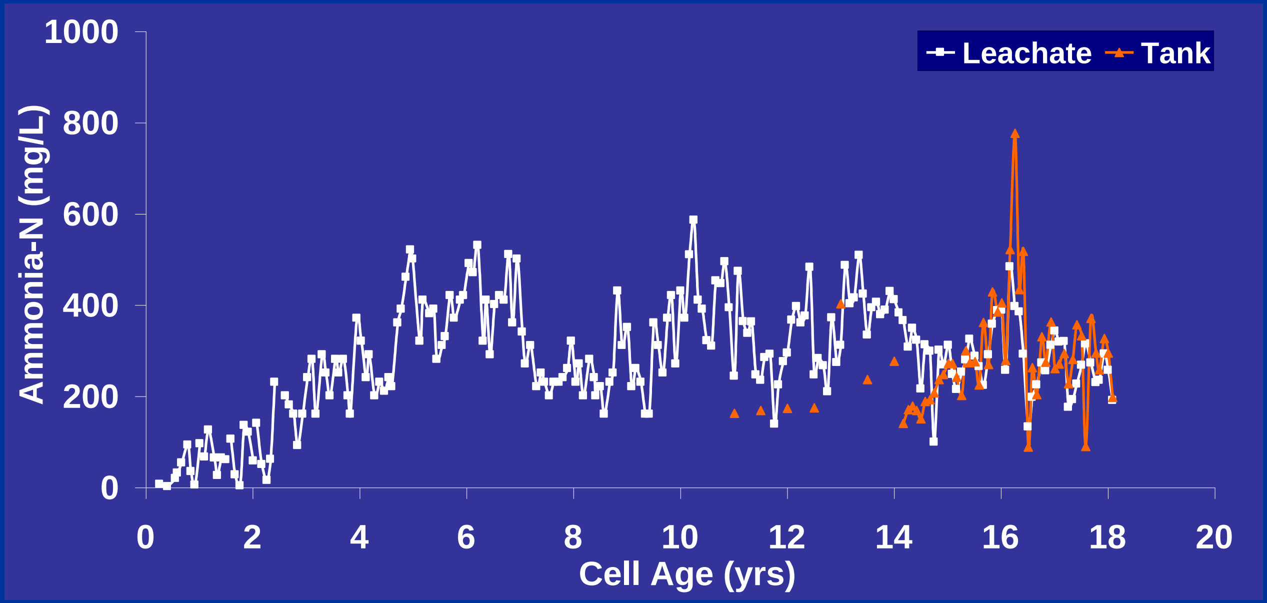
Landfill D Leachate Quality

- All leachate from the landfill is stored in 2-750,000 gallon tanks and then recirculated
  - The added leachate represents the entire landfill
  - Through mid-2006 Area A/B produced 60-80% of the leachate
    - Old cell with sandy cap and high moisture

Landfill D: Area C

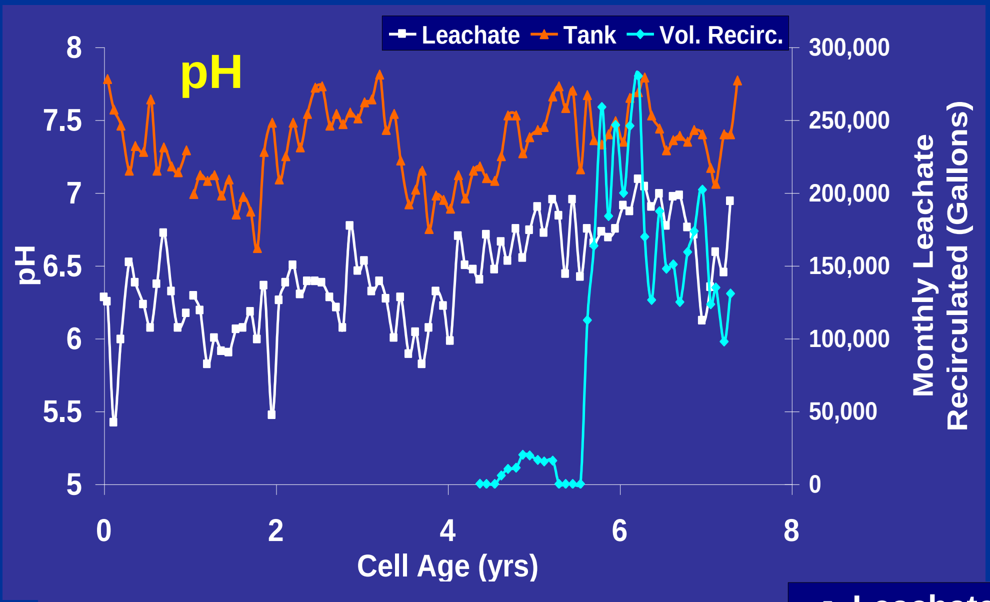


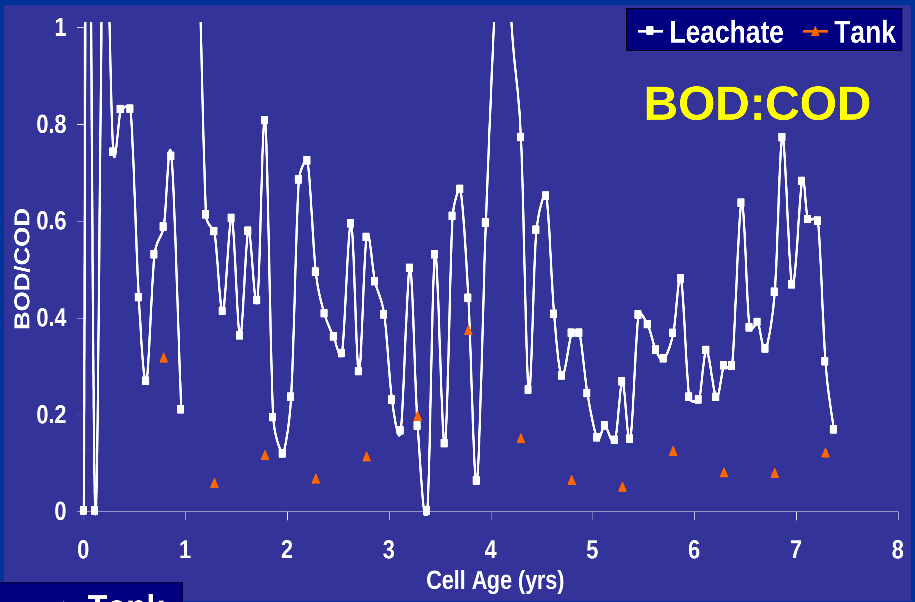


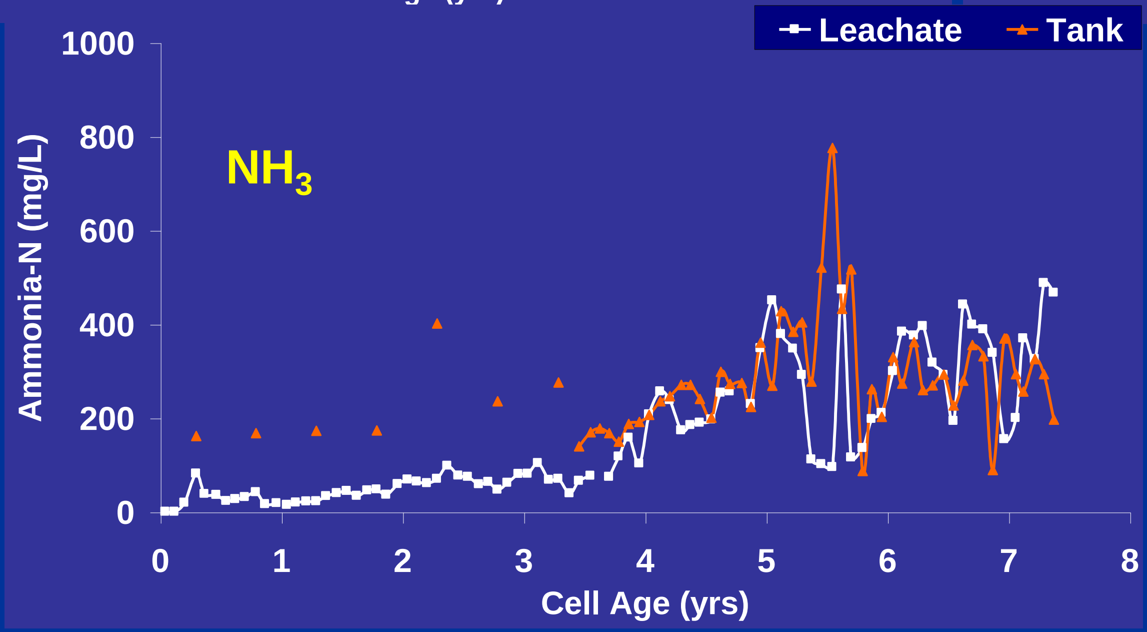


- Oldest leachate, decreasing BOD:COD
- neutral pH
- Stable ammonia

Landfill D: Area E





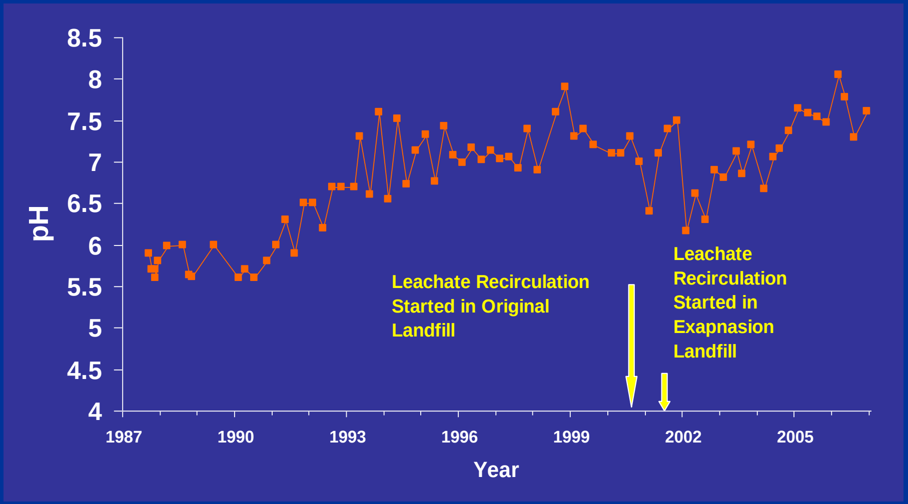


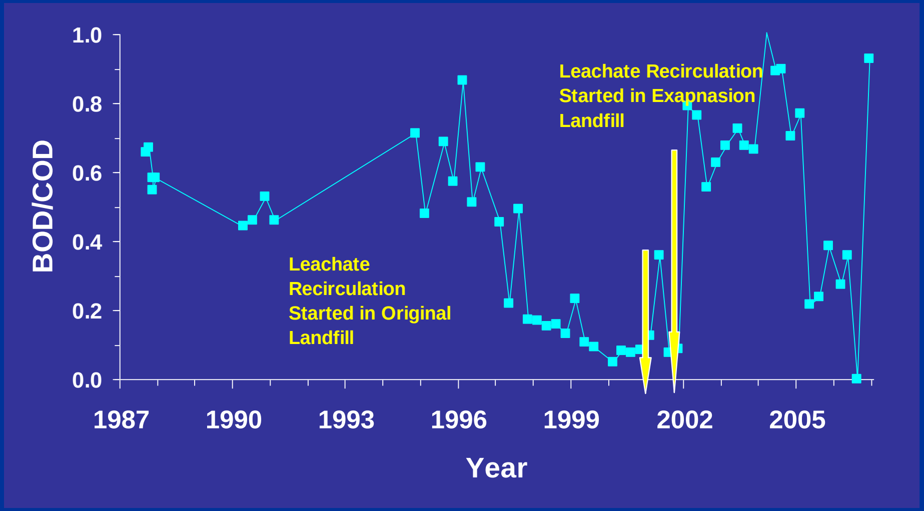
- Youngest leachate, highest BOD:COD but pH is neutral
- BOD:COD increased (yr 5 to 7) with start of recirc.

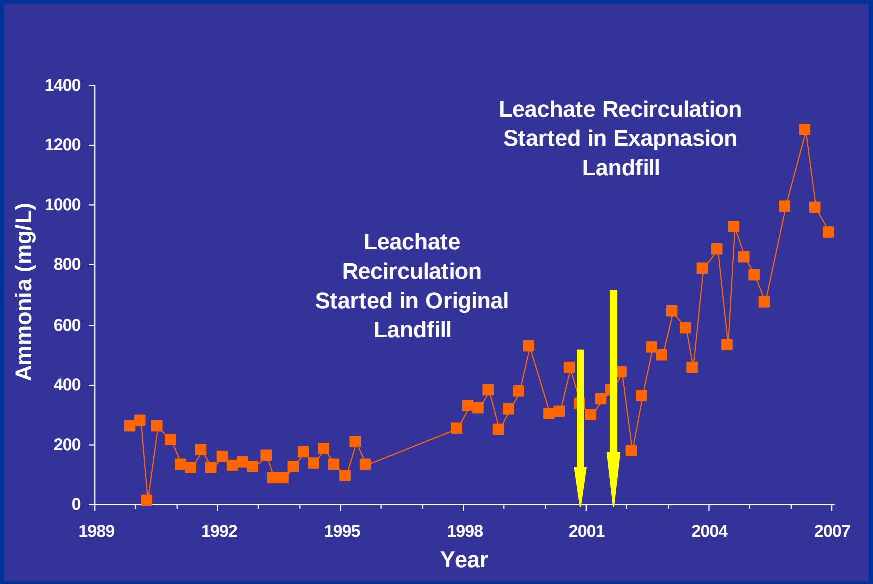
Leachate Quality – Landfill M

- Leachate from all cells (84 acres, 34 ha) stored in a tank and then added to bioreactor
  - The flux of material is greater than if recirculate from bioreactor only
  - 7.9 – 12.2% of site leachate is from the bioreactor

Landfill G Leachate Quality





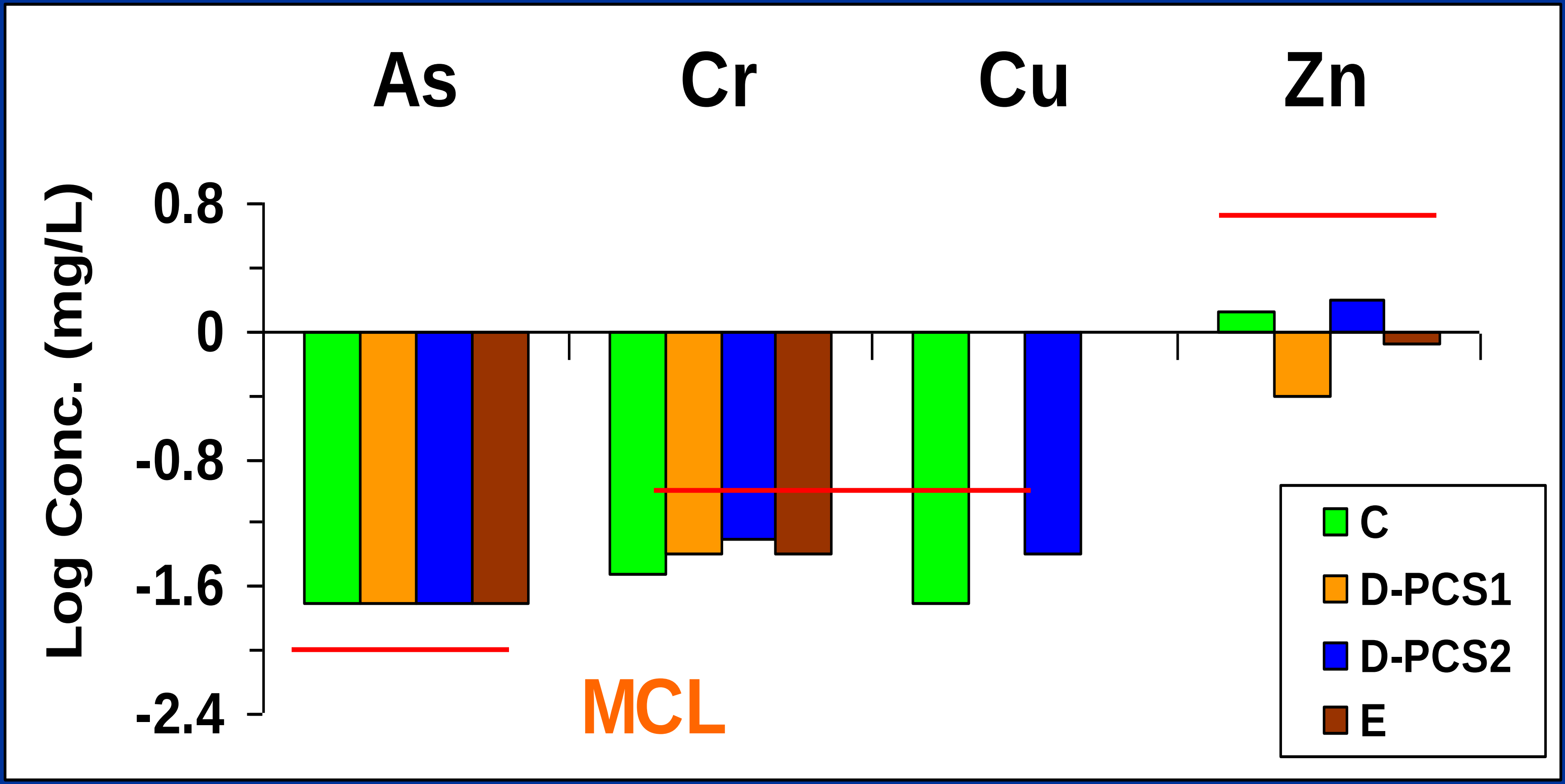


- Clear effect due to initiation of recirculation in expansion LF (younger refuse)
- Higher NH_3 than other sites

Leachate Quality

- The pH approaches 7
- The BOD:COD approaches 0.1
- There is an influence due to fresh refuse
- The ammonia can be 500-1000 mg/L

Metals Concentrations in Landfill D Leachate

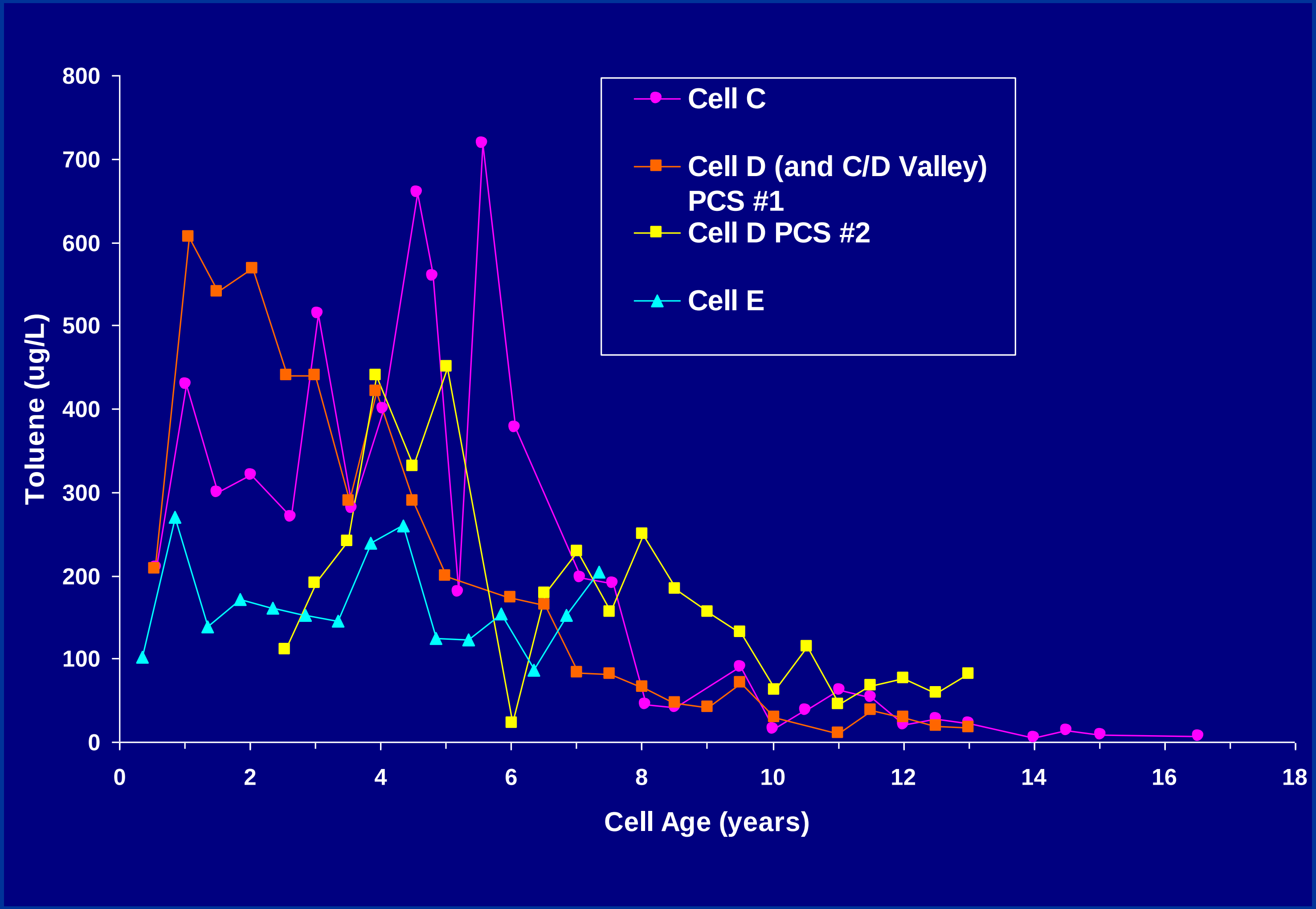


MCL – Maximum Contaminant Level

Metals

- No evidence that bioreactor landfill leachate contains higher metals concentrations than conventional landfills.
- The neutral pH associated with the onset of methane production is likely the critical factor controlling metals concentrations.
- As bioreactor landfills are operated to enhance methanogenic conditions, bioreactor landfill leachate will have less time in the acid phase when metals concentrations will be highest.

Leachate Quality: Toluene



Trace Organics

- Decreasing trends were observed for several organic chemicals.
- Biodegradation probably contributed to these trends, but evidence to confirm the role of biodegradation is not available.
- Benzene and vinyl chloride were most commonly detected above MCLs. Both of these chemicals are sufficiently volatile that the leachate concentration is likely influenced by the sampling point. For example, leachate stored in a tank is likely to release VOCs prior to sampling.

Permitting and Motivations

- Regulatory interaction varies by state
  - In one state a bioreactor viewed as a luxury permit and action was slow
  - In two landfills in the same state, the driving force was different
    - on-site leachate management (public owned)
    - economics as dictated by waste density and airspace recovery (private owned)

Monitoring

- The amount of data required to document performance exceeds that required for permitting
- Performance documentation varies by site:
  - Gas data at Landfill Y are convincing
  - Leachate data from all sites suggest similar or better quality
  - Surface emissions are a function of penetrations, not operations

Operations

- Operation of leachate addition trenches is still largely ad-hoc
  - Available leachate
  - Available personnel
- Only Landfill L had plans to use a leachate blanket

Operations

- In general, more labor required for water management
- Landfill Y has a full time employee plus 25% supervisory time and 30 hr/wk of interns on data analysis
- Landfill G facility had several people at the WWTP who also work on leachate recirculation
  - substantially higher workforce

Discussion

- Leachate: At many sites, the bioreactor area receives leachate from the entire landfill
- In-situ leachate treatment and fuel consumption
  - Landfill M estimated that they avoided 157,500 miles (252000 km) of hauling leachate in tanker trucks

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