Climate Action Reserve

Issue Paper

Aerobic and Anaerobic Bioreactor Project Protocol

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Acronyms

Acronym	Definition
BCS	Biogas Control System
BDT	Best Demonstrated Technology
BMP	Biochemical Methane Potential
CAA	Clean Air Act
C&D	Construction and Demolition
CDM	Clean Development Mechanism
CFR	Code of Federal Regulations
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
CRT	Climate Reserve Tonnes
DiAL	Differential Absorption LiDAR
EB	CDM Executive Board
EG	Emission Guidelines
EPA	United States Environmental Protection Agency
FOD	First Order Decay
FTIR	Fourier Transformed Infrared
GCCS	Gas Collection and Control System
GHG	Greenhouse Gas
GHGRP	Greenhouse Gas Reporting Program
kg	Kilogram
L_o	Methane Potential
Landfill protocol	Reserve Landfill Project Protocol, Version 4.0
LFG	Landfill Gas
LMOP	Landfill Methane Outreach Program
Mg	Megagram
MicroMet	Micrometeorological Eddy-Covariance
MSW	Municipal Solid Waste
mt	Metric Ton
N_2	Nitrogen Gas
NESHAPS	National Emissions Standards for Hazardous Air Pollutants
NMOC	Non-Methane Organic Compounds
N_2O	Nitrous Oxide
NSPS	New Source Performance Standards
NSR	New Source Review
O_2	Oxygen Gas
OWC protocol	Reserve Organic Waste Composting Project Protocol, Version 1.0
OWD protocol	Reserve Organic Waste Digestion Project Protocol, Version 2.0
PW	Present Worth
RCRA	Resource Conservation and Recovery Act
RD&D	Research, Development and Demonstration
Reserve	Climate Action Reserve

Acronym	Definition
SAIC	Science Applications International Corporation
SWANA	Solid Waste Association of North America
TDLAS	Tunable Diode Laser Absorption Spectrometry
VRPM	Vertical Radial Plume Mapping
VOC	Volatile Organic Compounds

1 Introduction

Solid waste production is a byproduct of modern human life, and management of waste generated is an inevitable consequence. In the United States, municipal solid waste (MSW) is generated at a rate of about 4.34 pounds per capita per day, of which 2.36 pounds are deposited in landfills.[1] Sanitary landfills are the third largest source of anthropogenic methane (CH_4) in the United States, generating just under 5.6 mmt CH_4 (117.5 mmt CO_2e), or about 17 percent of total anthropogenic methane in 2009. Of the approximately 1,800 operating landfills in the U.S., MSW landfills receive approximately two-thirds of the solid waste generated annually and result in 94 percent of the total landfill emissions, with industrial landfills accounting for the remainder.[2]

The MSW generation rate in the US is 4.34 pounds per capita per day, of which 2.36 pounds are deposited in landfills, resulting in 117.5 mmtCO$_2$e of GHG emissions annually.

The Climate Action Reserve (Reserve) operates as a national greenhouse gas (GHG) offsets program with the stated goal of ensuring integrity, transparency, and financial value in the US carbon market by developing high-quality standards for the quantification and verification of GHG emission reduction projects.[3] Among other offset project types, the Reserve currently administers three emission reduction protocols that target emissions from the solid waste sector. These protocols are:

1. Landfill Project Protocol Version 4.0[4]
2. Organic Waste Composting Project Protocol Version 1.0[5]
3. Organic Waste Digestion Project Protocol Version 2.0[6]

The Landfill project protocol reduces emissions from landfills by collecting and destroying landfill methane using a gas collection and control system (GCCS). Both the Organic Waste Composting and Organic Waste Digestion project protocols reduce emissions by diverting certain organic waste streams from landfills, and treating these wastes in a manner that either avoids the generation of methane emissions, or effectively captures and controls the methane emissions that occur.

In response to stakeholder interest, the Reserve hired Science Applications International Corporation (SAIC) to prepare this report to assess the viability of a fourth offset protocol targeting emissions in the solid waste sector. The project types contemplated in this issues paper include anaerobic bioreactors and *in situ* composting, also known as aerobic bioreactors. For clarity, we will use the terms aerobic and anaerobic bioreactor to describe the technology, and bioreactor to describe both forms. Bioreactors manage solid waste that has been deposited in landfills with the goal of expediting waste breakdown

[1] US EPA. *Municipal Solid Waste in The United States: Facts and Figures*. (December 2010) USEPA # EPA530-R-10-012. Page 9.
[2] US EPA. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009*. (April 2011) USEPA #430-R-11-005. Chapter 8, Waste (pp 8-1 to 8-4).
[3] Climate Action Reserve, *Program Manual.* (October 2011).
[4] Climate Action Reserve, *Landfill Project Protocol Version 4.0* (June 2011).
[5] Climate Action Reserve, *Organic Waste Composting Project Protocol Version 1.0* (June 2010).
[6] Climate Action Reserve, *Organic Waste Digestion Project Protocol Version 2.0* (June 2011).

and landfill stabilization. Like traditional landfills, anaerobic bioreactors break down waste in the *absence* of oxygen, but expedite the overall process significantly by introducing moisture to provide conditions for enhanced microbial activity, thereby accelerating waste decomposition. The rapid breakdown of waste under bioreactor conditions alters the timing and potentially the overall quantity of methane emissions. Aerobic bioreactors alter landfill dynamics by breaking down waste in the *presence* of oxygen, with the result that methane emissions can be drastically, if not entirely, reduced. The Reserve's Landfill Project Protocol Version 4.0 expressly excludes bioreactors because of important unknowns, including the drivers of bioreactor implementation, the quantity and timing of methane generation or methane avoidance, and complications of monitoring bioreactor operation.

Based on direction from the Reserve and SAIC's experience in the solid waste sector and offsets community, this paper is intended to inform the Reserve and its stakeholders about the viability of a bioreactor protocol, and tractability of known and unknown issues. More specifically, this paper provides:

- In ***Section 2***, an overview of landfill emissions, bioreactor operation and market acceptance
- In ***Section 3***, a summary of the drivers of bioreactor implementation including:
    - What are the benefits – fiscal, environmental, operational – associated with bioreactor operation?
    - What are the costs and drawbacks – fiscal, environmental, operational – associated with bioreactor operation?
- In ***Section 4***, a preliminary analysis of the potential eligibility of bioreactors in the context of regulatory considerations and current practice, such as:
    - Should bioreactors – aerobic and/or anaerobic – be considered additional?
    - Could such an additionality determination be standardized given the information available?
- In ***Section 5***, a discussion of unique quantification and monitoring considerations, including:
    - How do methane emissions from bioreactors vary from traditional landfills both temporally and over the lifetime of the landfill?
    - Can baseline emissions be quantified with acceptable certainty?
    - Can project emissions be quantified with acceptable certainty?
    - What monitoring might be required to conduct necessary quantification, and is it cost effective in the context of an offset project?
- In ***Section 6***, a brief summary of additional protocol considerations, such as:
    - Could a bioreactor protocol be gamed to undermine additionality or accuracy?
    - How might a bioreactor protocol interact with existing Reserve protocols?
    - What potential environmental impacts – both positive and negative – should the Reserve and project proponents be aware of?

- In ***Section 7***, a conclusion of findings from Section 2 through 6.

2 Background

2.1 Landfill Emissions

Landfill gas (LFG) is created by bacterial decomposition of organic waste deposited in landfills and by oxidation of cover soils overlaying the waste. It is comprised of roughly equal parts methane and carbon dioxide, and smaller quantities of non-methane organic compounds (NMOCs), nitrogen (N_2), oxygen (O_2) and other trace gases. While methane and carbon dioxide are GHGs that contribute to climate change, carbon dioxide emissions from landfills are considered biogenic (produced by natural processes). The most important component of LFG for GHG emissions accounting is methane, as the remaining gases present in LFG are not considered anthropogenic GHGs. methane is created when organic waste (which includes food, wood, and yard waste) is deposited in a landfill and decomposed anaerobically by bacteria (see Table 1). Initially, decomposition occurs in an aerobic (oxygen containing) environment. Aerobic bacteria, or aerobes, need oxygen to metabolize waste, and gain energy through the digestion of organic substrates contained in waste. This digestion process results in the rapid decomposition of waste solids, much more quickly than is possible in the absence of oxygen. Over time, as the waste is covered and oxygen is no longer available, an anaerobic (oxygen depleted) environment is formed, and anaerobic bacteria, including methanogenic (methane generating) bacteria, begin to decompose the waste. During the anaerobic degradation process, the waste components are converted to several intermediate stages including sugar, hydrogen and acetic acid before LFG is generated.[7] This anaerobic decomposition process can generate methane for up to 60 years following the initial disposal of waste.

While the amount of waste deposited at a landfill is a driving factor in methane generation, it is not the only variable that affects LFG generation. Landfill-specific characteristics (such as size and climate), waste composition and the influence of a GCCS also play important roles in the amount of methane released. With increases in organic material waste recovery (namely, paper products) and composting practices in the United States, total methane generation from these waste materials in landfills has declined. Additionally, the amount of LFG recovered at landfill sites has increased, from 20.3 mmt CO_2e in 1990 to over 150 mmt CO_2e in 2009.[8] These factors have resulted in a net decrease of approximately 20 percent of anthropogenic methane emissions from landfills since 1990. Despite this decline over the longer term, emissions in recent years have trended upward, as increases in MSW disposal associated with population growth have outpaced LFG recovery. Moving forward, MSW generation is expected to continue to increase as population grows, though the portion of generated MSW that is sent to landfills may decline, and the amount of LFG recovered may increase, affecting methane releases.

Modern sanitary landfills in the U.S. are predominantly managed through the "dry tomb" philosophy, whereby waste is separated from ground water by a liner system and kept dry by a landfill cap. This minimizes the quantity of leachate generated, and minimizes the risk of leachate infiltration into the ground water. The focus of "dry tomb" management is to keep the waste inert and biologically inactive, with moisture deprivation limiting biodegradation. This method of management requires continued monitoring and maintenance, even after the landfill ceases to accept waste, as it serves primarily as a

[7] ENSO Bottles, LLC. *Aerobic and Anaerobic Biodegradation.*
[8] US EPA 2011, Page 8-3. LFG recovered is the sum of EPA-reported CH_4 gas-to-energy and flared estimates.

long term storage system for solid waste. Without long-term maintenance, the landfill liner or cap may fail, increasing the risk of groundwater contamination or air pollution.

Table 1: Material Composition of Municipal Solid Waste, 2009. Waste materials shaded in green represent organically decomposable products.

Material	Percentage of MSW Generated
Paper	28.2%
Food Scraps	14.1%
Yard Trimmings	13.7%
Plastics	12.3%
Metals	8.6%
Rubber, Leather and Textiles	8.3%
Wood	6.5%
Glass	4,8%
Other	3.5%

Non-hazardous waste MSW landfills are regulated under Subtitle D of the Resource Conservation and Recovery Act (RCRA) which legally codifies the “dry tomb” philosophy toward waste management. Subtitle D sets minimum standards for the design, construction, and operation of MSW landfills, and is found in 40 CFR Parts 257-258. Emissions from MSW landfills are subject to New Source Performance Standards (NSPS), which are federally implemented, technology-based air pollution standards for stationary sources applying to new, modified and reconstructed facilities. The Standards are developed and implemented by the United States Environmental Protection Agency (EPA), with enforcement and compliance monitoring delegated to the states and regional authorities. Standards for landfills, found in section 40 CFR Part 60 Subparts CC and WWW of the Clean Air Act (CAA), were finalized in 1996 with the most recent finalized amendments in 2000. The landfill NSPS require that facilities emitting more than 50 metric tons per year of non-methane organic compounds (NMOC) control emissions through LFG recovery. (See Section 4.1)

In addition to mandated performance standards for larger landfills, facilities that exceed 25,000 $mtCO_2e$ of GHG emissions must report under the EPA’s Greenhouse Gas Reporting Program (GHGRP). Requirements for reporting, found in 40 CFR Part 98, Subpart HH of the CAA, compel large landfills to calculate and report GHG emissions annually to EPA. Landfill facilities may also voluntarily participate in federally supported programs to reduce emissions. The EPA’s Landfill Methane Outreach Program (LMOP), a voluntary initiative providing technical and marketing support to participants, encourages LFG recovery and reuse for energy purposes.

MSW landfills are regulated under:
- ***Subtitle D of Resource Conservation Recover Act (RCRA)***
- ***National Emissions Standards for Hazardous Air Pollutants (NESHAPS)***
- ***New Source Performance Standards (NSPS)***

On May 13, 2010, the EPA issued a final rule that establishes regulatory requirements for GHG emissions from stationary sources under the CAA permitting programs. The rule sets thresholds for GHG emissions that define when permits under the NSR and Title V permitting programs required for new and existing facilities. The rule, referred to as the "Tailoring Rule" incorporates permitting requirements for facilities that emit 10,000 $mtCO_2e$ per year or more of the combined GHG emissions listed in the rule, or propose a modification to their facility that increases GHG emissions by 75,000 $mtCO_2e$ per year. The initial rule enforcement is established to effect only large stationary sources that already maintain a Title V operating permit under the NSR program. Future rule enforcement will be broadened to include facilities that meet the program thresholds, but may not have a Title V operating permit due to low emissions for other criteria pollutants.

2.2 Reserve Project Protocols in the Waste Sector

As noted in the Introduction, the Reserve manages three protocols under which GHG offsets can be issued for emissions reductions in the waste sector. These three protocols are the:

1. **Landfill Project Protocol Version 4.0[9] (Landfill protocol)**. This project type is defined as the "installation of a system for capturing and destroying methane gas emitted from a landfill. The installation must exceed any regulatory requirement."[10] Projects install a gas collection system at active or closed landfills and destroy collected methane in any of a range of accepted destruction technologies. The Landfill protocol contains multiple Performance Standards for establishing project additionality, depending on the presence, absence, or configuration of pre-existing gas management systems.

2. **Organic Waste Composting Project Protocol Version 1.0[11] (OWC protocol)**. This project type is defined as the "diversion of one or more eligible waste streams (food waste and non-recyclable food soiled paper) to an aerobic composting facility where the waste is composted in a system that complies with best management practices as defined in the protocol.."[12] The OWC protocol issues offsets for the avoidance of methane that would have been produced under anaerobic landfill conditions had the eligible waste streams not been diverted to the composting facility.

3. **Organic Waste Digestion Project Protocol Version 2.0[13] (OWD protocol)**. This project type is defined as the "diversion of eligible organic waste and/or agro-industrial wastewater away from anaerobic treatment and disposal systems to a biogas control system (BCS) with methane destruction." Unlike the OWC protocol, the OWD protocol credits avoided emissions from both waste streams that would have been otherwise treated anaerobically at landfills, as well as waste streams from agro-industrial facilities that may have been treated onsite in lagoons or other methane emitting treatment systems. Like the Landfill protocol, OWD projects generate methane emissions that must be collected and destroyed.

[9] Climate Action Reserve, *Landfill Project Protocol Version 4.0* .(June 2011).
[10] Climate Action Reserve, *U.S. Landfill Project Protocol v4.0 Protocol Summary*. (June 2011).
[11] Climate Action Reserve, *Organic Waste Composting Project Protocol Version 1.0.* (June 2010).
[12] Climate Action Reserve, *Organic Waste Composting Project Protocol v1.0 Protocol Summary*. (June 2010).
[13] Climate Action Reserve, *Organic Waste Digestion Project Protocol Version 2.0.* (June 2011).

To date, the Landfill Project Protocol has been the most widely used Reserve protocol, accounting for 164 of 351 total projects that are at least at the Listed phase (publicly disclosed), 76 of 120 Registered or Complete projects (those that have been issued CRTs), and 7.1 million of 17.8 million total CRTs that have been issued (see Table 2). The original Landfill protocol was published in 2007, whereas the OWC and OWD protocols were first published in late 2009 and mid 2010, respectively. While the longer availability of the Landfill protocol partially explains its extensive use relative to the OWD and OWC protocols, the slow adoption of the OWD and OWC protocols is also due to smaller project size and poorer project economics.

Table 2: Summary of the Use of Reserve Protocols in the Solid Waste Sector

	Listed or Registered Projects	Registered or Completed Projects	Total CRT Issuance	Average Project Vintage CRT Issuance
Landfill Project Protocol	164	76	7,075,261	34,683
Organic Waste Digestion Project Protocol	2	1	44,457	22,223
Organic Waste Composting Project Protocol	18	0	0	0
Reserve Total	351	120	17,782,042	60,417

2.3 Opportunity and Objective

2.3.1 Bioreactor Landfill Management Philosophy

Bioreactor landfills are different from traditional landfills because the waste management processes are designed to encourage a favorable environment for accelerated waste decomposition and stabilization. Bioreactor landfill management encourages biological activity through the addition of liquid and/or air to waste in order to accelerate decomposition of its organic components. This practice stabilizes the waste, meaning that it results in relatively constant LFG generation rates, methane concentrations and leachate constituent proportions. Bioreactor landfills may become stable in as little as 5-10 years, while waste decomposition parameters may be seen in traditional landfill monitoring for decades after closure.

The specific qualifications defining a bioreactor system have evolved over time, and may be different depending on the source. Indeed, there is a gradient between traditional landfills and bioreactors as moisture content increases. This complicates the task of settling on an objective definition of the term bioreactor. Table 3, below, outlines various definitions over time.

[14]**Table 3: Definitions of a Bioreactor Landfill**

Source	Year	Definition
Performance of North American Bioreactor Landfills (2009 USEPA Report)	2009	"A landfill was considered to be a bioreactor in this study if (i) design and/or operational features were incorporated to facilitate leachate recirculation and/or addition of supplemental liquids and (ii) there was a concerted effort by the site owner to accelerate decomposition in some manner."
Florida Bioreactor Demonstration Project	2008	"In contrast to dry tomb landfills, bioreactor landfills aim to enhance and accelerate biodegradation of landfilled waste by providing better conditions for microorganisms. A bioreactor landfill enhances microbiological processes to transform and stabilize the readily and moderately decomposable organic waste constituents in a shorter period of time (typically 5 to 10 years) in comparison to a conventional landfill (typically 30 to 50 years, or more)."
Waste Management, Inc.	2006	"A bioreactor landfill is a landfill that is operated in a manner that is expected to increase the rate and extent of waste decomposition, gas generation, and settlement compared to a traditional landfill."
Interstate Technology and Regulatory Council	2006	"The team chose to use the USEPA ORD's definition of bioreactor, namely: Bioreactors are landfills where controlled addition of non-hazardous liquid wastes or water accelerates the decomposition of waste and landfill gas generation."
SWANA Bioreactor Training Course	2005	"A controlled landfill or landfill cell where liquid and gas conditions are actively managed in order to accelerate or enhance biostabilization of the waste. The bioreactor landfill significantly increases the extent of organic waste decomposition, conversion rates, and process effectiveness over what would otherwise occur with the landfill."
Clean Air Act NESHAP Regulations (40 CFR 63 1990)	2004	"A MSW landfill or a portion of a MSW landfill where any liquid, other than leachate or landfill gas condensate, is added in a controlled fashion into the waste mass (often in combination with recirculating leachate) to reach a minimum average moisture content of at least 40% by weight to accelerate or enhance the anaerobic biodegradation of the waste."
SWANA Bioreactor Landfill Committee	2002	"A bioreactor landfill is a controlled landfill or landfill where liquid and gas conditions are actively managed in order to accelerate or enhance biostabilization of the waste."
Dr. Debra Reinhart	1997	"…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."

[14] Table reproduced from Solid Waste Association of North America (SWANA). *The Solid Waste Manager's Guide to the Bioreactor Landfill FY 2009 Update*. (December 2009). Page 8.

To help resolve the many discrepancies in defining bioreactor systems, the Solid Waste Association of North America (SWANA) developed the following definition:

> "*A bioreactor landfill is a municipal solid waste landfill that is designed and operated in such a manner as to achieve maximum and rapid biostabilization of the landfilled waste through the addition of liquids other than leachate or landfill gas condensate*."[15]

Further, to clarify the distinction between biostabilization and stabilization, SWANA's Landfill Bioreactor committee developed the following definition of biostabilization:

> "*Biostabilization is the process of biologically decaying organic materials and reducing leachate organic strength*."[16]

Bioreactor landfills are permitted to operate under EPA Research, Development and Demonstration (RD&D) and EPA Project XL Programs.

Bioreactor landfills are different from traditional leachate recirculation landfills in several important ways. First, leachate recirculation landfills are managed solely through the reuse of leachate, while bioreactor landfills often include the addition of liquid and waste products to supplement leachate recirculation. Second, leachate recirculation landfills are generally managed with the intent of leachate treatment, while bioreactor landfills use leachate recirculation, among other management practices, with the intent of stabilizing waste through biological activity. Finally, leachate recirculation is permitted under RCRA Subtitle D regulations, while supplemental addition of liquids and alternative management practices are only allowed through EPA's Research, Development and Demonstration (RD&D) rules and Project XL program. The EPA RD&D Rule allows certain states to issue permits to MSW landfill facilities to operate in exception to Federal MSW landfill regulations for the purposes of research and development. The five states authorized to issue permits under the RD&D Rule include Minnesota, Indiana, Illinois, Wisconsin and Michigan.[17] EPA's Project XL was established in 1995 as a national-level pilot allowing regulatory flexibility for businesses, state and local governments, and federal facilities for research and development that contributes toward improved environmental and public health protection.[18] Since Project XL began, four bioreactor landfills in North Carolina, California and Virginia have been approved for operation under the Program.[19] Some states have interpreted Subtitle D regulations to prohibit only the addition of bulk liquid wastes and not liquid amendments to landfills. Therefore, pre-dating the implementation of the EPA RD&D rule, some states may have permitted landfills to operate as a bioreactor under a state-specific beneficial use legislation. As such, some states may be permitted to augment leachate recirculation with "clean" water addition, such as stormwater or groundwater. For example, the 2009

[15] SWANA 2009, Page 9.
[16] SWANA 2009, Page 9.
[17] US EPA. *Municipal Solid Waste Permits Rules and Information Collection Requests (ICR) Notices*. Accessed online October 2011 at http://www.epa.gov/osw/nonhaz/municipal/landfill/mswlficr/
[18] US EPA. *What is Project XL?* Accessed online October 2011 at http://epa.gov/projectxl/file2.htm.
[19] SWANA 2009, Pages 18-20.

SWANA report lists an EPA-approved change to Washington State's solid waste regulations that allowed controlled water addition into a Subtitle D landfill.[20]

2.4 Bioreactor Design

There are generally three bioreactor landfill designs: aerobic, anaerobic and hybrid. In all configurations, leachate is removed from the bottom of the waste and re-inserted into the landfill, often supplemented by the addition of uncontaminated water or wastewater sludge to enhance microbial decomposition.

- **Aerobic** – Aerobic management involves recirculation of leachate and injection of air into the waste. This promotes waste decomposition and accelerates stabilization.
- **Anaerobic** – Anaerobic management creates an oxygen depleted environment through the re-circulation of leachate to obtain optimal moisture content of 35 to 45 percent by weight.[21] This environment encourages methanogenic bacterial decomposition of waste, enhancing the generation of methane from microbial bacteria. The LFG generated may be recovered for energy production.
- **Hybrid**– Hybrid management employs both anaerobic and aerobic methods, aerating waste in the upper portion of the landfill to enhance degradation while collecting LFG from the lower portion. Hybrid bioreactor landfills generate methane earlier than strictly aerobically operated bioreactor landfills.

Bioreactors can be implemented "as-built" or "retrofit". As-built bioreactors are landfills which are designed from the initial landfill planning process to be bioreactors, giving the advantage of construction and operation while waste is actively deposited. This allows for airspace recovery while the landfill is active, and gives engineers more options for leachate and liquid recirculation methods (see Section 3.1). Retrofit bioreactors are built as traditional MSW landfills, with bioreactor technology implemented once the landfill nears or reaches capacity. Airspace recovery and technological implementation are more restricted in retrofit systems than with as-built bioreactors. There are approximately 30 active bioreactor landfills in North America.[22,23] Table 4, below outlines details of the active bioreactor landfills in North America.

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[20] SWANA 2009, Page 62
[21] Waste Management, Inc. *Introducing the Bioreactor Landfill: Next Generation Landfill Technology*. Accessed online October 2011 at http://www.wm.com/sustainability/pdfs/bioreactorbrochure.pdf.
[22] SWANA 2009, Page 14.
[23] SWANA defined bioreactor landfills as those facilities where water amendments other than leachate and LFG condensate were added to the landfill to enhance biostabilization. Of the 30 landfills, SWANA was unable to determine the type (anaerobic, aerobic, hybrid) of three facilities. It should also be noted that the database used for these estimates was last updated in March of 2004, though no new bioreactors were identified as implemented between 2004 and the time of the study, 2009.

[24]**Table 4: Active North American Bioreactor Landfills**

State	Landfill Name	Bioreactor	Start	Wetting Method	Scale (acres)
AL	Veolia Cedar Hill LF	Anaerobic	2000	Spray	Full
AL	Veolia Star Ridge LF	Anaerobic	2000	Spray/Injection	Full
Bahamas	Veolia Pine Ridge LF	Anaerobic	n/a	n/a	Full
CA	Kettleman Hills LF	Anaerobic	n/a	n/a	n/a
CA	Yolo County Central LF	Anaerobic	1994	n/a	Demonstration
FL	Highland Co. SWM Ctr	Anaerobic	2000	H. Leachate Inject.	Full
GA	LaGrange Sanit. LF	Anaerobic	2003	Pumped	50
IA	Central Disposal LF	Anaerobic	2001	Injection	Full
IL	Veolia Zion LF	Anaerobic	2002	n/a	Full
IL	Veolia Valley View LF	Anaerobic	1998	n/a	Full
IN	Veolia Blackfoot LF	Anaerobic	1999	n/a	Full
KY	Outer Loop RDF	Anaerobic	2002	Injection	n/a
MD	Millersville LF	Anaerobic	n/a	Injection	n/a
MI	Forest Lawn LF	Anaerobic	1999	n/a	n/a
MN	Spruce Ridge LF	n/a	n/a	n/a	n/a
NJ	Cape May County LF	Anaerobic	2001	Injection	Full
NJ	Burlington County LF	Anaerobic	2002	Injection	n/a
NJ	Cumberland County LF	Aerobic	2003	V. Injection Wells	11
OR	Columbia Ridge LF	n/a	n/a	n/a	n/a
PA	Veolia Greentree LF	Anaerobic	2000	n/a	Full
SC	Berkeley County LF	Anaerobic	n/a	Spray/Injection	Full
VA	King George County LF	Anaerobic	n/a	Injection	Full
WI	Deer Track Park LF	Anaerobic	n/a	Spray	Full
WI	Lake Area Disposal LF	Anaerobic	2001	n/a	n/a
WI	Metro Recyc./Disp LF	Hybrid	n/a	Injection	Cell
WI	Superior Glacier LF	Anaerobic	1999	Spray	Full
WI	Timberland Trail LF	Anaerobic	2001	n/a	n/a
WI	Veolia Hickory Mdws LF	Anaerobic	2002	n/a	Full
WI	Orchard Ridge LF	n/a	n/a	n/a	n/a
Canada	Aquatera Landfill	Anaerobic	2001	V. Injection	Demonstration

Typically, bioreactors are implemented on an individual cell within a landfill footprint.[25] Landfill cells are sized based on numerous variables, including state regulatory requirements, available financial resources, site topography and characterstics. Bioreactor design can accommodate almost any cell design sizes, given that the cell size allows for liquid distribution structures to maintain the prescribed

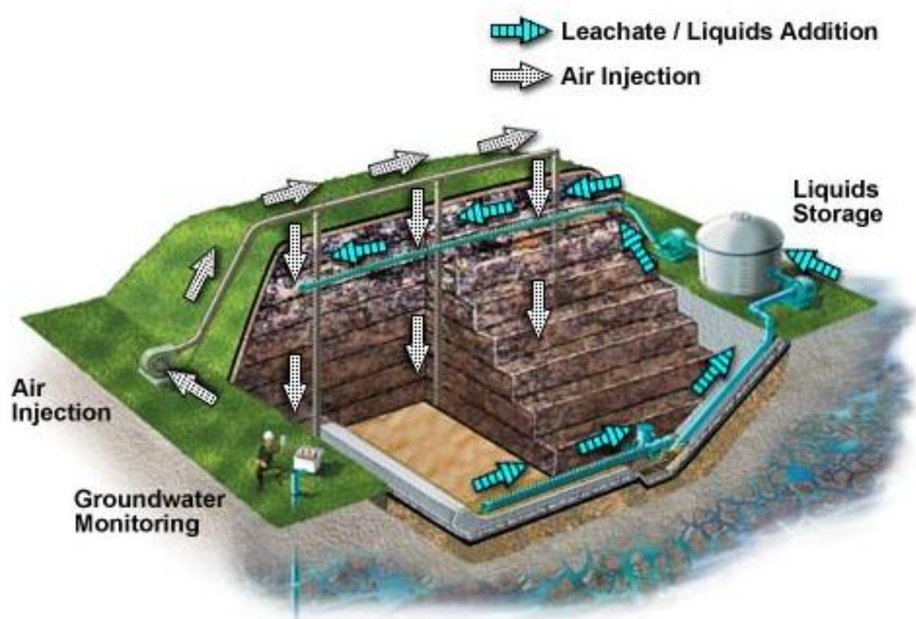
[24] Table reproduced, in part, from SWANA 2009, Pages 14-15.
[25] Confidential Clients

distance from landfill sideslopes to minimize the potential for seeps. Standard design recommendations prescribe a minimum of 50 feet from the liquid distribution structure to the landfill sideslope in any direction. Assuming 20 feet of waste must be in place on the floor of the landfill cell and the landfill is filled using a slope ratio of four to one, a cell would need to be at least 400,000 square feet to accommodate one structure within the waste for liquid injection. However, it should be noted that a landfill may be able to implement bioreactor technology using surface spray application without side slope placement restrictions.

2.4.1 Aerobic Bioreactors

Aerobic bioreactors are designed to take advantage of waste degradation by maintaining conditions for aerobic bacteria to thrive. Aerobic management accelerates waste decomposition by adding air and water to deposited waste, both of which are required for aerobic activity. The primary advantage of aerobic bioreactors is that they have been found to achieve waste stabilization more rapidly and result in greater leachate quality when compared with anaerobic systems.[26] Additionally, this type of waste management is optimal for landfills that cannot generate methane gas in sufficient quantities to make recovery for energy use possible. Figure 1, below, shows the path of leachate and liquid addition with air injection in a common aerobic bioreactor system.

Figure 1: Design of Common Aerobic Bioreactor System (Graphic developed by Waste Management, Inc. and retrieved from US EPA)



The Aerobic Bioreactor process is essentially a large-scale composting operation, hence its alternate name of *in situ* composting. As shown in Figure 1, air and liquids are added to the waste mass to

[26] The Hinkley Center For Solid and Hazardous Waste Management . *Florida Bioreactor Landfill Demonstration Project : Executive Summ*ary. (July 2008). Page 5.

promote favorable temperature and moisture conditions for aerobic decomposition. Temperature monitoring throughout the waste mass and air flow monitoring at gas vents allow the system operator to determine optimal quantities of air and liquid to add, allowing the degradation process to reach optimum biological activity.[27] Component systems frequently used in aerobic bioreactor operation include:[28]

- ***Air and Leachate/Liquid Injection Wells*** are generally spaced on grids at various depths throughout the waste mass to ensure uniform distribution of air and liquid addition
- ***Leachate Collection System*** is designed to collect and store leachate for recirculation
- ***Air Injection System*** includes blowers and distribution/control systems to inject air into the waste mass
- ***Leachate/Liquid Injection System*** is a leachate/liquid distribution system that disperses collected leachate from storage systems throughout the waste mass
- ***Ventilation Wells*** are designed to vent CO_2 and heat produced during decomposition, generally spaced at 50 to 100 feet intervals throughout the waste mass
- ***Temperature and Air Flow Monitoring Systems*** are placed throughout the waste mass

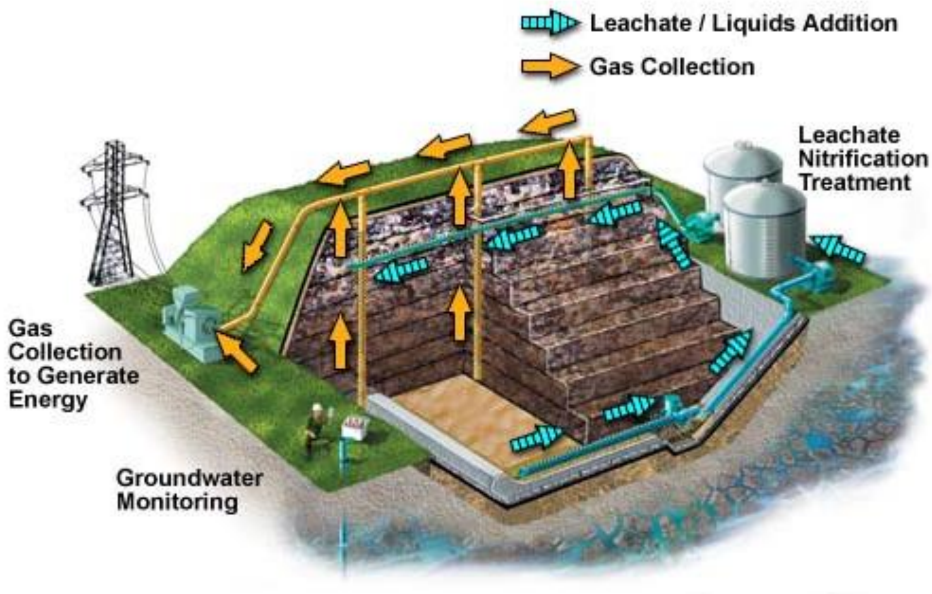
As of 2009, there was one documented aerobic bioreactor active in North America, the Cumberland County landfill in New Jersey, an 11-acre system that began operation in 2003 and utilizes vertical injection wells for component addition.[29]

2.4.2 Anaerobic Bioreactors

Anaerobic bioreactor management takes advantage of increased methane generation in an oxygen-depleted environment, created by the addition of leachate and supplemental liquids to reach an optimal moisture content of 35 to 45 percent by weight, near field capacity. This "wet" environment produces LFG at a faster rate than traditional "dry tomb" landfilling.[30] Increased methane yields allow landfill managers to economically benefit (through LFG collection and combustion) from management practices earlier than is possible through traditional landfilling, while reducing the need to manage GHG emissions in later years.[31] Additionally, criteria pollutant emissions are reduced when LFG is collected and combusted. Figure 2, below, shows the path of leachate and liquids addition with gas collection in a common anaerobic bioreactor system.

[27] Mundus Aer, LLC. Aerated Static Pile Composting: "The Aerobic Bioreactor Process". (April 2010) Page 3.
[28] Mundus Aer, LLC, 2010, Pages 1-2.
[29] SWANA 2009, Page 15.
[30] Reinhart, et. al. First-*Order Kinetic Gas Generation Model Parameters for Wet Landfills*. United States Environmental Protection Agency Air Pollution Prevention and Control Division. (June 2005). Page iii.
[31] Pacey, et. al. *The Bioreactor Landfill – An Innovation in Solid Waste Management*. White Paper. Page 6.

Figure 2: Design of Common Anaerobic Bioreactor System (Graphic developed by Waste Management, Inc. and retrieved from US EPA)



Equipment generally used in the operation of an anaerobic bioreactor system includes:

- ***Leachate/Liquid Injection Wells*** are generally spaced on grids at various depths throughout the waste mass to ensure uniform distribution of liquid addition
- ***Leachate Collection System*** is designed to collect and store leachate for recirculation
- ***Leachate/Liquid Injection System*** is a leachate/liquid distribution system that disperses collected leachate from storage systems throughout the waste mass
- ***Gas Extraction System*** to collect and extract methane generated by waste decomposition
- ***Flow Meters*** to monitor LFG flow and characteristics
- ***Monitoring Systems*** are placed throughout the waste mass to monitor temperature, systems and instrument operation

There were 25 documented anaerobic bioreactors in operation in North America in 2009, with all but two located in the United States. The 15 states housing anaerobic bioreactors include Alabama, California, Florida, Georgia, Iowa, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, Pennsylvania, South Carolina, Virginia and Wisconsin.[32]

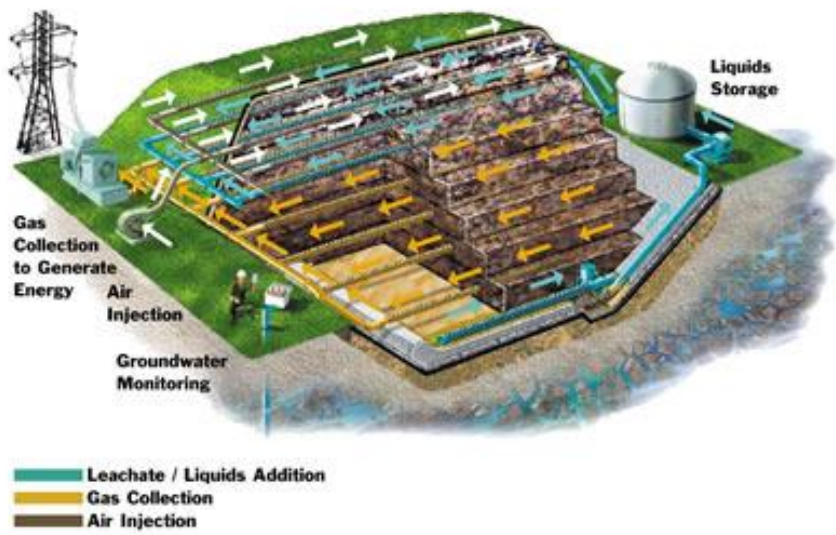
2.4.3 Hybrid Bioreactor

Hybrid bioreactor system management makes use of both anaerobic and aerobic methods, with the upper layer of waste in a landfill receiving aeration treatment while lower layers receive leachate

[32] SWANA 2009, Pages 14-15.

recirculation and liquid addition. The purpose of the hybrid bioreactor's sequential aerobic-anaerobic management is to facilitate rapid degradation of organic waste in the aerobic stage, which reduces the production of organic acids and results in accelerated methane generation in the anaerobic stage. The main benefit of hybrid management is that it combines the advantages of both the aerobic and anaerobic systems. That is, a hybrid bioreactor rapidly degrades waste during the aerobic stage, while enabling rapid methane generation with relatively simple implementation during the anaerobic stage. Figure 3, below, shows the path of leachate and liquids addition with gas collection and air injection in a common hybrid bioreactor system.

Figure 3: Design of Common Hybrid (Aerobic/Anaerobic) Bioreactor System (Graphic developed by Waste Management, Inc.)



Hybrid bioreactor operational systems contain components of both aerobic and anaerobic systems, as outlined in Sections 2.4.1 and 2.4.2, above. There was one documented hybrid bioreactor active in North America as of 2009, the Metro Recycling/Disposal landfill in Wisconsin.[33]

2.5 Precedent Protocols

The operation and characteristics of bioreactor landfills, both anaerobic and aerobic, differ significantly from the operation and characteristics of traditional landfills. For a variety of eligibility, accounting, and monitoring reasons discussed throughout this paper, the Reserve determined that bioreactors are sufficiently distinct from traditional landfills that its existing Landfill protocol should exclude bioreactors from the project definition. However, this paper uses the Landfill protocol as a jumping off point for considering the viability and appropriateness of a bioreactor offset protocol. The goal of this paper is to explore unique issues related to bioreactors in the context of the Landfill protocol, and determine

[33] SWANA 2009, Page 15.

whether it can be used as the basis for a new protocol that would bring bioreactors under the umbrella of solid waste technologies eligible for receiving offset credits under the Reserve.

At least two other programs have considered bioreactor technology as a stand-alone offset project, and determined that it is a viable offset project type. The Alberta Offsets System issued the *Quantification Protocol for Aerobic Landfill Bioreactor Projects* in May 2008, providing applicability rules, quantification guidance, and data quality standards.[34] The Protocol is limited to aerobic bioreactors, and does not apply to anaerobic or hybrid bioreactors. According to the Alberta registry, no projects have yet used this protocol to generate offset credits.[35]

In addition to the Alberta protocol, the Clean Development Mechanism (CDM) Executive Board (EB) approved AM 0083, *Avoidance of landfill gas emissions by in-situ aeration of landfills* in July 2009.[36,37] AM0083 also applies only to aerobic bioreactors, and cannot be used for crediting anaerobic or hybrid bioreactors. In addition, this methodology is limited to closed landfills or landfill cells. To date, only the Taibe landfill in Israel has used the methodology, generating an average 19,805 mt CO_2e per year, with a total expected yield of 138,636 tonnes for 2010 through 2016[38].

In addition to the Reserve waste sector protocols, the Alberta and CDM methodologies will be discussed throughout this report in the context of specific issues and potential solutions.

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[34] Alberta Environment, *Quantification Protocol for Aerobic Landfill Bioreactor Projects, Version 1.* (May 2008).
[35] C3, Government of Alberta. *Alberta Emissions Offset Registry*.
[36] UNFCCC. AM0083 *Avoidance of landfill gas emissions by in-situ aeration of landfills, version 01.* (July 2009).
[37] UNFCCC. *Executive Board of the Clean Development Mechanism Forty-Eight Meeting, Report Version 01.1.* (July 2009).
[38] UNFCCC. *Project Design Document for Methane Reduction at the Taibe'e Landfill using In-situ Aeration Version 1.5.* (September 2010).

3 Market Drivers, Project Viability, and Environmental Co-Benefits

In order to understand whether future bioreactors may be additional, we first need to understand why current ones exist. That is, what risks and benefits are associated with the implementation of a bioreactor system, and which factors play into landfill managers' choice calculus when deciding to employ a bioreactor system? This section describes the non-carbon market drivers and risks associated with bioreactor operation and viability. In addition, this section describes some of the environmental co-benefits and disadvantages of bioreactors, an important protocol screening criterion for the Reserve.

3.1 Unique Benefits of Bioreactors

There are several advantages associated with the implementation of bioreactor landfill management, though both beneficiaries and the scope of the benefits may vary from case to case. These may be economic, environmental, social or regulatory in scope. Descriptions of the most notable advantages cited for bioreactor system implementation follow, with an indication of their applicability to both aerobic and anaerobic bioreactors.

Accelerated Waste Decomposition and Stabilization

The primary benefit of all types of bioreactor systems is the accelerated and enhanced decomposition of waste. Waste handled in bioreactor landfills may be stabilized in under a decade, while waste deposited in traditional landfill systems may take 30 years or more to stabilize.

- Aerobic: Readily decomposable organic waste may be stabilized within two to three years of system implementation.[39]
- Anaerobic: Readily decomposable organic waste may be stabilized within five to ten years of system implementation.

Extension of Landfill Life

In traditional, "dry tomb" landfills, the facility is designed to accept a certain quantity of waste. Because waste degradation is slow in the absence of moisture and traditional landfills are operated with the intention of maintaining low moisture content, waste settlement is curbed and airspace recovery is limited. Alternatively, bioreactor landfills may see a 15 to 30 percent gain in landfill space because of accelerated waste decomposition.[40] This airspace recovery is a result of the conversion of solid waste to liquid gaseous form through biological processes, and the subsequent recovery of the liquids and gases; and increased density and settlement of waste due to biostabilization and moisture addition.[41] These factors combined increase the total amount of waste that a given landfill is able to hold, and can result in economic benefits for landfill managers as they take advantage of increased waste disposal revenues.

- Aerobic: Process allows for the potential to recapture airspace and extend landfill life.
- Anaerobic: Process allows for the potential to recapture airspace and extend landfill life.

[39] SWANA 2009, Page 39.
[40] Hinkley Center for Solid and Hazardous Waste Management. *What is a Bioreactor Landfill?* (2006). Accessed online October 2011 at http://www.bioreactor.org/info.html.
[41] SWANA 2009, Page 41.

Energy Generation

Anaerobic bioreactor management accelerates methane production over shorter time periods than traditional landfills, increasing the likelihood that methane recovery and use as an energy source would be economically viable. This potential for energy production is often cited as a driving incentive for anaerobic bioreactor system management.

- Aerobic: The potential for energy generation does not apply to aerobic bioreactor systems, as the aerobic process limits the production of methane.
- Anaerobic: Anaerobic bioreactors are designed to encourage methane production, and anaerobic management may result in increases in total methane yield over the life of the landfill.[42] As such, energy generation is a driving benefit of anaerobic bioreactor management.

Improved Leachate Quality and Management

Leachate is produced through normal landfill operation, and must be managed regardless of whether a bioreactor or leachate recirculation system is implemented, often involving treatment and disposal offsite, at significant cost. Organic components of leachate are transformed or consumed in the biostabilization process, so recirculation reduces both the quantity of leachate and the need for treatment of remaining leachate. While there are costs associated with the installation of a leachate recirculation system, these can be partially or completely offset by reduced offsite treatment and disposal costs.[43]

Recirculated landfill leachate is an important source of moisture, and is central to bioreactor process design. Leachate recirculation is permitted under RCRA Subtitle D, and many landfills, most of which are not bioreactors, practice leachate recirculation to realize the resulting economic benefits of leachate treatment.

- Aerobic: Process allows for improved leachate quality and reduced need for treatment and disposal offsite.
- Anaerobic: Process allows for improved leachate quality and reduced need for treatment and disposal offsite.

Reduced Post-Closure Facility Maintenance

There are three main concerns in post-closure maintenance: LFG production, waste settlement and leachate production. Under current regulations, landfills are required to monitor for these issues for several decades following closure, incurring significant costs. Accelerated waste decomposition in bioreactor landfills reduces the time period in which air and water releases are generated and increases the speed of waste settlement. This means that the length of time that landfill conditions may potentially be monitored and controlled is shortened in bioreactor landfills, relative to traditional landfills.

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[42] Pacey, et. al., Page 6.
[43] SWANA 2009, Page 44.

Landfill Gas Generation: In aerobic systems, methane production as a component of LFG is minimized through aerobic processes, while in anaerobic processes, methane production is accelerated in the early life of the landfill. In both cases, methane is not produced in significant quantities late in the life of the landfill, or post-closure. As such, bioreactor management allows landfill operators to close a landfill cell with little concern for methane generation.

Waste Settlement: Because bioreactor landfill management accelerates waste decomposition and settlement, landfill operators have little need for post-closure slope and cover maintenance. Settlement has already occurred.

Leachate Production: Landfill operators may be able to demonstrate that leachate composition is stable, with minimal environmental pollutants. However, long term monitoring of leachate composition may remain necessary for bioreactor systems as some components, such as ammonia nitrate, may be hazardous.[44]

An important component to the realization of reduced costs is the extent of regulatory monitoring requirements imposed by local and state authorities. Cost savings from reduced monitoring can only be realized if the landfill managers are actually allowed to lessen their monitoring burden. State and local regulatory authorities have yet to adjust long-term monitoring burdens for bioreactor management systems.[45]

- Aerobic: Methane production is minimized and waste settlement is accelerated through the aerobic processes, while leachate is treated through recirculation. Pending regulatory approval, all components require reduced monitoring frequency and duration in the long-term, post-closure phase.

- Anaerobic: Methane production is accelerated and maximized early in the life of the landfill, waste settlement is accelerated through the increased biological activity, and leachate is treated through recirculation. Pending regulatory approval, all components require reduced monitoring frequency and duration in the long-term, post-closure phase.

Reduced Air and Water Pollution Threat

The potential for air emissions and ground water contamination is minimized through bioreactor landfill management. Because waste is stabilized in a much shorter time frame, it is likely that LFG emissions are maximized and leachate composition is stabilized during standard landfill operation, while the facility is being monitored and the built infrastructure is relatively new.[46] In addition, both aerobic and anaerobic processes minimize LFG emissions and lessen leachate toxicity, reducing the likelihood that either will be released to the environment in harmful quantities.

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[44] SWANA 2009, Page 45.
[45] Townsend,T., Kumar,D., Ko,J. *Bioreactor Landfill Operation: A Guide for Development, Implementation and Montoring: version 1.0* (July 2008). Page 7.
[46] Townsend, et. al., 2008, Page 6.

- Aerobic: Methane emissions are minimized and leachate is treated through aerobic processes. In addition, waste is stabilized in a short time frame (two to three years), while the landfill is being monitored and the infrastructure is relatively new, reducing the likelihood that leachate will compromise the landfill lining.

- Anaerobic: Methane emissions are maximized early in the life of the landfill through the anaerobic process. In addition, waste is stabilized in a short time frame (five to ten years), while the landfill is being monitored and the infrastructure is relatively new, reducing the likelihood that leachate will compromise the landfill lining.

Reduced Greenhouse Gas Emissions

The US Department of Energy estimates that widespread application of controlled landfilling, including bioreactor landfill management technology, could reduce anthropogenic methane emissions by 10 to 20 percent.[47] Since methane is over 20 times as potent a GHG as carbon dioxide, this reduction could have a significant impact on climate change mitigation.

- Aerobic: Methane constituents of LFG are minimized through aerobic processes.

- Anaerobic: Methane generation is accelerated to maximize potential energy recovery. Capture and combustion of resulting LFG (for energy purposes or destruction) minimizes emissions to the atmosphere.

Issues Summary

Table 5*, below, summarizes the potential benefits associated with the implementation of aerobic and anaerobic bioreactor systems, as discussed in this section. It is of note that hybrid bioreactor systems enjoy the combined benefits of both aerobic and anaerobic systems, depending on the phase that the waste is undergoing.*

Table 5: Benefits of Aerobic and Anaerobic Bioreactor Systems

Benefit	Aerobic	Anaerobic
Accelerated Waste Decomposition and Stabilization	✓	✓
Extension of Landfill Life	✓	✓
Energy Generation		✓
Improved Leachate Quality and Management	✓	✓
Reduced Post-Closure Facility Maintenance	✓	✓
Reduced Air and Water Pollution Threat	✓	✓
Reduced Greenhouse Gas Emissions	✓	✓

[47] National Energy Technology Laboratory, United States Department of Energy. *Intelligent Bioreactor Management Information System (IBM-IS) for Mitigation of Greenhouse Gas Emissions and Carbon Sequestration*. (April 2008). Page 3.

3.2 Unique Risks of Bioreactors

While there are several potential benefits to the use of bioreactor technology, there are also risks and drawbacks to consider. This section outlines the potential issues, which, similar to the benefits outlined in Section 3.1, may encompass regulatory, environmental, economic, and social impacts.

Regulatory Barriers

As discussed in Sections 2.1 and 2.3.1, the operation and design of landfills are regulated under RCRA Subtitle D, unless the site has approval under an EPA RD&D or Project XL permit or state permit exceptions. This means that landfill equipment, design, and management practices must adhere to Federal regulations, except in explicitly permitted cases. Additionally, LFG collection at landfills is mandated under NSPS, and under NESHAP for bioreactor landfills. Requirements affecting bioreactors include:

Gas Collection: The landfill NSPS require that facilities emitting more than 50 metric tons per year of LFG control emissions through LFG recovery. Additionally, NESHAP requires that LFG collection and control systems be operational within 180 days of liquid addition, or within 180 days of the waste mass reaching 40 percent moisture by weight, whichever is later. For aerobic bioreactors, there is no need to install an LFG collection system, as methane generation is minimized. For anaerobic bioreactors, these required systems may be significant depending on the size of the landfill and its LFG generation potential.

Liner: For landfills practicing leachate recirculation, RCRA Subtitle D mandates a composite liner with specific engineering elements and a leachate collection and recovery system. This can significantly increase costs.

Liner Head Maintenance: Under Subtitle D regulations, the leachate head, or the volume of leachate collected at the base of the landfill cell, may not exceed one foot under normal operating conditions. This presents a challenge when leachate is recirculated, as the addition of moisture to a mass of waste that is nearing field capacity increases the likelihood that leachate will accumulate and exceed the regulated one foot limit.

The Eastern Research Group, along with R.W. Beck conducted a literature review and evaluation of five active bioreactor systems for EPA in 2007, which included an analysis of how the technology could fit within regulatory requirements. They determined that bioreactor landfills are able to comply with existing RCRA Subtitle D regulations and guidance, and that “(a)s with any solid waste landfill, the proper design and operation using good engineering and waste management practices will be sufficient for a successful bioreactor landfill.”[48]

- Aerobic: Currently, bioreactor systems must be authorized by state permitting authorities under RD&D or Project XL permits.
- Anaerobic: Currently, bioreactor systems must be authorized by state permitting authorities under RD&D or Project XL permits.

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[48] Eastern Research Group/R.W. Beck. *Bioreactor Performance Summary Paper*. U.S. EPA Office of Solid Waste, Municipal and Industrial Solid Waste Management Division. (2007). Page 5-4.

Structural Stability

Rapid waste settlement, as a consequence of accelerated waste decomposition, can compromise the structural stability of the waste mass if not managed properly. In addition, moisture addition may contribute to the physical instability of the waste, and could result in structural failures. These could include ruptured LFG collection pipes, leachate recirculation pipes, landfill irrigation systems or collapsed slopes.

There are significant maintenance and repair costs associated with LFG, leachate or irrigation pipeline system ruptures. Further, if LFG collection systems rupture, it may affect the quality of LFG collected at the site, and may result in dangerous gas buildups that result in landfill fires (discussed further in this section). Facility managers may mitigate this risk by monitoring the waste mass through standard geotechnical analyses, and by considering the possible effects of seismic activity in applicable locations.[49]

- Aerobic: Rapid waste degradation and settlement results in the potential for structural failures if not properly monitored.
- Anaerobic: Rapid waste degradation and settlement results in the potential for structural failures if not properly monitored.

Additional Monitoring and Control During Operational Life

Engineered systems associated with bioreactor landfill management, which include leachate recirculation and supplemental liquid addition systems, may result in air and water emissions. Increased liquid throughout the waste mass increases the likelihood of leachate seeps, while increased methane generation (in anaerobic bioreactor systems) could result in emissions if LFG recovery systems are not engineered to handle increased yield. These factors must be monitored to minimize environmental hazards. Additionally, accelerated waste settlement and density could rupture piping systems for leachate recirculation, LFG recovery, or irrigation systems, and therefore the waste mass must be closely monitored for potential hazards.

There are capital costs associated with monitoring equipment, in addition to costs from additional labor needed to conduct measurement and monitoring operations needed for bioreactor system operation.[50]

- Aerobic: Additional monitoring is required during the operational phase of the landfill due to leachate recirculation and accelerated waste settlement.
- Anaerobic: Additional monitoring is required during the operational phase of the landfill due to increased gas yield, leachate recirculation and accelerated waste settlement.

Leachate Release

The addition of leachate and supplemental liquids to the waste mass increases the possibility of leachate seeps, whereby leachate is released out of the side slopes of the landfill, rather than collecting at the

[49] Pacey, et. al., Page 9.
[50] SWANA 2009, Page 47.

base of the cell. This creates management costs, but seeps observed at active bioreactors have not occurred in significant quantities to pose water pollution risks.[51]

- Aerobic: Process may result in leachate seeps.
- Anaerobic: Process may result in leachate seeps.

Excess Gas Production

Anaerobic bioreactor management encourages rapid and enhanced methane generation through methanogenic bacterial decomposition. While this can be a great benefit, as outlined in Section 3.1, drawbacks may also result. First, the LFG recovery system must be large enough to accommodate increased LFG quantities, and must be installed and operational much sooner than an LFG system collecting gas from a traditional landfill. Second, rapid methane generation shortly following waste deposition could interfere with preexisting long-term LFG recovery goals and/or contracts.[52] Finally, surface emissions of LFG may also increase if the LFG system and oxidation system cannot be adjusted to accommodate increased yield.

At traditional landfills, LFG recovery systems are often installed after a cell is closed. Because anaerobic bioreactors generate methane so rapidly, LFG collection systems must be installed while the cell is still active.

- Aerobic: Excess LFG production is not a concern for aerobic bioreactors, as the aerobic process minimizes the production of methane.
- Anaerobic: Accelerated and enhanced methane production require that LFG recovery systems be installed and operated earlier with anaerobic systems than with traditional landfills, often while the waste accepting cell is operational.

Increased Odors

Bioreactor landfill management can result in amplified odors because of increased gas production, leachate seeps from moisture addition, and odor generation from leachate application. The risk of enhanced odors is far greater in aerobic systems (and hybrid systems with an aerobic phase). Odors may be partially mitigated by an odor control plan, which may include the addition of fragrance misting.[53]

- Aerobic: Significant risk of increased odor relative to traditional landfill management.
- Anaerobic: Less risk of increased odor, when compared with aerobic systems.

Landfill Fires

Significant heat is produced from the metabolic activity of aerobic bacteria during waste decomposition, raising the risk of landfill fires when temperatures reach high levels. Additionally, “hot spots” can develop in both aerobic and anaerobic systems, whereby LFG and air are trapped in pockets within the

[51] US EPA. *Landfill Bioreactor Performance: Second Interim Report: Outer Loop Recycling and Disposal Facility: Louisville, Kentucky*. (September 2006) US EPA # 600-R-07-060. Page ix.
[52] SWANA 2009, Page 47.
[53] SWANA 2009, Page 48.

waste mass, raising the potential for ignition as temperatures rise. This risk may be partially mitigated by temperature monitoring and moisture addition.

With the addition of air in aerobic bioreactors, there is an increased risk (compared to anaerobic conditions) for landfill fires. The addition of air and landfill conditions must be diligently monitored to minimize the potential for landfill fires in aerobic bioreactors.

- Aerobic: Risk present for elevated temperatures and landfill fires from increased metabolism of aerobic bacteria. Addition of air provides favorable conditions for landfill fires to develop and spread.
- Anaerobic: Lower risk for landfill fires, though hot spots can develop within the waste mass.

Issues Summary

Table 6, below, summarizes the potential risks and drawbacks associated with the implementation of aerobic and anaerobic bioreactor systems, as discussed in this section. It is of note that hybrid bioreactor systems are subject to risks and drawbacks of both aerobic and anaerobic systems, depending on the phase that the waste is undergoing.

Table 6: Risks and Drawbacks of Aerobic and Anaerobic Bioreactor Systems

Risk	Aerobic	Anaerobic
Regulatory Barriers	✓	✓
Structural Stability	✓	✓
Additional Monitoring and Control During Operational Life	✓	✓
Leachate Release	✓	✓
Excess Gas Production		✓
Increased Odors	✓	✓
Landfill Fires	✓	✓

3.3 Opportunity and Implementation Considerations

Bioreactor systems can be implemented as-built or retrofit to preexisting waste cells, as outlined in Section 2.3.1. The list that follows includes some important considerations in the implementation of a bioreactor waste management system.

Site Configuration

Traditional landfill design has evolved to generally favor deep waste cells which are closed within a five year timeframe.[54] This is optimal for bioreactor implementation, as cells with large surface area and limited depth do not benefit from increased waste compaction, while the weight of waste deposited in deeper cells maximizes this capability.[55] However, extremely deep landfill cells may result in lower levels

[54] Pacey, et. al., Page 8.
[55] Townsend, et. al. 2008, Page 9.

of waste being too compacted by the weight of upper levels to achieve adequate permeability for leachate recirculation. This can be mitigated by limiting leachate recirculation or developing internal systems.[56] An additional benefit to deeper cells with smaller surface area is the time frame in which they are closed, which allows landfill managers to take advantage of new technologies as new landfill cells are utilized.

Remaining Waste Capacity

Generally, bioreactor technology should be applied as early as possible in the waste deposition process, but early implementation is especially important to maximize airspace recovery and leachate recirculation. For airspace recovery, waste must be compacted as it is deposited in the landfill, and as cells reach capacity, the potential for recovery diminishes. For leachate recirculation, it may be difficult for liquids to penetrate lower levels of waste of the landfill as the cell nears capacity, and certain technologies may be limited or impossible, such as horizontal pipeline use for liquid addition.

Design and Extent of Leachate Collection and Recirculation Systems

RCRA Subtitle D regulations include a one foot limit to the depth of leachate head above the landfill liner. This means that leachate collection and recirculation systems must be designed to accommodate leachate flow and supplemental liquid addition without exceeding the Federally-mandated one foot liner head limit. In addition, the corresponding leachate storage system must be able to accommodate accumulated quantities of leachate and supplemental liquids at peak volumes. Typically, modeling is performed in the permitting phase to demonstrate that the addition of liquids and the design of the landfill leachate collection system will comply with liner head levels.

Design and Extent of LFG Recovery System

Because anaerobic bioreactors generate more methane in a shorter period of time than traditional landfills, the LFG collection system at the bioreactor site must be designed with larger pipes and equipment than systems designed for LFG collection at traditional landfills.[57] It is important to ensure that the LFG recovery system in place can accommodate increased gas flow to avoid structural compromise from gas buildup under the landfill surface, and to mitigate the risk of dangerous “hot spots” developing.

Soil Cover

Permeability of the waste cover is especially important for bioreactors, as a cover that is more permeable than the waste mass will allow for leachate and liquid flow through the waste, while a cover that is less permeable than the waste mass may prevent liquid circulation. Ideally, the waste mass should be covered with semi-permeable soil or an alternative semi-permeable cover, which may include a blanket, tarp, or spray. If a more impermeable cover must be used as a waste barrier, it should be partially removed or graded to enhance liquid flow.[58] Typically, landfills may use more impermeable cover materials on the landfill sideslopes in order to minimize the potential for leachate seeps.

[56] Pacey, et. al., Page 8.
[57] Pacey, et al., Page 9.
[58] Pacey, et.al., Page 10.

Waste Stream Composition

For optimal bioreactor system performance, a relatively homogenous mixture of materials throughout the waste mass is ideal. As such, waste should be sorted to the extent possible in advance of disposal in the landfill cell. This includes removing construction and demolition (C&D) waste, tires, and other bulky waste to the extent possible.[59] To maximize bioreactor processes, waste should initially be placed in the landfill with reduced compaction to promote liquid flow. Waste will be compacted through biological degradation and natural compaction (from the weight of overlying waste) throughout the decomposition process.

[59] Townsend, et. al. 2008, Page 11.

4 Additionality

One of the pillars of the Reserve offset program and offsets generally, is a dedication to the principle of additionality. As defined in the Reserve's Program Manual, "GHG reductions must be additional to any that would have occurred in the absence of the Climate Action Reserve, or of a market for GHG reductions generally. 'Business as usual' reductions – i.e., those that would occur in the absence of a GHG reduction market – should not be eligible for registration."[60] The principle of additionality is central to the environmental and market integrity of offset instruments, because the use of non-additional offsets in a carbon-constrained operating environment could have the perverse impact of increasing global GHG emissions.[61]

Consistent with the Reserve's approach to standardized additionality determinations, this section explores issues related to the additionality of aerobic and anaerobic bioreactor projects. As a starting point, SAIC uses the Reserve's existing landfill project protocol additionality standard to explore how this determination could be extended to encompass aerobic and anaerobic bioreactor projects. Issues unique to aerobic and anaerobic bioreactors that may require modification of the landfill performance standard are also addressed.

4.1 Legal Requirements Test

The Reserve's *Landfill Project Protocol Version 4.0* requires that LFG offset project activities not be required by "laws, statutes, regulations, court orders, environmental mitigation agreements, permitting conditions, or other legally binding mandates requiring the destruction of landfill gas methane"[62] Past reviews of the regulatory landscape performed by and for the Reserve indicate that the primary laws regulating LFG at the federal level are the:

- New Source Performance Standards (NSPS) for MSW Landfills, codified in 40 CFR 60 Subpart WWW – Targets landfills that commenced construction or made modifications after May 1991
- Emission Guidelines (EG) for MSW Landfills, codified in 40 CFR 60 Subpart CC. –Targets existing landfills that commenced construction before May 30, 1991, but accepted waste after November 8, 1987
- The National Emission Standards for Hazardous Air Pollutants (NESHAP), codified in 40 CFR 63 subpart AAAA – Regulates new and existing landfills

These regulations have been implemented to control emissions of NMOCs, which include volatile organic compounds (VOC) and other organic compounds.[63] The NSPS is the statute with the greatest bearing on GHG offset projects. Although methane is excluded from NMOC, and therefore not explicitly

[60] Climate Action Reserve. *Program Manual*. (March 2010).
[61] Trexler, Mark C., Derik J. Broekhoff and Laura H. Kosloff. *A Statistically-driven Approach to Offset-based GHG Additionality Determinations: What Can We Learn?* Sustainable Development Law & Policy (Winter 2006) p.30-40
[62] Climate Action Reserve. *Landfill Project Protocol, Version 4.0*. (June 2011). Page 9.
[63] US EPA. *Municipal Solid Waste Landfill New Source Performance Standards (NSPS) and Emission Guidelines (EG) -- Questions and Answers*. (November 1998).

regulated under NSPS, the Rule's requirements result in a *de facto* failure of the Legal Requirements Test.

Landfills with a design capacity greater than or equal to 2.5 million Mg and 2.5 million cubic meters are required to report emissions on a periodic basis to EPA. If reported emissions exceed 50 Mg NMOC annually, the landfill is then required to mitigate NMOC emissions using best demonstrated technology (BDT). As described by the U.S. EPA, BDT for MSW landfills includes "(1) a well designed and operated gas collection system, and (2) a control device capable of reducing NMOC in the collected gas by 98 percent by weight."[64] The landfill NSPS encourages the use of open flares or enclosed combustion devices, as these control devices do not have to go through rigorous testing to demonstrate a 98 percent NMOC reduction.[65] While a flare or combustion device is not specifically required by the NSPS, facilities using other means for NMOC control would need to go through demonstration and testing to show that any alternate control technologies meet the 98 percent NMOC reduction required by NSPS. Therefore, although the goal of the landfill NSPS is not the destruction of methane, destruction of methane is a direct and necessary result of compliance with NSPS for regulated landfills.

Bioreactor landfills under 2.5 million tons and 2.5 million cubic meters design capacity are not subject NESHAP rules requiring destruction of landfill gas.

In addition to NSPS rules at the Federal level, landfills are regulated under state and local laws, including rules promulgated under the authority of the CAA and RCRA. The Reserve Landfill protocol extends the Legal Requirements Test to all levels of regulation, including state and local.

The Landfill Protocol performance standard should readily extend to bioreactor projects as a minimum, with additional considerations discussed in the following sections.

4.1.1 Legal Requirements Test for Anaerobic Bioreactors

Extending the Legal Requirements Test to anaerobic bioreactors is complicated somewhat by the permitting process required to implement an anaerobic bioreactor. As described in Section 2.3.1, anaerobic bioreactors can be permitted through one of several channels, including Project XL and the RD&D rule. For regulatory purposes, the EPA defines a bioreactor as follows:

"Bioreactor means a MSW landfill or portion of a MSW landfill where any liquid other than leachate (leachate includes landfill gas condensate) is added in a controlled fashion into the waste mass (often in combination with recirculating leachate) to reach a minimum average moisture content of at least 40 percent by weight to accelerate or enhance the anaerobic (without oxygen) biodegradation of the waste."[66]

Regardless of the manner in which the bioreactor is permitted, a 2003 NESHAP rule requires that *once operational,* bioreactors must collect and control LFG. Whereas the requirement to collect and control

[64] US EPA 1998, Page 8.
[65] US EPA. *Municipl Solid Waste Landfills, Volume 1: Summary of the Requirements for the New Source Performance Standards and Emission Guidelines for Municipal Solid Waste Landfills*. (February 1999). Page 2-14.
[66] National Emission Standards for Hazardous Air Pollutants for Source Categories (NESHAPS). 40 CFR 63.1990.

LFG for traditional MSW landfills is triggered by meeting the twin requirements of design capacity over 2.5 million tons and 50 Mg per year NMOC, the bar for bioreactors is lower. Any landfill that is greater than 2.5 million tons design capacity and defined as a bioreactor must collect and control LFG, regardless of its NMOC emissions. Importantly, however, the requirement does not apply to bioreactor landfills that are less than 2.5 million tons design capacity, and as with traditional MSW landfills, these are excluded.

For bioreactors above 2.5 million tons design capacity, this EPA rule effectively means that a strict application of the Legal Requirements Test would cause any bioreactor to be deemed ineligible on the grounds that the installed gas collection and control system is legally required. Therefore, if the Reserve pursues a protocol for anaerobic bioreactors, it may need to include special provisions allowing, under very explicit conditions, bioreactors that are required to collect and control LFG. Precedent for this type of exception exists in the Reserve's OWD protocol – whereby projects are not considered ineligible on regulatory grounds if "[a] legally binding local mandate requiring diversion and aerobic treatment of the waste stream is enacted in conjunction with the project"[67] – or Forestry protocols which not only allow but may require enactment of a restrictive easement legally requiring the project activity. If a bioreactor protocol is developed, a similar clause could be included. This clause could dictate that if the landfill voluntarily became a bioreactor as part of the project activity, and only became regulated as a result of project implementation, then the project would retain its eligibility.

Issues Summary

1. *Anaerobic bioreactors above 2.5 million Mg and 2.5 million cubic meters design capacity may require special rules in order to pass the Legal Requirements Test.*
2. *The current Reserve landfill Legal Requirements Test is appropriate for anaerobic bioreactors below 2.5 million Mg and 2.5 million cubic meters design capacity.*

4.1.2 Legal Requirements Test for Aerobic Bioreactors

The definition of bioreactor promulgated by EPA[68] specifically targets anaerobic bioreactors, and does not regulate aerobic bioreactors. No additional legal standards apply to aerobic that may require the destruction or avoidance of landfill methane. However, by avoiding methane production (as opposed to destroying methane in traditional and anaerobic digester projects), aerobic bioreactors have the potential to preclude regulation that would have occurred in the absence of the project due to NMOC emissions.

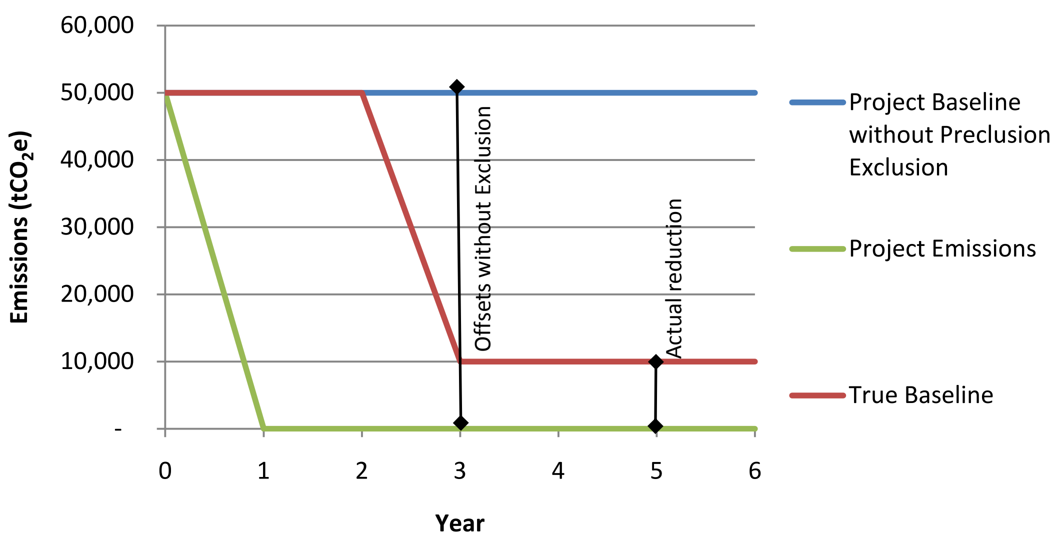
The intent of the Legal Requirements Test is to ensure that offsets are not granted for emission reductions that would have occurred in the absence of the offset project. Traditionally, the landfill

[67] Climate Action Reserve. *Organic Waste Composting Project Protocol, Version 1.0, Errata and Clarifications*. (July 2011). Page 8.
[68] NESHAPS 40 CFR 63.1990.

protocol and others ask the question "*is* the emission source required to be mitigated by law, regulation, etc.?" but in the case of aerobic bioreactors an additional question must be addressed "*would* the emission source have been required to be mitigated by law, regulation, etc.?" Take the following simplified example. A landfill with design capacity of 3 million Mg may be below the 50 Mg/year NMOC threshold for regulation, but trending upwards by 5 Mg/year. If the landfill's emissions were 40 Mg/year today, then it is likely that in two years the landfill would be required to collect and control NMOC emissions, and by extension the methane emissions intermixed in the LFG. However, if the landfill converts to aerobic bioreactor next year and its NMOC emissions instead remain steady at 45 Mg/year, then it will never be required to manage LFG. According to the standard conception of the Legal Requirements Test presented in the landfill protocol, this landfill would be considered eligible in year three, four, five, and onward, because NMOC emissions remain below a regulated level. However, beginning in year three, the landfill emissions would have been controlled *even in the absence of the offset project*.[69] Therefore, it would be inappropriate for offset credits to be issued beginning year three.

As shown in Figure 4, the project baseline might be assumed to be 50,000 tCO_2e because there *is* no requirement in year 3 to control emissions, and if project emissions equaled zero then the project would receive 50,000 tCO_2e of offsets. However, had the landfill not converted to an aerobic bioreactor emissions *would* have fallen to, for example, 10,000 tCO_2e. The project in year 3 has only improved 10,000 tCO_2e over the counterfactual baseline, and would be receiving 40,000 tCO_2e of non-additional offsets.

Figure 4: GHG Emissions Over Time for Example Landfill Project



The Reserve *Attestation of Voluntary Implementation*, used to meet the Legal Requirements Test, contemplates this form of gaming to a limited extent. The Attestation contains the following clause:

[69] Landfills are given 30 months to install gas collection and control systems, but for simplification the example is presented omitting this 30 month window.

> "Except as otherwise expressly permitted under the protocol developed by the Reserve that applies to the Project, the Project was not established or implemented, and was not at any time during the Reporting Period operated or conducted, in anticipation of, or to avoid or satisfy the anticipated requirements of, any Law that would require or would have required the Project Developer **to *use the Property in the manner contemplated by the Project*.**"[70](emphasis added)

The emphasized text explicitly references use "in the manner contemplated by the Project". However, no legal requirement identified for this review requires use of any property as an aerobic bioreactor, a use, in fact, markedly different from standard practice or installation of a GCCS. In order to avoid unwarranted crediting of offsets for emissions that would not reasonably be expected to occur in the baseline, the Reserve may need to alter the language of its Attestation. Such an exclusion would have to disallow projects where any use of the property that would have resulted in similar emission reductions would have been required, or the like.

Preclusion of regulation, as discussed in this section, involves a case where a landfill operator elects to utilize an aerobic bioreactor management system to avoid methane production and minimize NMOC emissions, and preclude regulation mandating landfill gas recovery and destruction. This case is highly unlikely, as the equipment necessary to operate an aerobic bioreactor system is comparable in cost, and may be more expensive, than an LFG recovery system. When coupled with permitting fees, the initial cost of implementing an aerobic bioreactor system is likely much higher than complying with LFG collection regulation, and so implementation of this system for the purpose of precluding LFG collection regulation is presented only as a theoretical possibility.

In practice, rules premised on a counter-factual are difficult to implement and enforce. As a standardized program, the Reserve will need to establish a standardized process and methodology by which it can determine when an aerobic bioreactor *would have* been regulated under NSPS and required to install gas collection and control systems. Alternatively, as is done in the Reserve's OWC and OWD Protocols, the baseline could assume that LFG *would have* been collected at a standardized collection efficiency as the baseline for aerobic bioreactor projects. However, for the OWC and OWD protocols this assumption is based on the fact that the landfill receiving diverted waste in the baseline is unknown, and its specific gas management system therefore cannot be modeled. In the case of aerobic bioreactors, the facility is known, but there may be some nominal uncertainty over the baseline landfill gas treatment system. Such an across-the-board assumption may be unduly conservative for aerobic bioreactors that are far from regulatory NMOC levels and which would have been highly unlikely to destroy landfill gas in the baseline.

[70] Climate Action Reserve. *Project Developer's Attestation of Voluntary Implementation*. (June 2011).

Issues Summary

1. *Aerobic bioreactors could potentially preclude regulation that would otherwise result in the mitigation of GHG emissions.*

2. *Standardization of rules around preclusion may be difficult to implement and enforce.*

3. *Addressing preclusion may require modifications to the* Attestation of Voluntary Implementation *in addition to protocol-specific language.*

4.2 Performance Standard

As with the Legal Requirements Test, this issues paper begins with the Reserve Landfill Project Protocol performance standard, and investigates whether it can be readily extended to apply to aerobic and anaerobic bioreactor projects. Version 4.0 of the *Landfill Project Protocol* represents a major revision of the Reserve's performance standard analysis. The analysis concluded that installation of flares at landfills in all regions of the country is relatively uncommon, and therefore eligible. But energy projects are more complex, and two primary findings emerged from the Reserve's analysis:

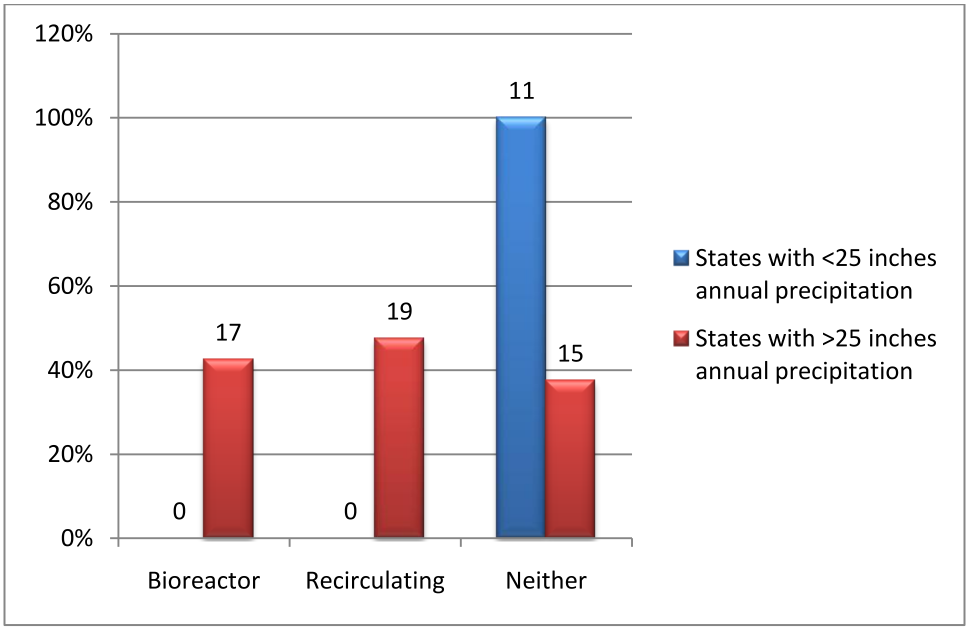
1) Landfill gas-to-energy projects are more common at *larger landfills*

2) Landfill gas-to-energy projects are more common in *wet regions*

On the basis of these findings, the Reserve concluded that a two-tier performance standard was appropriate for energy projects. Landfills in arid regions are eligible for the installation of a gas-to-energy project only if waste in place is less than 2.17 million metric tons. Landfills in non-arid regions are eligible for gas-to-energy projects only up to 0.72 million metric tons. Because methane production increases in non-arid regions, even small landfills in these regions may have sufficient economic incentive to produce energy without GHG offset revenue. In order to prevent gaming through the use of a bioreactor protocol, the existing landfill performance standard restrictions would need to be extended to gas-to-energy aerobic and anaerobic bioreactor projects. Absent such an extension, a landfill that would not be eligible under the Reserve's current landfill protocol could be converted into an aerobic or anaerobic bioreactor project and thereby skirt the eligibility rules and receive GHG offsets.

As with traditional landfill projects, aridity strongly influences the viability of aerobic and anaerobic bioreactors projects as well, due to their reliance on large volumes of moisture. As shown in Figure 5, states considered non-arid according to the Reserve (greater than 25 inches annual precipitation) are significantly more likely to have both bioreactors and leachate recirculating landfills. Of 11 states receiving less than 25 inches of annual precipitation on average, there are no bioreactors or even leachate recirculating landfills. Of the 39 states receiving an average of 25 inches precipitation or greater, only 15 (38 percent) did not have either a bioreactor, leachate recirculating landfill, or both.

Figure 5. Percent and number of states receiving greater than or less than 25 inches annual precipitation that have at least one bioreactor or leachate recirculating landfill.



Currently, the main incentive for landfills to consider implementing bioreactor technology is to provide a cost-effective means to manage the leachate generated at the site. In arid regions, landfills do not generate significant quantities of leachate compared to non-arid regions of the Country, as precipitation is the primary contributor to leachate generation in a landfill. Therefore, aridity is a strong driver of bioreactor implementation, and should be considered carefully in setting a performance standard for bioreactor offset projects.

The size of the landfill may also be a consideration in the establishment of a bioreactor project, in conjunction with aridity. The waste mass within the landfill must be capable of retaining the added moisture to optimize bacterial health and waste degradation. Based on the review of bioreactor landfills performed for this issue paper, the majority of landfills that have implemented bioreactor technology have been larger landfills (landfills that likely meet or exceed the NSPS size threshold of 2.5 million tons or cubic meters of waste in place). This is likely due to the fact that larger landfills are located in more populated areas, and therefore may have more costly options for leachate management, such as trucking offsite to a wastewater treatment plant. The method of leachate management available to the landfill will be an important consideration in the financial feasibility of bioreactor technology at a site. However, it should also be noted that as bioreactor landfill data continue to show an accelerated increase in methane production, smaller landfills may evaluate this option as a means to boost their landfill gas generation ability to make a landfill gas-to-energy project feasible. This has only been recently seen as a trend within the solid waste industry, and the more common approach to implementing bioreactor technology at a landfill has been as method of cost-effective leachate management.

4.2.1 Implications of Bioreactor Incentives on Eligibility Determination

For traditional landfills, the pivotal project activity is installation and operation of an LFG collection and control system. Projects that operate flares have little, if any, economic incentive or income associated with the project other than the potential for GHG offsets, whereas landfill gas-to-energy projects also reap the benefits (and higher capital and installation costs) associated with energy recovery. However, both aerobic and anaerobic bioreactors offer significant benefits that must be considered alongside energy production. For this reason, a more restrictive performance standard may be required for aerobic and anaerobic bioreactors.

A 2009 paper by Nicole Berge and colleagues provides one of the few quantified analyses of the potential economic tradeoffs associated with aerobic and anaerobic bioreactors projects.[71] Berge et al. compared six scenarios, modeling costs and benefits from construction, operation and maintenance, leachate management, methane utilization, closure and post-closure care, and airspace recovery. A summary of the six scenarios is provided in Table 7, with important model parameters reproduced in Table 8.

Table 7: Landfill scenarios modeled by Berge, et al. for cost-benefit analysis (reproduced from Berge, 2009)

Landfill type	Landfill definition	Potential monetary benefits
Traditional	Operated with intent of entombing waste	Utilization of CH_4 for electricity generation
Anaerobic retrofit bioreactor	Bioreactor operation commences following active filling (year 6)	Leachate treatment savings; utilization of CH_4 for electricity; airspace recovery
Anaerobic as-built bioreactor	Bioreactor operation commences during active filling	Leachate treatment savings; utilization of CH_4 for electricity; airspace recovery
Retrofit hybrid bioreactor	Bioreactor operation commences following active filling (year 6). Air injection occurs for periods ranging between 0.25 and 5 years	Leachate treatment savings; utilization of CH_4 for electricity; airspace recovery
As-built hybrid bioreactor	Bioreactor operation commences during active filling. Air injection occurs for periods ranging between 0.25 and 5 years	Leachate treatment savings; utilization of CH_4 for electricity; airspace recovery
Aerobic bioreactor	Bioreactor operation commences during active filling. Air injection occurs immediately and continues during entire bioreactor period	Leachate treatment savings; utilization of CH_4 for electricity; airspace recovery

[71] Berge, Nicole D., et al. *An assessment of bioreactor landfill costs and benefits*. Waste Management 29: 1558-1567. (2009).

Table 8: Landfill design and base case parameters and conditions (reproduced from Berge et al., 2009)

Parameter	Value
Waste receipt/day	550 mg
Volume	$3.1 \times 10^6\ m^3$
Density	650 kg/m^3
Waste: soil	4:1
Area of the landfill	13.4 ha
Tipping fee	US$ 40/Mg waste
Inflation rate	3%
Sinking fund interest rate	4%
Interest rate	5%
Total settlement	20%
% Leachate recirculated	75%
Year field capacity is attained	3
Number of injection wells/acre	16
Area of landfill aerated	25%
Oxygen utilization efficiency	75%
LandGEM gas degradation rate during bioreactor operation	0.15/year
LandGEM gas degradation rate for traditional landfills	0.04/year
Gas capture efficiency while filling	35%
Waste methane potential	100 m^3 CH_4/Mg waste
Gas capture efficiency after temporary final cap placement	90%
Electricity price	US$ 0.05/kW-hr
Gas-use efficiency (% of gas collected used for electricity)	70%
Leachate generation rate before closure	9350 L/ha-day
Post-closure care period length	30 years
Air flowrate	75% of maximum
Waste biodegradable fraction	0.45
On-site leachate treatment	US$ 0.024/L
Off-site leachate treatment	US$ 0.061/L

Berge, et al. applied each scenario to a generic landfill with the characteristics summarized in Table 8. Additional assumptions were included to account for differences between landfill operations, representing variation in both costs and benefits, and explicitly assigning costs and benefits temporally in the model to account for inflation, interest rates, and other economic considerations. Important costs and benefit assumptions that varied from the traditional landfill scenario are as follows:

1. As-built bioreactors incur additional costs at construction for air and/or water circulation systems. Retrofit bioreactors incur additional costs at closure for air and/or water circulation systems.

2. Air injection costs are incurred only for aerobic bioreactors. Liquid circulation costs are incurred for both anaerobic and aerobic systems.

3. Operation and maintenance costs increase as a result of bioreactor operation due to potential leachate outbreaks, electricity consumption, sampling, and engineering.

4. As-built bioreactors begin accruing benefits from decreased leachate treatment costs immediately. Retrofit bioreactors accrue these benefits only after closure.

5. As-built anaerobic bioreactors begin accruing revenue from gas utilization immediately. Retrofit bioreactors accrue these benefits only after closure.

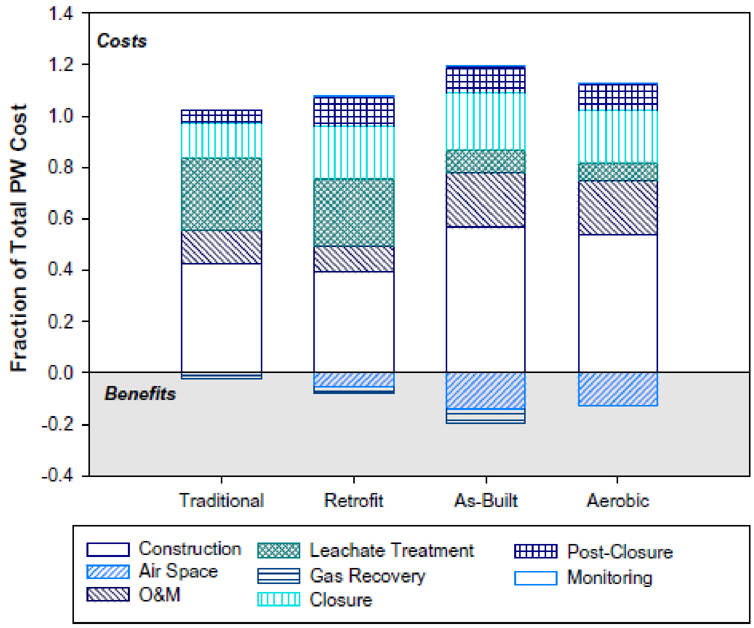
6. As-built bioreactors are able to utilize recovered airspace in real-time to increase revenue, and gain the additional benefit of reduced future cell construction costs. Retrofit bioreactors are unable to capture incremental airspace recovery until the end of operation.

Based on these assumptions and scenarios, Berge et al. calculated that present worth total landfill costs for the six scenarios varied from $37/Mg to $50/Mg, with the retrofit anaerobic bioreactor being 8.7 percent *more* expensive than continued operation as a traditional landfill. However, the as-built anaerobic bioreactor was found to be 20 percent *less* expensive than the traditional landfill, and the as-built aerobic bioreactor 13 percent *less* costly.[72] One of the distinguishing characteristics of the as-built systems was the ability to recapture airspace and increase site revenues, while decreases in leachate treatment requirements and improved gas utilization were also important factors. Retrofit systems were considered less efficient at recapturing airspace and reducing leachate treatment costs.

Interestingly, Berge found that closure and post-closure costs increased for bioreactors, despite the fact that this is a commonly asserted benefit of bioreactors. Increases in closure costs result from installation of both a temporary final cap constructed after filling, and a final cap installed subsequent to bioreactor operations. Post-closure costs increased due to necessary operation and monitoring activities performed subsequent to closure. Figure 6 offers a breakdown of costs and benefits from a traditional landfill, a retrofit anaerobic bioreactor, an as-built anaerobic bioreactor, and an as-built aerobic bioreactor.

[72] Berge, et. al., 2009.

Figure 6: Distribution and comparison of bioreactor and traditional landfill present worth (PW) costs (reproduced from Berge, 2009)



Berge concludes that "Based on simulations…both the as-built and aerobic bioreactor landfills have lower [present worth] costs than the retrofit bioreactor and traditional landfills. This is primarily because of the profit realized from airspace recovery and savings associated with reduced leachate treatment requirements."[73] Importantly, the comparative traditional landfill in this study included LFG utilization. Therefore, the suggested conclusion from this analysis pertaining to the performance standard would be to suggest that the threshold at which methane destruction and/or avoidance become economically feasible may be *lower* than for traditional landfills. The Reserve has established size cutoffs of 0.72 and 2.17 million metric tons waste in place for arid and non-arid regions, respectively. For as-built anaerobic bioreactor and aerobic bioreactors, these sizes may need to be reduced. On the other hand, retrofit bioreactors are no more economically viable than traditional LFG utilization projects. On this basis, the Berge study suggests that the current landfill performance standard is likely appropriate for retrofit systems.

To supplement Berge et. al.'s modeled results, provided in Table 9 are a sampling of costs and benefits for three leachate recirculating projects (i.e., not full bioreactors) for which SAIC provided engineering and feasibility services. These figures do not include all possible costs, and reflect a combination of incurred and forecast costs. Additionally, it should be noted that these three projects *were* implemented, showing that they had positive economics. As such, they represent very specific conditions and are provided for informational purposes only to supplement Berge et. al.'s modeled landfills. Also note that while recovered air space benefits are allocated based on the amount of air

[73] Berge, et. al., 2009. Page 1567.

space recovered in a given year, the monetary benefit of this airspace would only be accrued at what would have been the end of the landfill or cell's useful life, when that life could be extended.

Table 9. Cost and Benefit Data for Three Leachate Recirculating Landfills (costs rounded to $1,000).[74]

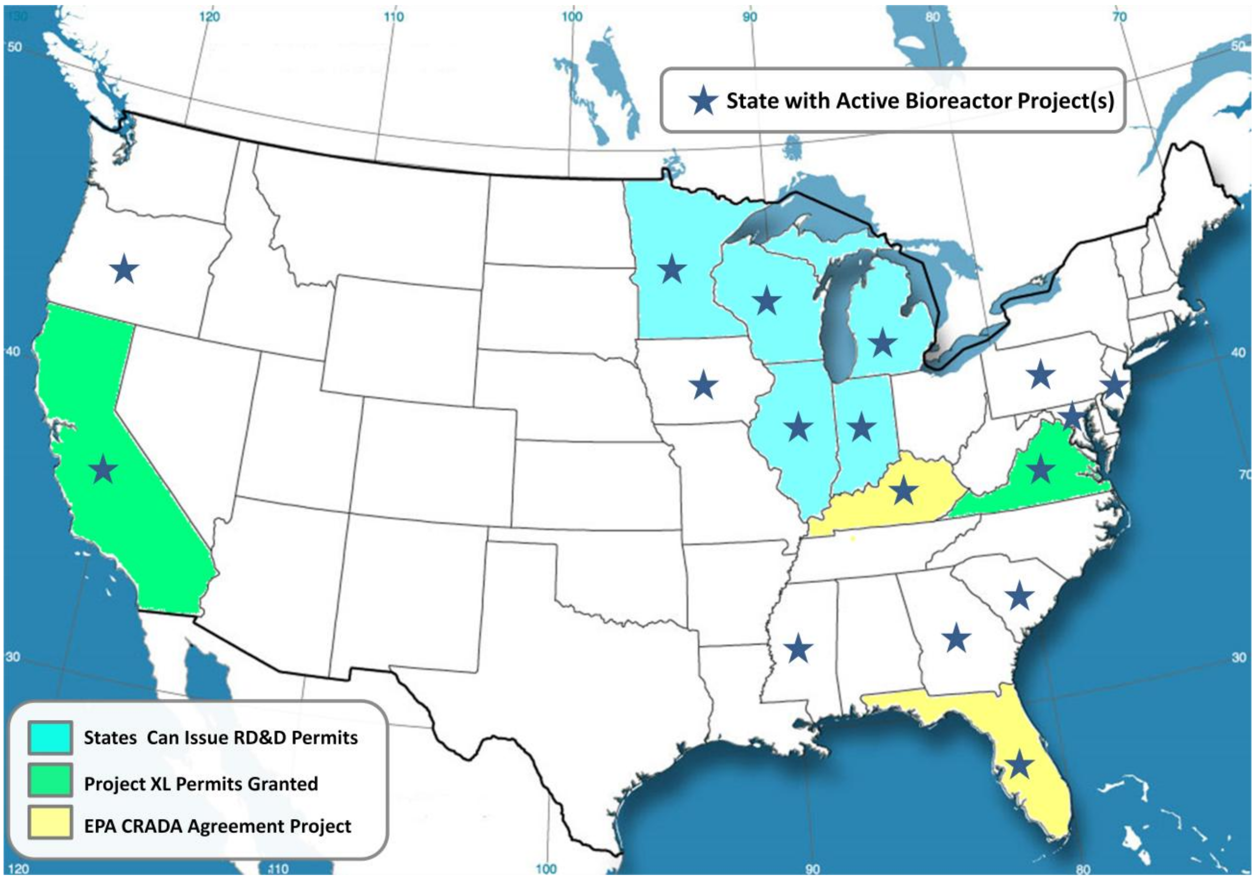
Year	Engineering & Permitting Costs	Capital Costs	Monitoring Costs	Operation & Maintenance Costs	Leachate Disposal Benefit	Recovered Airspace Benefit	Net Benefit
Landfill 1							
1	$ (72,240)	$(265,825)	$(10,120)	-	$44,500	-	**$(303,685)**
2	-	-	$ (13,500)	$(55,000)	$62,080	-	**$ (6,420)**
3	$ (40,000)	-	$(22,820)	$ (71,200)	$84,500	-	**$(49,520)**
4	$ (25,000)	-	-	$ (8,350)	$63,000	-	**$29,650**
5	$(28,000)	-	-	-	$26,000	$945,840	**$943,840**
Total	**$(165,240)**	**$(265,825)**	**$(46,440)**	**$ (134,550)**	**$280,080**	**$945,840**	**$613,865**
Landfill 2							
1	-	-	-	-	$3,000	-	**$3,000**
2	$(34,000)	$(34,000)	$(3,000)	-	$75,000	$713,000	**$717,000**
3	$(35,000)	$(35,000)	$(5,000)	-	$90,000	$859,000	**$873,000**
4	$(25,000)	$(25,000)	$(5,000)	-	$18,000	$826,000	**$789,000**
5	$(24,000)	$(24,000)	$(5,000)	-	$(65,000)	$307,000	**$190,000**
6	$(13,000)	$(13,000)	$(5,000)	-	$(114,000)	$65,000	**$(80,000)**
7	$(9,000)	$(9,000)	$(5,000)	-	$(93,000)	$561,000	**$445,000**
Total	**$(140,000)**	**$(140,000)**	**$(30,000)**	**-**	**$(86,000)**	**$3,332,000**	**$2,937,000**
Landfill 3							
1	$(61,000)	$(165,000)	-	-	-	-	**$(226,000)**
2	$(12,000)	$(30,000)	-	$(1,000)	-	$78,000	**$35,000**
3	$ 9,000)	-	-	$(4,000)	$62,000	$270,000	**$319,000**
4	$ (24,000)	$ (37,000)	-	$ (4,000)	-	$418,000	**$353,000**
5	$ (31,000)	$ (122,000)	-	$ (19,000)	$48,000	$545,000	**$421,000**
6	$ (189,000)	$ (1,000)	$ (5,000)	$ (5,000)	$38,000	$237,000	**$75,000**
7	$ (64,000)	$ (44,000)	$ (7,000)	$ (4,000)	$85,000	$274,000	**$240,000**
8	$ (120,000)	$ (89,000)	$ (7,000)	$ (10,000)	$64,000	$326,000	**$164,000**
9	$ (120,000)	$ (86,000)	$ (7,000)	$ (19,000)	$136,000	$671,000	**$575,000**
10	$ (154,000)	$ (48,000)	$ (7,000)	$ (23,000)	$195,000	$450,000	**$413,000**
11	$ (99,000)	$ (108,000)	$ (27,000)	$ (30,000)	$182,000	$541,000	**$459,000**
Total	**$ (883,000)**	**$ (730,000)**	**$ (61,000)**	**$ (120,000)**	**$811,000**	**$3,810,000**	**$2,827,000**

Despite the modeled financial viability of bioreactor projects, implementation is not common, as there are only 30 active bioreactor projects in North America. As discussed in Section 3, the risks and

[74] Data from confidential clients, reproduced with permission.

drawbacks to bioreactors can be considerable. Among these, regulatory barriers provide the most significant obstacle to implementation. Figure 7, below, summarizes the regulatory environment for bioreactor permitting, which is discussed in detail in Sections 2.3.1 and 3.2. Permitting costs can be significant, and the time frame for permit approval can be extensive.

Figure 7: Permitting Mechanisms for Bioreactor Projects, States with Active and Pending Bioreactor Projects[75,76]



In addition to regulatory barriers, physical conditions at the landfill site and uncertainty present significant challenges for landfill managers. Physical conditions include the climate and the actual landfill construction site. As was shown in Figure 5, bioreactors appear to be feasible only in states that receive greater than 25 inches of rainfall per year, due to the requirement for liquid addition in the project design. Additionally, a bioreactor must be designed to handle additional liquid and rapid waste settlement (in the case of as-built systems), or must have an adequate liner system in place to handle these factors (in the case of retrofit systems). This limits the geographic area for feasible projects, and limits the type of landfills that may become bioreactors.

[75] Active bioreactor projects that do not fall under Federal permitting programs are given authority to operate by their state regulatory authority. These projects operate under specific permitted conditions determined by the state authority, or they are state-funded demonstration projects.
[76] Data on States with active bioreactor projects from SWANA 2009. Data on states that can issue RD&D projects from EPA. Data on states with Project XL permitted projects and EPA CRADA projects from SWANA 2009. Blank map of United States courtesy of the Nations Online Project.

In addition, uncertainty surrounding the technical feasibility and economic benefits of bioreactor systems has also inhibited their widespread adoption. There are few site-specific performance studies, and too little project sustainability experience to serve as evidence for the technical success of bioreactor projects.[77] Additionally, until the recent Berge study, the full scope of project economics had not been analyzed or documented for bioreactor landfills.[78] This lack of quantifiable evidence of the benefits of bioreactor systems has contributed to uncertainty surrounding bioreactor projects, and may have been a discouraging factor to site managers considering bioreactor systems.

An additional deterrent to implementation, though not as significant as those mentioned previously, is upfront capital investment. Though these projects frequently reduce costs and generate revenue over time, the initial investment involved in constructing an as-built system, or in retrofitting an existing landfill can be significant. The Polk County landfill in Florida cited costs of lining 41 acres of landfill space among the significant challenges involved in project implementation. In total, despite realizing a net savings over time, the Polk County site invested over $2.5 million on liners, vacuum pumps and bioreactor-LCS upgrades.[79] Even with a modeled positive long-term payback, the upfront investment required for bioreactor projects coupled with significant remaining uncertainties complicates a simple cost-benefit analysis such as the one conducted by Berge et. al. Additional revenue from generating a stream of offset credits may ease access to capital, and improve economics enough to compensate for regulatory, investment, and technological risk.

Issues Summary

1. *The market penetration of bioreactors varies based on climatic conditions and landfill size.*
2. *As-built bioreactors may be non-additional due to the financial value of non-carbon benefits.*
3. *Retrofit bioreactors are more likely to be additional than as-built bioreactors.*
4. *Both anaerobic and aerobic bioreactors are capable of generating significant cost savings over traditional landfills due to reductions in leachate treatment costs and air space recovery.*

[77] Pacey, et. al., Page 11.
[78] Berge, et. al., 2009, Page 1558.
[79] Stayer, Brooks. *Polk County Florida Bioreactor Project First Year of Operation*. (2008) Presented to the Solid Waste Association of North America.

5 Quantification and Supporting Monitoring

As central to the viability of an offset protocol as the rules governing project eligibility and additionality is the ability to accurately quantify emission reductions that result from project activities. This section addresses the available methodologies, uncertainties, and issues related to calculating both baseline and project emissions from aerobic and anaerobic bioreactors. In addition to quantification methodologies, this section also addresses the monitoring activities that would be necessary to provide needed data.

5.1 Existing Protocol Resources

5.1.1 Reserve Landfill Protocol

The Reserve *Landfill Project Protocol Version 4.0* quantifies baseline and project emissions by monitoring LFG destruction, electricity use, and other minor sources. One of the major assumptions of the Landfill protocol is that implementation of project activities will not alter the production of methane in the landfill, and that the measured methane that is destroyed fairly represents emissions that would have occurred in the baseline. Essentially, baseline emissions are assumed to be equal to the quantity of methane collected and destroyed by the project, adjusted for oxidation. This assumption is justified in traditional landfill projects because installation of a GCCS does not significantly alter landfill dynamics or microbial processes.

Unlike traditional landfills, the express intent of aerobic and anaerobic bioreactors is to alter landfill dynamics and microbial processes in order to expedite waste breakdown and landfill stabilization. Because this is done by increasing methane production in anaerobic bioreactors, extending the assumption that collected LFG equals baseline emissions would result in over-crediting for anaerobic bioreactors on a year-on-year basis. On the other hand, extending this assumption to aerobic bioreactors would grossly under-estimate the GHG benefits of the project activity because extremely small quantities of methane would be collected.

Another complication for quantification arises in accounting for project emissions. The Reserve Landfill protocol does not assume that collected LFG is equal to total baseline emissions at the landfill, but rather that any gas not collected during the project would also have been emitted in the baseline, and can therefore be excluded from analysis as equal in the project and baseline scenarios. Methane emissions during the project activity are a potentially significant emission source for both aerobic and anaerobic bioreactors, and would need to be quantified for calculating emission reductions.

In short, the fact that installation of a GCCS at a traditional landfill does not significantly alter methane production during the project allows for two simplifying assumptions that may not hold for aerobic or anaerobic bioreactors projects. These assumptions are:

1. Once adjusted for oxidation, all of the methane collected and destroyed during the project would have been produced and emitted in the baseline.

2. Methane emissions resulting from surface flux during the project constitute emissions that would have also occurred in the baseline, and can therefore be ignored.

The impact of extending these assumptions to aerobic and anaerobic bioreactors is summarized in Table 10. In both cases, reliance on these assumptions and use of the Landfill project protocol accounting methodology is likely to result in inaccurate calculation of annual emission reductions.

Table 10: Baseline, project, and emission reductions for aerobic and anaerobic bioreactors quantified according to assumptions in the current landfill protocol, relative to traditional landfill

	Baseline Emission	Project Emissions	Emission Reductions
Anaerobic Bioreactor	↑	↓	↑
Aerobic Bioreactor	↓	=	↓

5.2 Temporal Considerations Related to Baseline Emissions

Although it is clear that anaerobic bioreactors will increase methane emissions in early years, resulting in increased gas collection, and likely increased surface emissions, there remains some uncertainty surrounding aggregate emissions over the lifetime of the landfill. Bioreactor technology advances LFG production, as compared with conventional "dry-tomb" landfill disposal methods, in which LFG is generated over a longer period of time at reduced rates.[80] This concept is illustrated by Figure 8. Generally, there are three main variables that are used to model LFG and methane generation volumes. The first variable is the mass of waste disposed. This includes historical tonnage records and future project waste amounts. All else being equal, a greater mass of waste will produce a greater quantity of LFG. The second variable is known as the methane potential. The methane potential is a function of the quantity of organic material in the waste, and is represented as a volume of methane per unit mass. The higher the methane potential, the more methane we would expect to be emitted over the course of waste decay. The third variable corresponds to the rate at which the waste decays under specific conditions. The decay rate is a function of moisture content, waste type, and waste placement and can be highly site-specific. This section discusses the ability of bioreactor management to affect both the decay rate and methane potential.

[80] Townsend, T.G., et. al. *Landfill Gas Collection from an Operating Bioreactor Landfill*. (Mar 27-30, 1995). 18th Annual Landfill Gas Symposium Proceedings, New Orleans LA.

Figure 8: Moisture impact on LFG generation

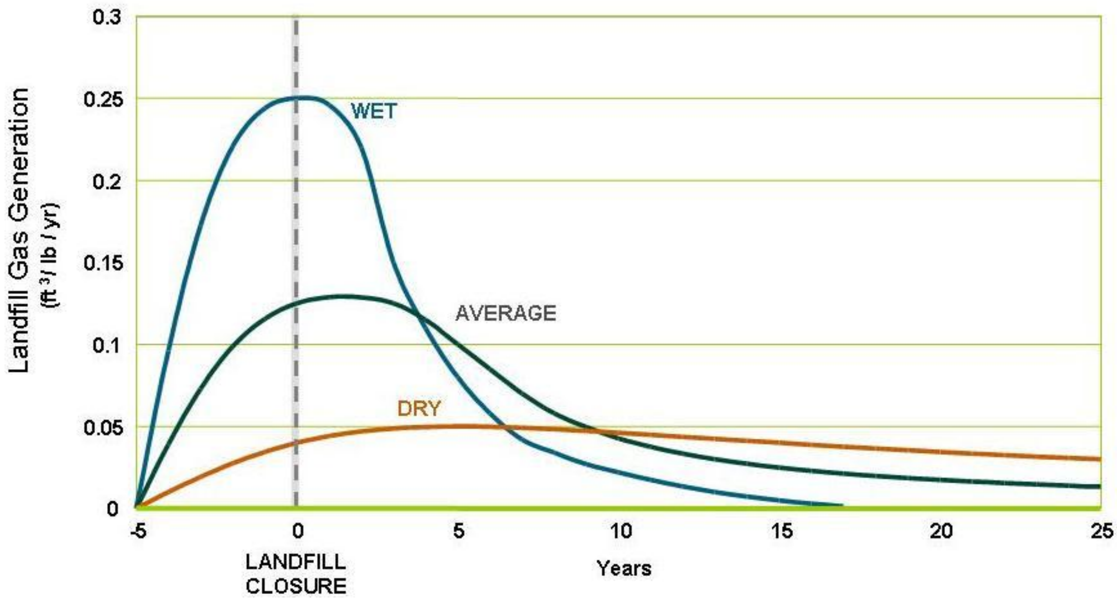


Figure 8 shows how moisture impacts LFG generation, demonstrating accelerated LFG production by bioreactor (wet) landfills and the equally rapid decline of LFG production after the landfill ceases to receive waste. The conventional theory addressing the overall quantity of gas produced by the landfill is that over the life of the project, methane generation will be of equal yield, regardless of whether bioreactor technology is implemented. In other words, the total quantity of gas produced by the landfill over its life (or the area under the curves depicted in Figure 8) is a fixed value. Some theories posit that bioreactor technology may result in more LFG production, as the engineered distribution of the moisture may enhance biodegradation of the waste that otherwise may not have fully degraded. However, during the development of this issue paper we found no published studies addressing this specific theory that bioreactor technology achieves more complete biodegradation of waste, therefore producing more overall gas over the entire life of the waste.

It should be noted that LFG generation is unique to each site, and that the graphic in Figure 8 is intended to provide an overall relationship between bioreactors and LFG production. Many factors contribute to the production of LFG, and there several different models used in the solid waste industry to predict LFG generation at landfills, as discussed in Section 5.4.

For implementing LFG generation models, evidence has shown that increasing the moisture content of the waste increases the decay rate over a traditional dry tomb landfill.[81] Specifically, increasing the moisture content of the waste has an effect on both the rate of decay and the methane potential of a given unit of waste.[82] Wet cells have been observed to produce gas at a faster rate during the early years after initial waste placement, which leads to lower gas output at the end of the landfill life

[81] Faour, A., D. Reinhart and H. You. *First-Order Kinetic Gas Generation Model Parameters for Wet Landfills*. (June 2005). Orlando, FL. EPA# 600-R-05-072.
[82] Faour, et. al., 2005.

compared to conventional landfills, particularly after closure, while more effective wetting occurred. The introduction of moisture into the waste mass allows the methane potential of a given unit of waste to be reached more quickly than conventional landfills, thus generating an equal quantity of gas in a shorter period of time. Gas generation at dry cells is likely inhibited by moisture limitation. Thus, the ideal methane potential may not be achievable in dry cells over a measurable time period.[83] In dry cells, LFG generation can persist for hundreds of years after closure.

Additional studies have further evaluated LFG generation with respect to the relationship between the rate of decay and the methane potential of waste, with a focus on moisture content. In a 2005 SWANA report, the parameters affecting methane potential and the decay rate were empirically evaluated.[84] Methane potential is directly related to the amount of organic material in the waste, and is therefore, easier to measure using multiple methods. Laboratory tests, or test landfills, were used to estimate the methane potential of different waste masses, and resulted in a range of values of approximately 40 to over 100 cubic meters of methane potential per Mg of dry waste. The decay rate is a more difficult variable to measure and is highly affected by moisture in the waste, depth and age of waste, pH of the waste, and the presence and operation of an active collection system.

The 2005 SWANA report notes that further testing was completed by reviewing actual LFG collection data and comparing these data to projection models for 13 landfills in the US. The LFG collection data were used to determine both the decay rate and the methane potential with respect to annual precipitation. The purpose was to determine the effect that precipitation may have on both of the variables used for modeling LFG generation. Although limited to areas that receive precipitation within the range of 12 to 54 inches per year, it appears that both methane potential and decay rate increase as the quantity of precipitation increases.

The testing did not directly measure LFG generation, but compiled historic LFG collection data for the testing sites. These collected data were assumed to represent 75 percent of the total LFG generated, as the active collection system had a75 percent collection efficiency. The study generated site-specific data to generate the decay rate and methane potential for landfills that receive a given amount of precipitation. These values represent the decay rate and methane potential for the inputs of the EPA LandGEM LFG generation model. In general, the results provide reasonable LFG generation estimates for the landfills that fit within the parameters of the study, which were landfills operating as a dry tomb, with precipitation falling within 12 to 54 inches per year, and general MSW is accepted for disposal.

The methane potential may be affected by the same factors that affect the decay rate, as noted above. Increasing moisture in the landfill through bioreactor technology will accelerate LFG generation, and may also lead to an increased methane potential. This is because liquids addition will provide additional nutrients to the bacteria decomposing the waste, allowing the waste to realize its full methane potential.[85] Additionally, waste depth may affect the anaerobic conditions and temperature where the

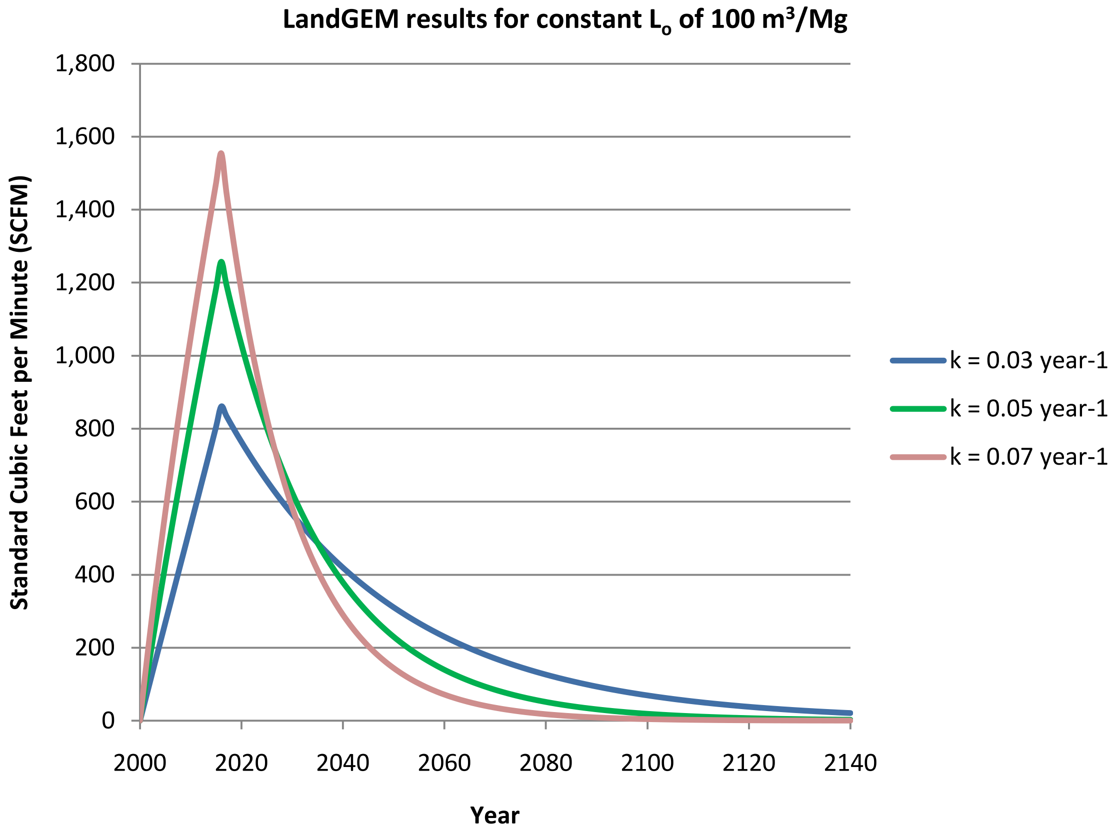
[83] Faour, et. al., 2005.
[84] Pierce, J., L. LaFountain and R. Huitric. *Landfill Gas Generation and Modeling Manual of Practice*. (2005). Solid Waste Association of North America.
[85] Pierce, et. al., 2005.

biological activity occurs. Waste near the surface will be more susceptible to ambient temperature and air intrusion, which will inhibit anaerobic conditions. For landfills with active collections systems, the operation of the system may also impact methane potential and methane production. Introducing air into the waste mass will create areas of aerobic decomposition, which will lead to lower methane production in those areas if, or when, they become anaerobic.

The empirical data presented above demonstrate that moisture has a large impact on the decay rate, and also has a slight impact on the methane potential of waste. However, for moderate variations in the decay rate, the effect on the methane potential is negligible. Therefore, it can also be assumed that for a given methane potential, a slight change in the decay rate will result in an accelerated LFG generation, and a rapid decline after peak generation. Therefore, over the life of a landfill, the total amount of LFG produced from a given unit of waste is generally thought to be equal, regardless of the decay rate.

This is demonstrated in Figure 9 below, where the area under each curve is equal. The areas under the curve represent the total methane generated over the life of the landfill. Although the LFG generation values will eventually approach zero, the results from the LandGEM model are provided for 140 years beyond initial waste placement, and therefore, the areas under all three curves are not identical in the given timeframe. In Figure 9, a constant methane potential of 100 cubic meters of methane per 1 megagram of waste is compared to decay rates of 0.03, 0.05 and 0.07 per year. The total calculated area under each of the curves is approximately 36,000 standard cubic feet per minute over 140 years.

Figure 9: LandGEM Modeling of constant L_o



5.3 Precedent for Calculating Baseline Emissions

Several well-vetted methodologies exist for calculating emissions from landfills, and are discussed individually in this section to highlight advantages and disadvantages of each.

5.3.1 Alberta *Quantification Protocol for Aerobic Projects*

Applicable to aerobic bioreactor projects, Alberta's *Quantification Protocol for Aerobic Projects* assumes that all methane produced by the landfill would have been vented to the atmosphere, even in cases where existing gas collection and control systems are removed. Alberta applies a Biochemical Methane Potential (BMP) assay calculation to estimate baseline emissions. This method operates by calculating at various times the maximum quantity of methane that could be generated from the waste if degraded under anaerobic conditions. The BMP variable L_o is calculated in units of $kgCH_4$ per tonne of waste, then multiplied by the estimated mass of waste in the landfill to estimate total potential methane emissions. As waste degrades, aerobically producing carbon dioxide instead of methane, the L_o value will decrease to the extent that the raw ingredients for methane production are removed through other processes.

By comparing the BMP value at the beginning of the project and, for example, one year later, the Alberta protocol estimates the amount of methane emissions that would have occurred if the waste had broken down under anaerobic conditions, setting this value equal to the baseline. The BMP methodology's strength is that a decrease in L_o provides a high level of certainty (provided the sample is statistically robust) that methane emissions have been precluded. If the project failed in the future and the landfill reverted to anaerobic conditions, the credited methane emissions could not be reversed because the necessary ingredients have been demonstrably removed from the system.

However, while the BMP methodology is capable of calculating the quantity of emissions precluded, it is not exactly calculating baseline emissions in a given year. Baseline emissions are those which would have occurred *in the crediting year.* Under aerobic bioreactor conditions, waste breaks down significantly more rapidly than under traditional management practices, and this expedited breakdown is directly linked to L_o values. If an aerobic bioreactor project operates for five years and achieves waste stabilization, then it will have achieved a level of L_o reduction comparable for 10, 20, or more years under traditional management. Accordingly, the BMP method would overestimate baseline emissions from the crediting period, including within those five years the emission that would have occurred over many more years.

Applying the BMP method to aerobic bioreactors is analogous to applying the Reserve Landfill protocol methodology to anaerobic bioreactors. The expedited breakdown that lowered L_o rapidly under aerobic conditions would similarly lower L_o under anaerobic conditions, only in this case the transformed L_o would actually result in captured methane emissions. Measuring the LFG collected from an anaerobic bioreactor in any given year would similarly result in measuring LFG that would have been emitted over a much longer time horizon in the baseline.

5.3.2 CDM AM 0083: Avoidance of landfill gas emissions by in-situ aeration of landfills

Unlike the Alberta protocol, AM 0083 includes provisions to account for instances where there may be baseline or mandated gas collection and control through application of an adjustment factor and compliance factor. These factors are applied only after baseline methane emissions representing the amount of methane generation in the absence of the project have been calculated.

AM 0083 applies a tailored method to calculate baseline emissions based on the *Tool to determine methane emissions avoided from disposal of waste at a solid waste facility*.[86] CDM 0083 applies a first order decay (FOD) model. Like the Alberta methodology, this requires beginning with an L_o value that represents the methane production potential of the waste. However, rather than compare L_o from year to year, the FOD model applies a decay factor to estimate annual emissions in each subsequent year according to a constant, site specific rate of decay and initial methane potential. The primary advantage of the FOD model is that it can be run according to conditions at the landfill *in the absence of* the project and calculated baseline emissions are not dependent on project-influenced site conditions.

One disadvantage of the FOD model is its level of uncertainty (See Section 5.4) AM 0083 applies a correction factor (R) to modeled baseline emissions to correct for some of the uncertainty introduced through modeling. Prior to project initiation, AM 0083 requires execution of a baseline campaign of at least three months in which emissions are both modeled according to the FOD model, and metered

[86] UNFCCC. *Tool to determine methane emissions avoided from disposal of waste at a solid waste disposal site, Version 05.1.0*.

using on site equipment. If measured emissions are lower than modeled emissions, then subsequent baseline estimations must be scaled down by the ratio calculated during the baseline campaign. If measured emissions exceed modeled emissions, no adjustment is made.

The use of a practice-independent FOD model to calculate baseline emissions and adjustment factor to field validate the model represents a significant improvement over the Alberta protocol if the goal is to be temporally consistent. The baseline will not be artificially inflated due to rapid waste stabilization, and uncertainty is diminished through execution of a baseline campaign. Finally, while AM 0083 was written for aerobic projects, the baseline methodology could be extended for use in anaerobic facilities as well.

5.3.3 Reserve Organic Waste Protocols

Whereas the Landfill protocol did not require baseline modeling, both the OWD and OWC protocols model baseline emissions that result from landfilling. Of course, rather than achieve reductions through methane destruction or avoidance associated with landfill management practice, the point of intervention for these protocols is further upstream, but the methodology is generally consistent.

These protocols vary significantly in how project emissions are monitored and quantified, but both the OWD and OWC protocols utilize a FOD model to quantify baseline emissions. The Reserve's FOD calculation is derived from the *Tool to determine methane emissions avoided from dumping waste at a SWDS*[87], adjusted for multi-year aggregation. The FOD model quantifies baseline emissions based on a user-inputted methane potential (L_o) and decay rate (k). Methane potential is a waste-specific variable corresponding to the amount of methane that could be produced if the waste was broken down entirely under anaerobic conditions, and the decay rate is driven by the climatological conditions of the modeled landfill and representing how rapidly waste breaks down.

FOD models will be discussed in the following section with other options.

5.4 Options for Modeling Baseline Emissions

Baseline LFG generation estimates can be calculated using a variety of modeling techniques. Depending on the information available for inputs and the intended use of the model, the model can be straightforward or significantly complex. As previously noted, LFG generation is the result of a dynamic process driven by site and waste conditions, time, and treatment, and is estimated using a combination of inputs based on assumed or empirical values.

Note that methane generation and LFG generation are sometimes used interchangeably in the literature. However, the LFG generation models presented below provide estimates of methane generated, unless otherwise noted. Landfill gas is typically considered to be 50-percent methane by volume, therefore the methane generation estimated is 50-percent of the total LFG volume or the total LFG volume is two times that of the model results. When measuring methane from actual field data, a

[87] UNFCCC. *Tool to determine methane emissions avoided from disposal of waste at a solid waste disposal site, various versions*.

total mass flow meter and gas analyzer is required to measure methane content in the LFG in order to calculate actual methane volume.

The basic LFG modeling techniques are listed below:[88]

- **Zero-order model[89]** – LFG generation is constant over time and the age of waste is neglected. Other model items to note:
    - Gas generation is a function only of the methane potential, L_o.
    - The methane potential is held constant for all waste disposed over the life of the landfill.
- **First-order model[90]** – the age of waste is included and LFG production for a given unit of waste declines exponentially over time. This type of model assumes the highest period of generation is immediately upon disposal, unless a lag factor is included. Other model items to note:
    - Gas generation is a function of a rate of decay and the methane potential, k and L_o, respectively.
    - The methane potential and decay rate value are held constant for all waste disposed over the life of the landfill.
- **Modified first-order model[91]** – similar to the first-order, except that LFG generation is initially lower, then increases to a maximum before exponentially decreasing. This model assumes that LFG generation occurs immediately, but the initial amount is lower. Other model items to note:
    - The decay rate value and methane potential value are similar to that for the first-order model, k and L_o, respectively.
    - The equation includes an additional coefficient constant that reduces initial LFG generation. This works in the same sense as a lag time period, but instead of representing the lag time as a zero value, it applies some gas generation to the lag period.
- **Multiphase Model[92]** – uses two rates of decay for different periods of the life of a given unit of waste. The model establishes different decay rates for differing fractions of waste types with varying rates of decomposition. The fraction of waste that more rapidly decomposes (food, wood, and yard waste) has a higher decay rate, the fraction of waste that more slowly decomposes (textiles) is assigned a smaller decay rate. This is generally applied to only two

[88] Faour, et.al., 2005.
[89] Solid Waste Association of America (SWANA). *Comparison of Models for Predicting Landfill Methane Recovery*. (1998) Publication #GRLG 0075.
[90] SWANA, 1998.
[91] SWANA, 1998.
[92] SWANA, 1998.

types of waste, but could in theory be expanded to include additional fractions. The methane potential is held constant for all waste types . Other model items to note:

- The methane potential is similar to that under the above first-order models, L_o.
- The fractions representing different variations of decomposable waste are represented by F_1 and F_2.
- The decay rates for the differing fractions are applied accordingly as k_1 and k_2.

- **Second-order Model**[93] – includes multiple scenarios of FOD reactions happening at different rates. It is similar to a multiphase first-order model, but includes a large number of first-order reactions. This model technique increases in complexity as it takes into consideration different parts of the waste that are decaying and producing differing amounts of LFG at different times. For example, a given unit of waste may decay at a higher rate initially, and then the rate at which it decays will lessen over time. Whereas, the multiphase first-order model assigns a single decay rate to a given unit of waste for its life in the landfill.
- Additional models have been developed that are some variation or combination of the above.[94]

Specific derivations of LFG modeling include the following:

- **US EPA LandGEM**[95]. LandGEM is a FOD model created and managed by the US EPA, and is one of the most popular and widely used. Common uses include estimating initial LFG generation and regulatory reporting. LandGEM uses three inputs to quantify LFG generation estimates: tons of waste placed, the methane potential per unit mass, and the decay rate. For purposes of regulatory compliance, the model includes default values that can be used, though site-specific values for methane potential and decay rate are needed in order to make the model useful for estimating actual LFG production. However, as noted above, for a given unit of waste, different decay rates will apply at different times over the course of the landfill life. LandGEM is designed to only allow inputs for single decay rate values and methane potential values that are assumed constant over the life of the landfill. In reality, there may be different decay rates occurring in different areas at the same time. It may not be reasonable to assume a single umbrella decay rate for the entire life of a landfill. For GHG offset accounting purposes, LandGEM may provide reasonably accurate estimates (within 50 percent) of traditionally operated (dry tomb) landfills. However, as the dynamics of the landfill increase with liquid addition, it becomes more difficult to use LandGEM to model these changes.

[93] Weekman, V.W. and D.M. Nace. American Institute of Chemical Engineers, Vol. 16 (3), pp.397, 1970.
[94] Faour, et.al., 2005.
[95] Thorneloe, S.A., et. al. *The U.S. Environmental Protection Agency's Landfill Gas Emissions Model (LandGEM)*. (October 1999). Proceedings of Sardinia 99 Sixth International Landfill Symposium, Volume IV-Envionmental Impact, Aftercare and Remediation of Landfills, Pages 11-18.

- **Scholl Canyon Model**[96] - The Scholl Canyon Model is a FOD model similar to LandGEM that is used to estimate methane generation. It assumes no lag period and that methane generation peaks immediately then follows with exponential decay. The difference between the Scholl Canyon Model and LandGEM is in the determination of the methane potential value.

- **Palos Verdes Model**[97] – The Palos Verdes Model is a two phase FOD model. This model includes an initial phase in which the gas generation rate increases exponentially followed by a phase of exponentially decreasing. The model also takes into consideration different fractions of varying organic degradation (for example, highly degradable and moderately degradable). The first phase of generation represents decomposition of the readily degradable waste, and the subsequent phase represents the decomposition of the moderately degradable waste. The model also assumes that the amount of LFG generation in the initial phase is equal to the second phase.

- **GASFILL Model**[98] –GASFILL is a two phase model that incorporates an initial lag time factor. The GASFILL model assumes that the readily decomposable waste rapidly produces LFG resulting in a hyperbolic spike initially, and is then followed by an exponentially decreasing decay phase as the less readily degradable waste decomposes.

- **LFGGEN Model**[99] –LFGGEN is a multiphase model that incorporates a lag time factor. The first phase of methane generation is estimated to increase linearly and the second phase is a FOD that decreases exponentially. The model also incorporates additional variables, including moisture content assumptions and biodegradable waste types and variations.

- **Proprietary Models** – Propriety LFG generation models exist. However, these are generally used for specific landfill needs, such as modeling LFG generation rates for commercial purposes or LFG reuse projects. While these may result in more accurate estimations, a high level of effort and site-specific data are required. This includes using all the site specific data listed for the above models to create a general baseline model. Additional information that can be used include waste placing methods, daily cover material and placement and actual liquid recirculation values. The baseline model can then be adjusted based on field tests of LFG extraction from the landfill. For landfills that have active collection systems, this would be using the collected data from the system and an estimated collection efficiency to adjust the model. The model would likely be more representative for future estimates. This procedure is likely to continue for several years to create a LFG generation model that is more accurately able to predict future generation. For landfills without active collection systems, this can be performed by completing extraction tests at specific locations throughout the landfill. Generally, this

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[96] EMCON Associates, *Methane Generation and Recovery from Landfills*. (1980). Ann Arbor Science Publishers, Inc.
[97] Faour, et.al., 2005.
[98] Findikakis, A.N., et. al. *Modeling Gas Production in Managed Sanitary Landfills*. (1988). Waste Management and Research, Vol. 6, pp. 115-123.
[99] Keely, D. K. H. *A Model for Predicting Methane Gas Generation from MSW Landfills*. (1994). Thesis, Department of Civil and Environmental Engineering, University of Central Florida, Orlando, Florida.

consists of drilling a test well and applying a small blower system to extract LFG as though it were part of an active gas collection system. The results obtained from these tests can be applied similarly to those noted above, though there is generally no method to independently verify these models.

5.4.1 Uncertainty

In general, any of the above modeling methods can be used, but the results are given with a wide margin of accuracy (up to 50 percent error) due to a variety of reasons. Some of the reasons for the inaccuracies include:

- Errors or inaccuracies in waste tonnages and types of waste
- Inaccurate variable assumptions
- Variability in the nature of the decomposition due to:
    - Areas of high or low moisture
    - Lack of homogeneity
    - Presence or lack of presence of inhibitors or nutrients

For bioreactor, or wet, landfills, the increase in moisture content will result in an increase in the decay rate of decomposition. This is demonstrated when using any of the modeling techniques listed above, with the exception of the zero-order model. Since the timing and rate at which liquids are added will affect LFG generation, it is difficult to estimate using a single phase first-order decay model, unless multiple combinations are used and then aggregated. However, even in this case, LFG generation is difficult to model. For a given unit of waste that is deposited, there will likely be a brief period of aerobic decay while exposed or near the surface, and the moisture content of the waste will likely be lower than optimal until it reaches a depth suitable for liquids addition. The addition of liquids will provide an initial increase in moisture content. Therefore, a single unit of waste will likely encounter multiple decay rates over the first few years following placement.

Landfill gas modeling for regulatory reporting is typically completed using the FOD LandGEM equation (or combinations). The FOD model is able to produce reasonable estimates of LFG generation within a margin of error up to 50 percent. For any model technique to provide reasonable LFG generation values, site-specific data are required. In order to obtain site-specific data, accurate records of waste tonnages, organic waste fractions, moisture content, liquids additions (if any), and others are needed.

- The tonnage input values are usually obtained from scale records. Some facilities dispose multiple waste types in the same landfill, such as MSW, industrial, C&D, contaminated soils, and others. Generally, organic components of MSW are the main source of LFG. In order to provide further detail, a waste characterization study may be performed to find the potential amount of organic content in the MSW stream. General estimates provided by the EPA may be used for organic content if actual data are not available.

- The methane potential is related to the amount of organic content in a given unit of waste. Assumptions for this value can be made using documented information from various studies that exist, and the methane value used will depend on the model used. For LandGEM, values are estimated using data prescribed in the CAA, although the user may input known site-specific values, which are obtained from laboratory tests of actual landfill waste. Field samples may be obtained from drilling into the waste mass, or may be collected from the landfill working face (for example, the active area of waste deposit). This sampling method will require knowing the approximate age of the waste and types of waste deposited in the area.

- The decay rate value depends on the type of organics in the waste and the moisture content of the waste. EPA provides default values based on climate. However, liquids addition can result in a different value than those presented by EPA.

- The 2005 study by Reinhart, et al., provides empirical data that can be used for generating a first-order decay model.[100,101]

Values for the organic fraction are generally taken from waste characterization studies or may also be obtained from directly collecting a sample of waste from the landfill working face. Using these samples, methane potential maybe determined in a laboratory. Moisture content may be estimated by taking field samples. Waste moisture content is estimated using records of liquids addition and volume removed through the landfill leachate collection system. It should be noted that because incoming waste is heterogeneous, the sample may not be representative of the entire waste stream, and assumptions are required to apply sample data to the entire waste mass.

5.5 Precedent for Calculating Project Emissions

In addition to quantifying baseline emissions, a Reserve protocol for aerobic and anaerobic bioreactors would need to accurately account for GHG emissions that occur during project implementation. The existing Landfill protocol accounts for the following project emission sources:

1. Emissions from the use of purchased electricity

2. Emissions from the use of supplemental fuels

Emissions from surface fluxes of methane are not explicitly quantified in the Landfill protocol because these emissions are assumed to be emitted in the baseline as well at equal quantities. However, for aerobic and anaerobic bioreactor projects these emissions must be accounted for. Anaerobic bioreactors will increase methane generation in the short-term, as discussed in the discussion of baseline emissions. As a result, if an LFG collection system has an efficiency of 80 percent, for example, then the uncaptured 20 percent of LFG may increase in direct proportion to the annual increase in overall LFG generation. If annual methane generation doubles, then project emissions from methane

[100] Reinhart, et al., 2005.
[101] Faour, et.al, 2005.

surface fluxes may as well. This may represent a temporal shift in when fugitive emissions occur, increasing near-term emissions even if total fugitive emissions for the life of the landfill remain constant. Given the Reserve's preference to avoid forward crediting, this increase could be quantified and mitigated in one of two ways:

1. Quantify surface flux emissions based on an assumed LFG capture efficiency. This efficiency could be based on standard protocol assumptions, or derived from engineering specifications. The efficiency could be applied to the quantity of collected LFG and used to estimate un-captured LFG.

2. Measurement of surface flux. This option requires direct or indirect monitoring of emissions, and is discussed in Section 5.6.

Monitoring surface emissions from aerobic bioreactor projects is important for another reason as well. These projects are intended to avoid methane emissions altogether rather than collect and destroy methane, and it is therefore extremely important to ensure that project activities are having the intended effect of reducing methane emissions. The Reserve OWC protocol recognizes this performance concern and includes requirements for Best Management Practices, and also quantifies project methane and nitrous oxide emissions using default emission factors for specified composting processes.[102]

In addition to precedent in the Reserve OWC protocol, the two aerobic bioreactor protocols from Alberta and the CDM also contain rules for quantifying project emissions.

5.5.1 Alberta *Quantification Protocol for Aerobic Projects*

The Alberta *Quantification Protocol for Aerobic Projects* requires that project developers perform continuous methane monitoring in order to properly account for emissions from the bioreactor system. Specifically, requirements in the Protocol's applicability section that address LFG monitoring include provisions that:[103]

- The landfill or applicable landfill cells must be covered to minimize fugitive methane releases
- Monitoring of the methane concentration and flow in the venting wells must be maintained consistently
- Monitoring must be maintained at a minimum five-day frequency during shut-downs of the aeration system
- Fugitive methane emissions must be measured four times per year using a flux chamber to calculate the flow rate and methane concentration of passive landfill emissions. These measurements must be approximately three months apart to account for seasonal variations

5.5.2 CDM AM 0083: *Avoidance of landfill gas emissions by in-situ aeration of landfills*

CDM AM 0083, *Avoidance of landfill gas emissions by in-situ aeration of landfills,* which applies only to aerobic bioreactors, requires monitoring of various parameters in different phases of the project, as shown in Table 11, below.

[102] Climate Action Reserve, *Organic Waste Composting Project Protocol Version 1.0* (June 2010)
[103] Alberta Environment, 2008. Page 4.

Table 11: Overview of monitored parameters in both project phases. Table reproduced from UNFCCC CDM AM 0083.

Parameter	Monitored?	
	Air-injection Phase	Post-injection Phase
Vented emissions – volume, methane and nitrous oxide emissions	Yes	No
Surface emissions - volume, methane and nitrous oxide emissions	Yes	Yes

In order to monitor actual methane emissions from the landfill, CDM requires that vented and surface methane are measured. Surface emissions must be monitored in both the air-injection and post-injection phases, while vented emissions must be monitored in the air-injection phase alone.

For vented emissions, both methane and nitrous oxide concentrations must be continuously monitored. The monitoring system used to measure these parameters must be installed in accordance with the German VDI Guideline 3860, part 2.7.[104] For surface emissions, CDM allows both passive and active flux boxes, with quarterly measurements at a minimum. Monitoring flux boxes must adhere to German VDI Guideline 3790 or to the guidance from the UK environment agency.[105,106,107]

5.6 Calculating Project Emissions for Aerobic Bioreactors

As indicated in the Alberta and CDM methodologies, monitoring of surface fluxes or emissions can be done using a variety of methods. This section discusses the various options, costs, and uncertainties associated with measuring project emissions not covered by the Landfill protocol. There are two distinct options for monitoring surface emissions: surface emission factor methods, and mass flux methods. Surface emission factor methods take measurements from a portion of the total area, and then require extrapolation of the measurements to apply to the rest of the landfill area. Mass flux methods are able to capture a whole picture of the emissions from the landfill. It should be noted that surface emissions may also be estimated by collecting a sample of the LFG generated within the waste mass and applying factors to account for conditions that affect the fate and transport of the generated gas through the landfill surface. The factors would depend upon the landfill cover profile and materials, and would need to be based on engineering specifications.

The waste composition within a MSW landfill is heterogeneous, and therefore waste decomposition rates will vary in different areas of the landfill. As a result, the emissions from the landfill surface will vary from location to location. Additional factors affecting surface emissions include the profile and material of cover soils, cracks in the surface soils, direct conduits to the surface (passive gas vents) and atmospheric conditions. These factors may result in a sample that is not representative of entire landfill emissions if measurements are obtained from only specific locations on the landfill surface. Surface emission factor methods utilize multiple samples from different areas of the landfill to provide an

[104] UNFCCC CDM AM0083. Page 20.
[105] UNFCCC CDM AM0083. Pages 20-21.
[106] VDI Guideline 3790 *Environmental meteorology - Emissions of gases, odours and dusts form diffuse sources; Part 1 Fundamentals*. (2005); *Part 2 Landfills* (2000).
[107] Environment Agency: UK. *Guidance on monitoring landfill gas surface emissions.* (September 2004).

overall average of mass flux emissions. The mass flux methods are designed to include the entire landfill footprint at once to provide an overall average of emissions. Since atmospheric conditions (barometric pressure, wind speed and direction) have an impact on emissions, measurements are usually taken over a period of time (from a week up to two months) to obtain a more representative result.

5.6.1 Surface Emission Factor Methods

Surface emission factor methods gather empirical data from a portion of the overall landfill, and make various assumptions to extrapolate the collected data to the entire landfill. Most importantly, emission factor methods assume uniformity across the landfill: emissions per unit area calculated from the monitored area represent the emissions for the entire landfill. Unless emissions are measured over an area that captures both covered and non-covered waste, the measurements may be skewed. If taken from a closed area, it will not include emissions from the working area, and thus the results will be lower than actual, and vice versa for the working face area. Because of this possible skew, the measured results may not be useful for extrapolation. As a result, emission factor methods will be most applicable to landfills that are relatively uniform in waste characteristics, age, geology, and operating status.

Flux Chambers

Flux chamber sampling methodology uses canisters that are placed at predetermined locations around the landfill to mechanically collect samples. Sample emissions and constituents are then measured with a gas chromatograph.

Flux chambers can only collect samples from areas having intermediate or final cover, and the method cannot be used in the working face area. Therefore, the results may be limited when trying to extrapolate. Also, the canisters collect samples at small, specific locations. The quantity and sampling frequency of the flux chamber placement would depend on the accuracy requirements. For a general rule of thumb, NSPS requirements for NMOC emission monitoring requires 2 sample locations per hectare. For purposes of quantifying total landfill emissions, the samples per area could be increased. In order to capture a large area, additional canisters are needed which requires significant manpower and will increase the costs for performing the tests.

Costs for performing the laboratory testing of the collected samples can be as much as $300 per sample. Additional costs for obtaining and applying the field test equipment and a report need to be included. Assuming one test per acre over a 20-acre site, costs would likely exceed $15,000.[108]

Vertical Radial Plume Mapping

VRPM is a variation of TDLAS that is commonly used to measure surface flux of large ground areas, usually around several hundred square meters. The method utilizes tunable diode lasers and receivers to measure the emission flux from non-point sources over a specified area. The wavelength of the lasers is “tuned” to a target gas’ wavelength. If the target gas is present, a portion of the laser’s intensity will be absorbed and the remaining intensity is detected by specialized receivers called retroreflectors. It is then quantified using computer software. The laser is usually set up to measure a single target gas at a

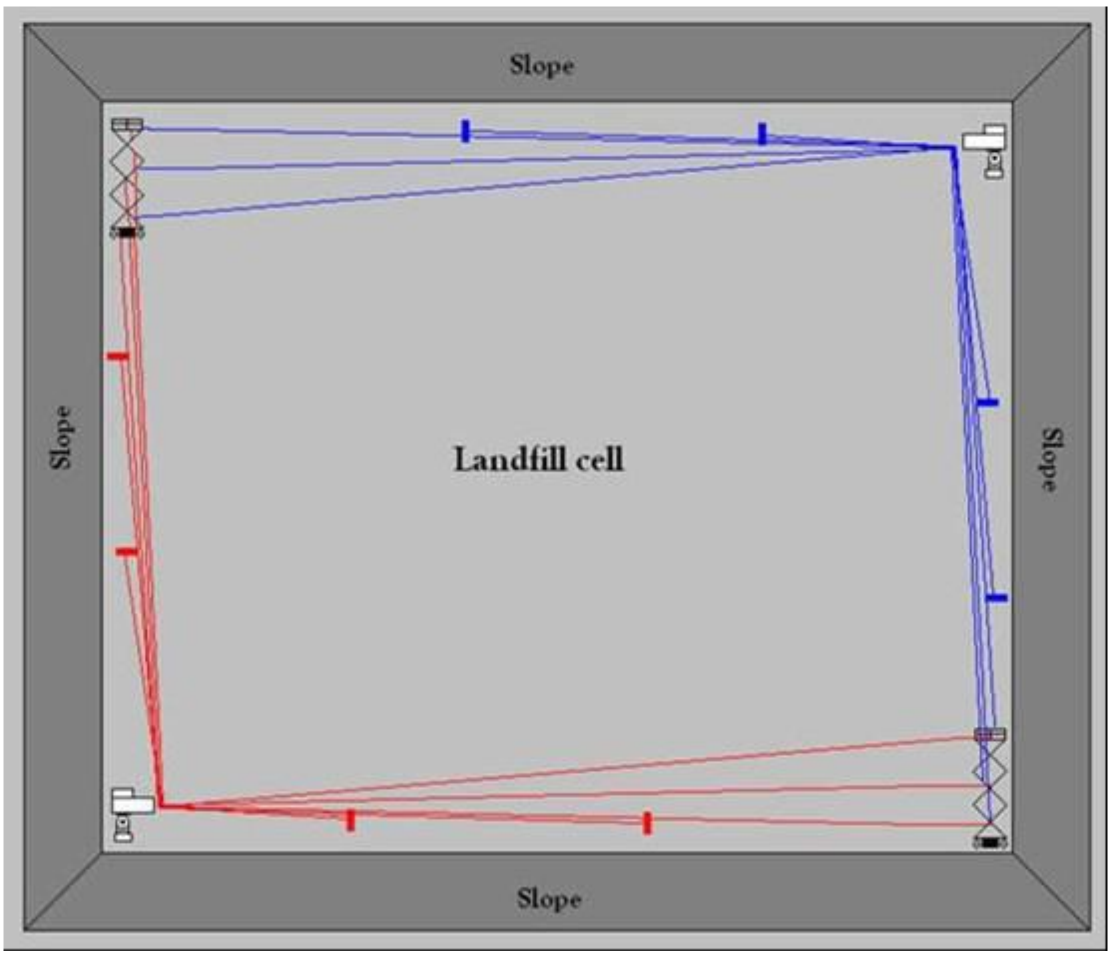
[108] Valdez Air Quality. *Air Monitoring Options for Measuring Benzene Concentrations in Valdez*. (March 2003).

time by being "tuned" to the target gas wavelength. For landfills, the target gas is usually methane, but additional species can be measured including carbon dioxide, nitrogen oxides and hydrogen sulfide.

The VRPM method has been employed at landfills for research purposes. In general, this method requires two lasers placed in opposite corners of a square with retroreflectors placed on the adjacent corners in a "four corners" set-up, see Figure 10. Scissor-lift equipment (shown in the upper left and lower right of Figure 10) is required on the ends with reflectors. The VRPM method detects a range of emission measurements and compiles a total mass flux for the area measured.

Costs for testing with optical sensing equipment such as VRPM can be up to or more than $30,000 per test. The equipment used in tests can be over $100,000, but is usually rented during a test.[109]

Figure 10: Schematic of Landfill VRPM, Obtained from EPA 2007



Obtaining accurate results from VRPM generally requires a large area (300 meters by 300 meters) that is relatively flat (less than five percent slope), with larger areas yielding more accurate measurements. In a study by Babilotte and colleagues, VRPM was able to provide a measurement of flux emissions for the

[109] US EPA. *Evaluation of Fugitive Emissions Using Ground-Based Optical Remote Sensing Technology*. (February 2007). EPA #600-R-07-032.

area monitored within a 50 percent error.[110] However, the accuracy depends on the size of the area measured, the topography, and wind speed. Additionally, VPRM is limited in its ability to accurately measure side slope emissions, which is generally where most of the landfill emissions occur. Instead, the software uses wind speed and direction associated with measurement timeframe to calculate side slope flux values. And because the areas measured by VRPM are generally those having soil cover, this method is not practical for monitoring emissions from the active or working face areas of the landfill due to the constant activity on that area. As such, VRPM may be most suitable for monitoring surface fluxes at closed landfills with relatively uniform characteristics and lacking active or working faces that may adulterate results.

Micrometeorological eddy-covariance

MicroMet uses a procedure similar to that of the VRPM to take measurements from a known footprint smaller than the whole landfill. A stationary tower at a known distance, equipped with sensor equipment, takes measurements at rapid intervals of approximately 10 Hertz and calculates the flux for the area observed. Since the measurements are taken for only a portion of the landfill, they are given as emissions per unit area. Because of the nature of this method, the spatial variability has a large impact on the readings. Although flux chambers and VRPM are affected by this variability, the MicroMet method relies on the assumption that the emissions are homogenous.[111] In order to account for the assumption of homogeny, the measurements are usually taken over a period of a month or longer to average out any heterogeneity.[112]

As with the other methods that monitor conditions over a distance, MicroMet is subject to variations with wind speed, wind direction, and topography. The procedure to measure surface flux is relatively simple, but the results obtained may not allow for extrapolation. In addition, if there are areas in the monitored zone that have increased methane emissions (for example, a leaking gas well or a crack in the surface), the results may not necessarily be applicable to the entire landfill.

Costs for MicroNet testing, which would include equipment rental and reporting, would likely range from $20,000 to $30,000 for a site test and report[113]. Equipment costs can range up to $60,000 if purchased, but would likely be rented or leased for a portion of that total costs. Additional costs would be for services associated with testing and documentation.

5.6.2 Mass Flux Methods

Mobile Plume Fourier Transformed Infrared (FTIR) spectroscopy

FTIR is a form of a tracer gas method. This method uses a release of a controlled amount of a known tracer gas at target points around a landfill. In the 2010 Babilotte study evaluated, the tracer gas used was nitrous oxide.[114] Extractive sensors that use a multi-pass cell are mounted onto a vehicle that

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[110] Babilotte, et.al. *Field Intercomparison of Methods to Measure Fugitive Methane Emissions*. (2010).
[111] Huitric, Raymond and Dung Kong. *Measuring Landfill Gas Collection Efficiency Surface Methane Concentrations*. (2006). Whittier, California.
[112] Babilotte, et.al, 2010.
[113] LI-COR Biosciences. Personal communication to M. Cook, December 2011.
[114] Babilotte, et.al, 2010.

traverses a pre-determined path at a specified distance from the landfill. The cells are designed to measure methane and the nitrous oxide. With atmospheric conditions known (wind speed and direction), the concentration of nitrous oxide is used to calculate the dispersal of the landfill emissions (in this case, methane). This method must be set up to account for wind speed and direction, but can measure emissions from the whole landfill surface.

Using a tracer gas to measure surface emissions requires optimal conditions. In order for the sensors to accurately complete measurements, the wind speed and direction must be continuously monitored, and the topography must be relatively uniform or flat from the landfill to the sensor equipment. There should be a relatively clear line of sight with minimal obstructions. The great distance needed between the landfill and the sensors, may result in interference from an outside source of methane. The measured methane concentration in conjunction with the calculated dispersal of the tracer gas are used to calculate the total landfill methane emissions.

Equipment rental costs to conduct tests, along with reporting costs would likely exceed $30,000.[115]

Differential Absorption LiDAR (DiAL)
The DiAL method uses a pulsed laser radiation directed towards the area to be monitored. The radiation is disturbed by variations in the constituents of the atmosphere above the target area. Knowing the distance to the area and the pulse frequency, gas concentrations of a particular type can be measured by tuning the laser wavelength to that of the target gas. Computer programs interpret the measurements to obtain readings of landfill emissions.

The equipment used in DiAL requires a significant and clear line of site, thus requiring relatively flat topography with no obstructions (trees or structures). The equipment is placed between approximately 400 meters and 800 meters from the target area. The time required to take the measurements is generally less than 30 minutes, calm or uniform wind conditions through the line of sight are required, and variations in the topography can create areas of unstable wind. The DiAL method is able to provide relatively useful data, provided the ideal conditions are met.

For testing, similar equipment is used for LiDAR as for VRPM. However, costs are likely increased for LiDAR testing due to additional equipment which may be needed.[116]

Direct LFG Sampling
As mentioned previously, another potential method for estimating landfill emissions is to take a direct sample of the gas generated within the waste mass and apply assumed factors to account for the gas generation rate and transport through the landfill cover as surface emissions. A sample of the LFG may be collected through installed surface probes, from a passive gas vent or if an active gas collection system is installed, from a sample port in the system. These are common sampling practices performed for NSPS Tier 2 NMOC testing. For estimating methane emissions, a default value is applied to account

[115] US EPA. *Evaluation of Fugitive Emissions Using Ground-Based Optical Remote Sensing Technology*. (February 2007). EPA #600-R-07-032.
[116] US EPA 2007.

for methane oxidation through bacteria present in soil as the LFG travels through the cover material. A factor of 10 percent is commonly used for this oxidation factor, though recent industry research suggests this value may vary significantly depending on cover material and site conditions. It should also be noted that recent industry studies have not demonstrated a direct correlation between surface flux and LFG generation.[117]

Monitoring of surface flux or mass flux from landfills will depend highly on atmospheric conditions. Each of the methods described above have limitations associated either with atmospheric conditions or an inability to be extrapolated because the test area may not represent the whole. In field tests for the above, it is shown that the methods show minimal repeatability.[118] Regardless of the method used, the results obtained from emissions monitoring are limited to the specific time in which they were obtained since overall emissions are affected by a variety of factors included atmospheric pressure, soils in the waste, and where the testing occurred.

A Landfill is a dynamic system that undergoes a variety of decomposition processes over its life. As a result, there may be variations in measurements depending on the location at which the measurements are taken, the length of time over which the measurements are taken, the time of year, or weather conditions. Results from field testing show a range of variation from five percent for the Tracer method to 400 percent for the Flux Chamber method.

The two mass flux methods appear to provide a smaller variation in measurements. For estimating entire landfill emissions, field testing has demonstrated that the DiAL method or the Tracer Gas method would likely yield the most consistent results. However, because of the variability in emissions, a single sampling may not produce a representative emission value. Rather, multiple sampling events would likely be needed to generate a more realistic emission rate.

[117] Goldsmith, C.D., et. al. *Methane Emissions from Temperate Zone Bioreactors in the United States as Measured by OTM-10*. (2010).
[118] Babilotte, et.al, 2010.

Issues Summary

Table 11, below, provides a summary of various methods described above.

Table 12: Summary of Emission Testing Methods

Test Method	Cost	Test Variability[1]	Test Range[3]	Testing Time[6]	Testing Effort
Flux Chambers	~$15,000	100 – 400%[2]	<5%[4]	<1 week	Dependent upon testing density and may require intensive labor efforts
VRPM	>$30,000	10 – 90%[2]	~15%[5]	<1 week	Equipment set up may require intense labor, but actual effort during testing is limited.
MicroMet	>$25,000	>30%[2]	~30%	>30 days	Effort is focused on maintaining equipment during long testing timeframe.
FTIR	>$30,000	5 – 15%	Whole Landfill	<1 week	Mobile measuring equipment is required during the testing period
LiDAR	>$30,000	20 – 50%	Whole Landfill	<1 week	Effort is focused during equipment set up and labor required for set up and testing is limited

[1]Test Variability means spatial variations in similar testing methods and variations from test to test at different times for the same area. The higher the number means there is a greater difference between testing. The variability in the FTIR and LiDAR methods are low because these methods measure the entire landfill. Information from Babliotte, et. al. 2010

[2] The variability for all Flux Chambers, VRPM and MicroMet can be greatly impacted by cracks in the services and by passive venting that allow for direct conduits of emissions into the atmosphere.

[3] Test range refers to the total area of the landfill that is measured.

[4] The range for Flux Chambers is highly depended on the density of testing.

[5] The range for VRPM testing is depended upon the size of the crown of the landfill relative to the area of the side slopes. This value can vary depending on the landfill's shape.

[6] The testing time refers to the time to perform a single set of testing. In order to minimize potential spatial, seasonal, and atmospheric variability, multiple tests are likely needed.

6 Additional Protocol Considerations

This final section discusses a variety of issues related to protocol development for aerobic and anaerobic bioreactor projects. These issues are generally non-technical in nature, and relate to policy considerations, gaming, and logistics of developing protocols.

6.1 Interaction with Existing Reserve Protocols

The Reserve's three waste-related project protocols have been discussed throughout this paper as they relate to aerobic and anaerobic bioreactors. Generally, these protocols provide valuable precedent. However, if the Reserve moves forward with a protocol for aerobic and anaerobic bioreactors, the following issues should be specifically addressed:

Gaming: As discussed in Section 4, eligibility and quantification rules should be constructed so that activities or emissions that are not currently creditable under the Reserve's landfill protocol are not creditable under a bioreactor protocol. Although the risk is abstract and difficult to judge, a project that is not eligible under the Reserve's current standards should be prevented from gaming the system and receiving otherwise non-additional offset credits through a bioreactor protocol.

Perverse Incentives: Another abstract risk exists when a bioreactor protocol is considered in the context of the Reserve's OWC protocol. In particular, it is possible that increased use of bioreactors could impact the relative incentives for traditional composting projects. Increasing the readily-degradable portion of waste entering a bioreactor would be incentivized by the ability to receive offsets for the avoided methane emissions. If this were the case, waste streams that may otherwise have been composted – a practice with many non-GHG benefits – could instead be landfilled in bioreactors.

6.2 Temporal Crediting Fidelity

As a technical matter, this paper makes clear that in both aerobic and anaerobic bioreactors methane is either produced, or precluded from being produced, more rapidly than in traditional landfills. This means that in any given year baseline emissions would be less than the amount of gas destroyed in an anaerobic bioreactor project, or precluded by an aerobic project. To resolve this issue, baseline quantification methods that deviate from the current Landfill protocol have been discussed in Section 5. Instead of using these methods, there is a valid policy question as to whether temporal fidelity matters, or whether some variation may be permissible. Indeed, operating a bioreactor intensively for five or ten years (or less) may be more effective in the long-run than operating a traditional landfill project for a variety of reasons.

Most importantly, the large majority of methane would be destroyed or precluded while the landfill is being actively managed as a bioreactor. Methane production at traditional landfills tapers off more gradually, and gas collection and control systems may be shut down when volumes drop. Although the emissions after the gas system is shut off might not be credited by the Reserve under its ten-year crediting period, these emission reductions may be considered real and permanent. Additionally, bioreactors can be implemented in active cells more readily than traditional landfill projects, and are able to capture methane that would escape traditional projects.

The Reserve has permitted some temporal disconnect in several of its protocols. The OWD, OWC, and Ozone Depleting Substances[119] protocols credit precluded emissions that would have been emitted over a ten-year period. This construction is consistent with a ten-year crediting period, and may be readily adaptable to bioreactor projects. There are two potential options that are conceptually consistent with the Reserve's ten year crediting period, and which would provide for emissions reductions to be generated for reductions of GHG emissions that would have occurred after bioreactor operation cessation.

Annual Crediting of Avoided Crediting After Project Cessation

Section 5 of this paper discussed options for calculating annual avoided emissions based on models such as EPA LandGem. One option for the Reserve may be to allow projects to continue to quantify and verify emissions reductions according to a temporally consistent model even after bioreactor operations cease. Under this system, projects would receive offsets while the project is operational for only the quantity of emissions calculated for baseline conditions. For subsequent years, the project may not be operational because methane potential has been effectively diminished. However, because of reduced methane potential in the initial years, emissions even after termination of project activities may remain below calculated baseline levels, and this difference could be issued as offsets.

One complication of this approach would be in quantifying project emissions at the landfill site after bioreactor activities are terminated. Some surface emissions would be expected to occur even with greatly diminished methane potential, and these should be quantified and subtracted from modeled baseline emissions to ensure no over-crediting occurs in post-bioreactor years. This baseline monitoring could be conducted using the same techniques outlined in Section 5, though this could introduce significant costs. Alternately, the Reserve could apply default emissions assumptions based on historical surface fluxes measured during the years in which the bioreactor was operational.

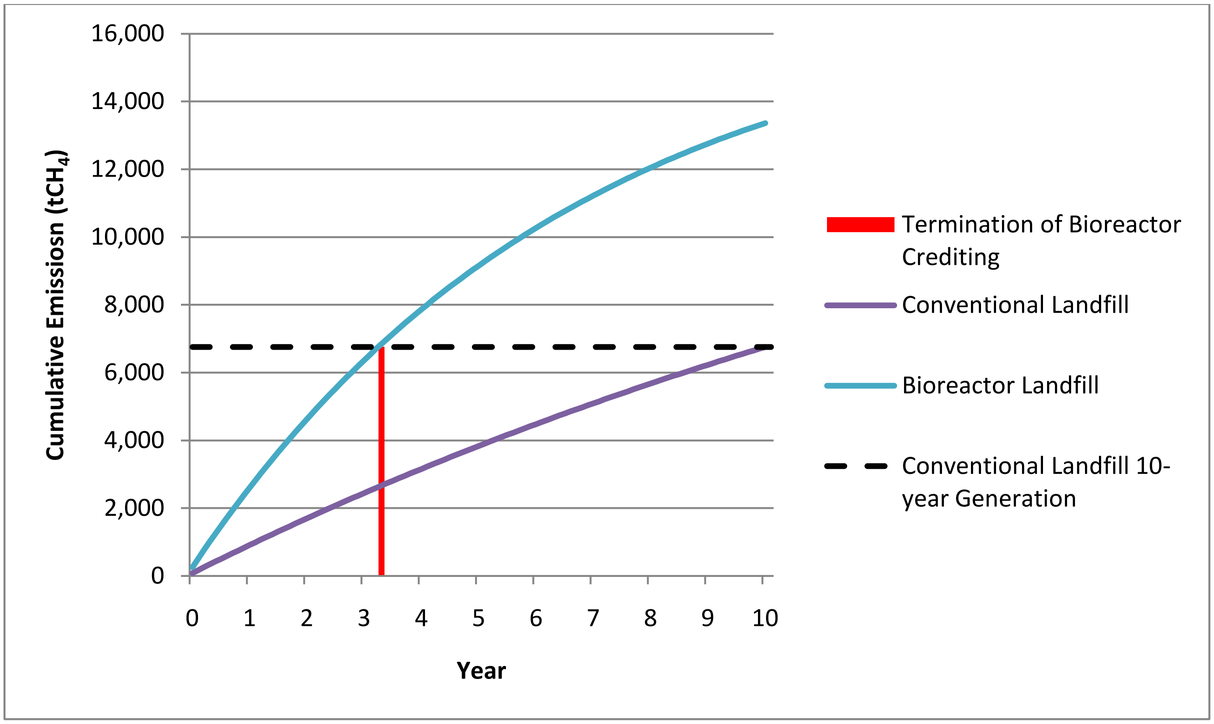
Immediate Crediting for Future Avoided Emissions

The second option would follow the model of the Reserve's OWD and OWC protocols, in which projects receive credit for the entirety of future avoided landfill emissions when those emissions are successfully precluded by biodegradation of waste. The Reserve documents its rationale and requirements for this policy in a 2010 memorandum *Policy on Immediate Crediting for Future Avoided Emissions.*[120] This policy could be implemented by crediting annual reductions in the amount of permanently precluded emissions *up to* a maximum that corresponds to the modeled emissions over a ten-year period. Figure 11 demonstrates how this would function in practice using the LandGem model to calculate emissions under a conventional conditions (k=0.05) and bioreactor conditions (k=0.15). The purple line represents *cumulative* emissions from the conventional landfill over a ten-year period. The blue line represents the *cumulative* emissions over this same period from operation of an anaerobic bioreactor (or avoided emissions from operation of an aerobic bioreactor). In total, the conventional landfill in this example would produce approximately 6,500 tonnes of methane over ten years, represented by the black dotted line. The immediate crediting for future avoided emissions option could be constructed to allow

[119] Climate Action Reserve, *U.S. Ozone Depleting Substances Protocol Version 1.0* (February 2010)
[120] Climate Action Reserve, *Policy on Immediate Crediting for Future Avoided Emissions* (September 2010).

crediting of total precluded emissions by the anaerobic or aerobic bioreactor project up until total precluded emissions are equal to 6,500 tonnes of methane, represented by the red vertical line at approximately 3.5 years. This crediting structure would allow project developers to recover costs more rapidly compared to the previously discussed crediting structure. Credits would only be issued for permanent and real reductions, but project economics could be significantly improved by condensing the payback period.

Figure 11: Illustration of Crediting for Bioreactor Projects Under and Immediate Crediting for Future Avoided Emissions Scenario.



Crediting immediately for future avoided emissions does however carry a risk that projects would cease operation once they receive maximum reductions. In the scenario illustrated in Figure 11, the project proponent would have no *carbon* incentive to continue operating after 3.5 years when offset generation has been exhausted. If bioreactor activities were terminated, the risk is not that issued offsets would be environmentally compromised, but rather that the bioreactor may not maximize emissions reductions: continued operation would have resulted in additional, but un-credited, emissions reductions.

A second, more material risk, exists if the bioreactor does continue to operate. Bioreactor activities require energy inputs resulting in project emissions, and may increase surface emissions compared to traditional landfill operation. If all crediting and monitoring ceases when offset generation is maximized and the bioreactor continues to operate, there will be *project* emissions that will be unaccounted for.

This risk could be handled in several ways. First, the Reserve could withhold a portion of credits in a buffer pool (similar to the one used in the Forestry protocols), and require projects to continue monitoring and reporting project emissions for the duration of the ten-year crediting period. At the termination of the crediting period the project would receive the remaining credits in the buffer account once project emissions had been deducted.

The second resolution would be to disregard future project emissions resulting from continued bioreactor operation on the assumption that any increase in project emissions in the remaining years of the crediting period would be more than compensated for by diminished emissions in the years after the crediting period. However, this approach requires an assumption about landfill operation after the termination of the crediting period, and an implicit crediting of emission reductions beyond the Reserve's standard ten-year crediting period.

6.3 Additional Crediting Periods

The Reserve allows the ten-year crediting period for non-sequestration projects to be renewed one time, provided that the project meets the requirements of the then-current version of the protocol.[121] Depending on the definition of the project – whether it is defined as a cell or an entire landfill – the bioreactor activity may no longer be operational. Nonetheless, it may be possible to allow a second crediting period that allows bioreactor projects to generate precluded emissions from years 11-20. The second crediting period could credit under either of the policies outlined in the previous section, issuing credits only as avoided emissions actually would have occurred (corresponding to Annual Crediting of Avoided Crediting After Project Cessation) or up front when the project registers for a second crediting period (corresponding to Immediate Crediting for Future Avoided Emissions). As discussed previously in this paper, the Reserve may or may not wish to allow for a second crediting period, but if it does the policy should mirror the accounting and issuance policy for the first crediting period.

6.4 Defining the Project as a Single Cell or Entire Landfill

The Reserve defines landfill offset projects in relation to the host landfill. Generally, LFG projects will operate on multiple landfill cells simultaneously, as gas production is stretched out somewhat evenly over many years. Bioreactors, however, may be implemented on a sub-landfill scale both due to the requirements for liquids and technology, and the collapsed operational lifetime. As one cell is operated as a bioreactor the next cell is filled. As that cell is fully filled, the bioreactor reaches stabilization, and capital-intensive equipment can be expanded in the newly-filled cell.

One option would be to define bioreactor projects in relation to individual waste cells, rather than the landfill as a whole. This conception is consistent with the project definition employed by the Reserve's Coal Mine Methane (CMM) protocol[122]. That protocol permits multiple ventilation air methane (VAM) projects to operate on multiple ventilation shafts at one mining facility. As with VAM projects, bioreactors can be implemented on a cell-by-cell basis whereby the same equipment may be deployed on one cell, and after methane levels subside, expanded or shifted to another cell.

Traditional bioreactor systems consists of a series of pipe, either vertical or horizontally orientated, within the waste mass with additional piping located outside of the landfill footprint, along with pumps and valving structures and possibly aeration equipment if the bioreactor will be operated as an aerobic

[121] Climate Action Reserve, *Program Manual* (October, 2011), p.11
[122] Climate Action Reserve. *Coal Mine Methane Project Protocol* (October 2009)

bioreactor. The piping structures within the waste mass are not removed as portions of the bioreactor are shut down, and additional piping is installed as the landfill grows in size. Although the initial capital investment will be much more substantial, there is still a significant cost associated with system expansion as subsequent cells are filled and the bioreactor technology expands. It should be noted there are other options to implement leachate recirculation, such as waste working face spray, where the moisture application equipment may simply be shifted as the working face area moves. However, this type of application may not realize the full accelerated LFG generation effects without the long-term moisture application of a traditional internal piping moisture application bioreactor system. Economic analysis to determine if implementing bioreactor technology must be done on a site-by-site basis, as costs to treat and dispose of leachate vary greatly across the country. In addition, the revenue from gained airspace due to accelerated waste settlement will be dependent upon the site's tipping fees, which also vary greatly geographically.

From a protocol implementation perspective, implementing a protocol on an individual cell rather than the whole landfill site should not be a significant burden. The LFG generation boost observed subsequent to bioreactor implementation is generally easy to identify when reviewing facility monitoring records. In addition, gas collection structures typically have individual monitoring stations at the collection points, so data may be verified in the bioreactor cell at the gas collection points and compared to the data recorded at the destruction device monitoring station.

Absent such a cell-by-cell definition, some projects may have trouble operating beyond the Reserve's ten-year crediting period. Traditional landfill projects require relatively modest operational costs once constructed, but bioreactor projects may have significantly more costly management requirements.

6.5 Market Potential

The current driving factor for facilities to consider implementing bioreactor technology is to have a cost-effective method of managing generated leachate. Including financial incentives for carbon offset credits associated with implementing bioreactor technology will be dependent upon economic conditions. The current US market value of carbon offset credits will likely not produce a significant quantity of landfills pursuing bioreactor technology as a means to reduce methane emissions.

7 Conclusions

This paper has explored offset-related issues in the context of both aerobic and anaerobic bioreactors. and discussed the technical, financial, regulatory, and market factors that drive bioreactor implementation in the US. In summary, this section recounts some of this paper's findings and provides conclusions about the level of consistency between aerobic and anaerobic bioreactors and the likelihood that the two could be combined into one Reserve protocol.

As shown in this paper, aerobic and anaerobic technologies share significant overlap, but also entail markedly different requirements for issues including eligibility, monitoring, and quantification. Below, we us the Reserve's typical protocol structure to summarize major protocol elements and the level of consistency that could be expected between anaerobic and aerobic bioreactor protocols.

Project Definition: Per Section 6.4, the project definition for both anaerobic and aerobic bioreactors may need to be adjusted due to their applicability at the landfill cell level. This element should be reasonably consistent, and a workable project definition encompassing both technologies seems reasonable.

Legal Requirements Test: The general Legal Requirements Test applied in the existing Landfill protocol could be extended to both aerobic and anaerobic bioreactor projects. However, this element may need unique sections related to each sub-project type. Aerobic bioreactors are unique in the possibility that they could preclude regulation. Anaerobic bioreactors are unique in that, once implemented, they would technically be required to operate gas collection and combustion equipment. During the course of researching this paper, no regulations requiring bioreactor implementation were identified.

Performance Standard: The current Landfill protocol performance standard provides a sound starting point for a bioreactor performance standard. Both landfill size and regional aridity are appropriate factors for calibrating eligibility criteria for bioreactors. However, the Berge, et al. study reveals that there are significant differences in project economics between aerobic and anaerobic bioreactors. Therefore, one standardized performance standard may not readily capture the uniqueness of the two project types, and multiple analyses may be appropriate.

Calculating Baseline Emissions: Both protocols require a practice-independent means of quantifying baseline emissions. A common technique should be appropriate. However, as discussed in Section 6.2, it may be appropriate to allow flexibility in the temporal fidelity of crediting avoided baseline emissions following the models developed in the Reserve's OWD, OWC, and ODS protocols.

Calculating Project Emissions: For slightly different reasons, both aerobic and anaerobic bioreactor projects would require robust monitoring of surface emissions. For anaerobic bioreactors this would be required to ensure that these emissions do not increase due to project activity. For aerobic bioreactors this would be required to ensure proper operation of the facility. These emissions may need to be monitored even after bioreactor activities cease for the duration of the crediting period.

Monitoring: Because baseline and project emissions estimation methodologies could reasonably be developed in a consistent manner, the accompanying monitoring requirements would also be expected to be shared between anaerobic and aerobic bioreactors. To support baseline and project emission calculations, the monitoring requirements of the current Landfill protocol will likely require significant additional elements.

Based on our research, it seems that the majority of issues related to bioreactors could be included in a single protocol. However, some sections, and certainly the specific equations used to quantify emission reductions, would need to be tailored to the specific technology. Finally, the authors conclude that a protocol for quantifying emission reductions from anaerobic and aerobic bioreactors should be technically feasible. However, eligibility is a much more policy-driven issue, and the developing evolution of bioreactors complicates performance standard analyses. While it is true that there are fewer than 50 active bioreactors in the US, the technology is relatively young and disciplined research quantifying costs and benefits is only beginning to emerge. As this research is digested by landfill operators, it is uncertain whether adoption of bioreactor technology would occur naturally, or whether an additional, supplemental incentive from the carbon offsets is required.

8 References

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