United States Environmental Protection Agency

State of the Practice for Bioreactor Landfills

Workshop on Bioreactor Landfills Arlington, Virginia September 6-7, 2000

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by

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Notice

This document was compiled from presentations and open discussion at an EPA Workshop on Landfill Bioreactors held September 6-7, 2000, in Arlington, VA. The agenda, as well as participants, is given in the appendices. Case studies from several states have been included as well. The purpose of the Workshop was to provide a forum for discussion of the state of the art for the bioreactor theory, operation, monitoring, and regulatory control. Comments have not been attributed to individuals in the Workshop. Information presented herein does not necessarily represent the views of EPA, nor is it specifically tied to reference materials. In many cases, the information presented is the opinion of the speaker, generated by his or her background and operations experience. Every attempt has been made to capture the Workshop discussion as a tool for looking at the research and regulatory needs of the landfill industry. The document is not intended as an operational guide and should not be quoted or used as such.

Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threatens human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
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Acronyms

ASTSWMO	Association for State and Territorial Solid Waste Management Officials
BOD	biological oxygen demand
CAA	Clean Air Act
C & D	construction and demolition
cfm	cubic feet per minute
CO_2	carbon dioxide
CO	carbon monoxide
COD	chemical oxygen demand
CRADA	Cooperative Research and Development Agreement
CWA	Clean Water Act
DOE	Department of Energy
DQO	data quality objective
DSWA	Delaware Solid Waste Authority
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FTIR	Fourier Transform InfraRed
HAP	hazardous air pollutant
HPLC	high pressure liquid chromatography
LIDAR	light detection and ranging
MACT	maximum achievable control technology
MSW	municipal solid waste
MSW-DST	municipal solid waste decision support tool
NCER	National Center for Environmental Research
NMOC	nonmethane organic compounds
NO_x	nitrogen oxide
NRMRL	National Risk Management Research Laboratory
NSPS/EG	New Source Performance Standards and Emission Guidelines
NYSDEC	New York State Department of Environmental Conservation
ORD	Office of Research and Development
OSW	Office of Solid Waste
POTW	publicly owned treatment works
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act
RD&D	research, development, and demonstration
SBREF	A Small Business Regulatory Enforcement Fairness Act
SCADA	supervisory control and data acquisition
SITE	Superfund Innovative Technology Evaluation
STAR	Science to Achieve Results
SWANA	Solid Waste Association of North America
TDS	total dissolved solids
TSS	total suspended solids
VOC	volatile organic compound
WMI	Waste Management, Inc.
XL	eXcellence and Leadership

1.0 Introduction

Increased interest in advancing landfill technology and encouraging results from laboratory research and pilot program field studies suggest that municipal solid waste can be rapidly degraded and can be made less toxic. EPA is interested in evaluating this potentially promising technology to help verify claims being made and document potential environmental benefits or impact. A method of active landfill operation, discussed in this document as a landfill bioreactor, operates with the express purpose of degrading waste mass inside a modern containment system. Degradation can be accelerated and optimized through a variety of processes and/or steps with the goal of minimizing long term environmental risk. There are a variety of different designs, but typically these systems include liquid, usually leachate, and/or air circulation systems, with leachate and gas collection. Such bioreactor landfill operations may be able to degrade the waste mass within a shorter period of time than is experienced in traditional landfill operations. As a result of these operations, leachate may rapidly improve and landfill volume may decrease. This recovered airspace would offer landfill operators the opportunity to utilize the landfill volume more efficiently and to extend the landfill's useful life and may reduce the need for construction of new landfill sites.

Bioreactor landfill operations may also result in significantly increased landfill gas emissions and at a faster rate over those seen in conventional municipal solid waste landfills. These landfill gases consist of methane, carbon dioxide (CO_2), trace amounts of volatile organic compounds (VOCs), and hazardous air pollutants (HAPs) for those landfills operated anaerobically. Landfills are typically in urban areas and their impact on air quality has resulted in Clean Air Act (CAA) regulations requiring large landfills to collect and control landfill gas. However, these rules were based on conventional landfilling practice and not the increased rate and amount of landfill gas that can result from bioreactors. Landfill gas can be flared or recovered for its energy potential which helps to offset fossil fuel consumption. One of the potential advantages of bioreactors is to help make energy recovery projects more economical by increasing the quantity and rate of landfill gas production.

The purpose of the Environmental Protection Agency (EPA) Workshop on Landfill Bioreactors, held September 6–7, 2000 in Arlington, Virginia, was to provide a forum to EPA, state government, local government, solid waste industry, and academic research representatives to exchange information and ideas on bioreactor landfills. This interactive workshop provided opportunities to:

- Assess the state-of-the-practice of bioreactor landfill design, operation, and maintenance
- Hear case studies of bioreactor landfill use, especially where data exist for comparison between conventional and bioreactor approaches

- Discuss long-term monitoring needs for environmental compliance for groundwater, gas emissions, leachate quality, liner stability, physical stability, and other factors to satisfy life-cycle integrity and economic viability concerns

- Exchange views, technical concerns, and implementation concerns regarding pending and planned regulations affecting landfills in general and the regulatory framework to be developed for bioreactor landfills

- Examine the economic viability, impacts, and benefits of bioreactor landfill implementation at full scale

- Identify additional research needs.

This document is intended to summarize the Workshop discussions, presentations, and recommendations. It addresses the salient features of the discussions, but does not present a transcript of discussions nor specific participant remarks. Furthermore, this summary of Workshop discussions is not intended to reflect EPA policy and does not constitute guidance to states or to landfill owners.

This document is organized as follows:

- Section 2 summarizes the information presented on the current regulatory framework for landfills, Federal regulatory agency concerns and data needs, and state agency experiences in regulating and operating bioreactor landfills

- Section 3 presents information on bioreactor definitions, designs, operations, monitoring, closure, and potential benefits as described throughout Workshop presentations

- Section 4 provides an overview of bioreactor landfill economic analyses conducted by Federal agencies and private industry as well as economic or financial considerations identified by Workshop participants

- Section 5 discusses current EPA-sponsored bioreactor landfill research as well as research needs and data gaps for bioreactor design, operation, and monitoring identified in Workshop presentations

- Section 6 identifies potential issues and considerations in developing regulations for bioreactor landfills

- Section 7 highlights conclusions from the Workshop.

Supporting this Workshop summary are three appendices. Appendix A provides the Workshop agenda, Appendix B lists the Workshop attendees, and Appendix C summarizes the six case studies presented during the Workshop. An acronyms list is also provided at the beginning of the document.

2.0 Regulatory Framework

This section summarizes the existing and planned Federal regulatory framework applicable to bioreactor landfills, Federal regulatory agency concerns and data needs, state regulatory program experiences, and state agency experiences with bioreactors and leachate recirculation. Section 2.1 presents the status of landfill regulatory programs under the Resource Conservation and Recovery Act (RCRA) Subtitle D as well as information needs sought in the April 6, 2000 *Federal Register* requests pertaining to bioreactor landfills. Section 2.2 reviews the recent effluent guidelines established under the Clean Water Act (CWA) for hazardous and nonhazardous waste landfills. Section 2.3 summarizes the existing and planned regulatory requirements for municipal solid waste landfills under the CAA as well as air-related concerns regarding bioreactor landfill gas generation, monitoring, and management. Section 2.4 addresses the bioreactor experience and regulatory issues confronted by state government agencies as both regulator and landfill operator.

2.1 RCRA Subtitle D

On October 9, 1991, EPA issued minimum national standards for municipal landfills under the provisions of 40 CFR Part 258 of RCRA Subtitle D, which is administered by the Office of Solid Waste (OSW). As of August 11, 2000, EPA acknowledges 48 fully or partially approved state and municipal solid waste landfill permitting programs under D. While the Subtitle D standards allow for leachate circulation in a municipal landfill with a specified composite liner, other Subtitle D requirements (e.g., daily cover, closure/post-closure care, limitations on liquid addition to landfills, and prohibiting leachate recirculation at landfills with alternative liner systems approved by states) may be barriers to bioreactor operation.

Upon initiation of 40 CFR Part 258, EPA had not received any formal requests to change these standards as they related to leachate recirculation and the associated limitations to bioreactor operations. However, over the last 2 years, EPA, state and local governments, and the solid waste industry have engaged in a significant amount of discussion regarding leachate recirculation and bioreactors. One outgrowth of these discussions is the potential need for EPA to consider making changes in the RCRA Subtitle D municipal solid waste landfill requirements to support more widespread application of these waste management techniques.

At the same time, Section 610 of the Small Business Regulatory Enforcement Fairness Act (SBREFA) requires a review of regulations affecting small businesses every 10 years. These requirements specifically affect the economic impact analysis prepared prior to issuing the RCRA Subtitle D requirements in October 1991. EPA announced this SBREFA review in the *Federal Register* on November 22, 1999 and requested comments by February 29, 2000 on the entire EPA solid waste management program. In the April 6, 2000 *Federal Register*, EPA issued a public request for additional data and information on alternatives for liner performance, leachate recirculation, and bioreactor landfills with a comment response deadline of August 7, 2000, and a later date (October 6) for bioreactor landfill responses. As feedback from these information requests is compiled and assessed, EPA expects to issue additional information request notices.

EPA is interested in receiving information about the RCRA landfill rules in general and the bioreactor landfills in particular. Specific topics of interest include, but are not limited to, the following:

- Liners
  - Alternative liner performance as compared to composite liners
  - Types of alternative liner design for leachate recirculation

- Leachate Recirculation
  - Impacts of leachate quality, quantity, and loading on the liner system
  - How quickly leachate recirculation affects the rate and extent of landfill waste mass stabilization
  - How to measure stabilization
  - How to determine when a landfill is sufficiently stabilized

- Bioreactors Landfill Design, Operation, and Closure
  - Nature and scope of current bioreactor projects
  - Design, operation, and performance
  - Advantages and disadvantages of leachate generation
  - Gas generation
  - Experience with alternative liner designs
  - Modifications needed to daily and final cover requirements
  - Monitoring needed to ensure proper bioreactor functioning
  - Technology and timing impacts on current closure and post-closure requirements
  - Impacts of adding liquid wastes other than recirculated leachate to a landfill (types of liquids, volumes, performance impacts)
  - Methods for waste mass aeration and aerobic bioreactor landfill operations
  - Methods of waste mass temperature monitoring, and control
  - Management and safety issues associated with gas generation, internal waste mass temperatures, air injection, and other aspects of bioreactor landfill operation and whether additional regulation will be needed in these areas
- Economics

- Costs associated with bioreactor design, construction, and operation
- Comparative cost-effectiveness of bioreactor landfill versus composting organics in a conventional municipal landfill

- Regulatory changes potentially needed to allow bioreactor operation if bioreactors are found to be protective of human health and the environment.

Information received from the *Federal Register* notices as well as independent literature searches will form the basis for EPA determinations of the need for any regulatory changes to Subtitle D. EPA recognizes that there are many different definitions of bioreactors and that leachate recirculation and bioreactor landfills are not necessarily the same. Therefore, if any new regulations are developed, they will have to address a broad range of liquid additions and/or recirculation, and at all times will emphasize protection of human health and the environment.

2.2 Effluent Guidelines

Effluent guidelines are national baseline regulations for both direct dischargers (to waters of the United States) and indirect dischargers (to publicly-owned treatment works [POTWs]). These guidelines are industry-specific, numerical, and technology-based, but do not directly address bioreactor landfills. The landfill effluent guidelines cover less than 150 facilities nationwide and are estimated to reduce pollutant discharges to surface waters by over 900,000 pounds per year, including significant quantities of ammonia and toxic organic constituents.

EPA first proposed the landfill effluent guidelines in the *Federal Register* on February 6, 1998 with the final rule published on January 19, 2000. The landfill effluent guidelines apply to both RCRA Subtitle C (hazardous waste) and Subtitle D (municipal) landfills. However, these guidelines do not apply to "captive" landfills associated with industrial facilities since EPA found in the background research for developing these guidelines that the leachate generated in the industrial landfills was generally similar to the industrial product at the site rather than to leachate generated in other types of landfills. This leachate was typically treated in the facility's industrial wastewater plant because of its similarity to other onsite waste streams.

In addition, the landfill effluent guidelines did not establish POTW pretreatment standards for a number of reasons. Theses include the small quantity of landfill wastewater discharged to POTWs, few instances of POTW upset or interference resulting from landfill leachate, and the preference to address ammonia discharges locally.

The landfill effluent guidelines address the following types of wastewater from landfills and their operation:

- Leachate
- Gas collection condensate
- Drained free liquids
- Contaminated storm water
- Laboratory-derived wastewater
- Truck equipment wash water.

The landfill effluent guidelines exclude the groundwater and wastewater from recovery pumping wells from regulation. The rationale for this exclusion involves the dilute nature of these waste streams, the site-specific nature of the constituents, and the management controls already in place under RCRA corrective action measures. The guidelines also exclude non-contaminated storm water such as runoff from cap, daily cover, intermediate cover, and final cover because these flows are believed to be adequately controlled by the storm water multi-sector general permit as published in the *Federal Register*, Volume 60, page 50803.

In developing these effluent guidelines, EPA conducted extensive background research involving the following:

- Screening surveys of 4,000 facilities regarding landfill type, amount of waste landfilled, amount of leachate generated, wastewater discharges, and wastewater treatment

- Detailed questionnaire surveys of 220 facilities regarding landfill type, amount of waste landfilled, wastewater treatment types, wastewater monitoring data, wastewater treatment design, and economic data

- Detailed monitoring questionnaire surveys of 27 facilities requesting up to 3 years of analytical data

- Raw wastewater grab sampling at 15 landfills (commercial, private, municipal)

- Raw wastewater and treated effluent sampling at 6 landfills (hazardous and nonhazardous).

From this information, EPA established different effluent limitations for each landfill category (hazardous, nonhazardous). This subcategorization was necessary because EPA found that while both landfills had similar concentrations of ammonia, hazardous waste landfills had a wider range of toxic organic pollutants and higher concentrations of metals. For the nonhazardous waste landfills, EPA identified 32 pollutants of interest and established surface water discharge limits for biological oxygen demand (BOD), total suspended solids (TSS), ammonia, zinc, phenol, paracresol, and benzoic acid. For the hazardous waste landfills, EPA identified 63 pollutants of interest and established surface water discharge limits for BOD, TSS, ammonia, seven organics, and three metals.

In this regulatory development process, EPA identified 9,882 Subtitle D landfills and 595 Subtitle C landfills. Many are closed and no longer discharge.

EPA research indicated that simple gravity flow drain fields are the most common type of leachate collection system. Other systems in use include french drain, compound collection, and a number of miscellaneous technologies. No leachate collection systems were found at 46 nonhazardous landfills.

EPA also found that over 338 landfills had no direct wastewater discharges to surface waters or to a POTW. These landfills manage their wastewater by recirculation back into the landfill, transport off-site for treatment/disposal, and underground injection.

Access to publicly available landfill effluent guideline data in the form of development documents and databases is provided on the Office of Water website at http://www.epa.gov/ost/guide/landfills/.

2.3 Air Regulations

EPA concerns regarding bioreactor landfill operations are primarily linked to the compliance timing for gas collection and control in current municipal solid waste regulations developed under Section 111 of the CAA (40 CFR 60 Subparts WWW and Cc) and the rapid generation of large quantities of landfill gas produced under bioreactor landfill operations. Changes in landfill gas constituent concentrations and leachate gas generation potential are additional concerns.

2.3.1 CAA Section 111 New Source Performance Standards

EPA developed new source performance standards and emission guidelines (NSPS/EG) for municipal solid waste landfills (40 CFR 60 Subparts WWW and Cc) under the statutory authority of Section 111 of the CAA. The rulemaking effort began in 1987, the rule was proposed in May 1991, and the final rule was promalgated in March 1996. Bioreactor landfills and leachate recirculation were not considered in the development of this regulation.

The goal of the NSPS/EG regulation is to establish performance standards for new sources and existing sources that reflect the degree of emissions limitation and the percentage reduction achievable through best available technology. Landfill gas is the pollutant of interest in the landfill NSPS/EG (40 CFR Part 60 Subparts WWW and Cc), which uses nonmethane organic compounds (NMOC) as a surrogate for landfill gas. Therefore, the standard limits are specified as a reduction of NMOC. However, it should be noted that some level of co-control exists since the control devices also destroy VOC and HAP contained in the landfill gas.

This standard applies to municipal solid waste landfills that accepted waste after November 7, 1987. Compliance requirements depend on the landfill size and the volume of estimated emissions. For many landfills, compliance generally involves only reporting and recordkeeping. However, landfills over a certain size (2.5 million megagrams of waste and 2.5 million cubic meters in size) must estimate uncontrolled NMOC emissions. For landfills with uncontrolled NMOC emissions estimated at 50 Mg/yr or more, additional compliance requirements apply, including collection/control of landfill gas and adherence to specific operational standards.

This regulation also establishes time limits for installing and beginning operation of a landfill gas control system once the size NMOC thresholds are exceeded. Installation timing varies depending on the age of the waste in place and the landfill cell status (e.g., active, at final grade/closed). Clearly, existing air regulations are based on conventional landfilling practices and do not address concerns associated with bioreactor operations.

2.3.2 CAA Section 112 MACT

The goal of Section 112 of the CAA is to reduce the emissions of toxic air pollutants from all affected sources to levels achieved by the best performing affected sources using a technology- based approach. Pollutants of interest are the HAP listed in Section 112(b) of the CAA. Of the 188 HAPs listed, EPA identified approximately 30 HAPs typically contained in landfill gas.

EPA is developing a maximum achievable control technology (MACT) regulation (40 CFR 63 Subpart

AAAA) under the statutory authority of Section 112 of the CAA. Publication of the proposed MACT in the *Federal Register* occurred on November 7, 2000. Publication of the final promulgated rule is anticipated in September 2001.

MACT standards typically apply to major source categories, but can include area sources. These regulations establish emission limits either for a single HAP or for a combination of HAPs. The landfill MACT regulation will affect landfills that accepted waste after November 7, 1987, and are major sources as defined in the regulations. In addition, there may be some circumstances where these regulations also apply to area sources since landfills were listed as an urban air toxic concern under the Urban Air Toxics Strategy.

Landfills affected by these regulations are required to:

- Comply with NSPS regulations
- Develop and follow a startup, shutdown, and malfunction plan
- Continuously comply with control device operational standards
- Conduct semiannual rather than annual compliance reporting.

2.3.3 Landfill Bioreactors and Air Regulation/Compliance Issues

The primary bioreactor concern identified by EPA with regard to air quality is the impact of the increased quantity and faster generation rate of landfill gas over what is typically seen in traditional municipal solid waste landfills. Additional concerns included changes in landfill gas constituents, concentrations, and in landfill gas generation potential. The current air regulations do not adequately address the design and operation issues specific to bioreactor landfills. Of particular note is the potential for bioreactor landfills to see significant gas generation within 60 to 90 days after recirculation begins, while the regulations allow 30 months to 5 years before a gas collection and control system must be installed and operating.

EPA currently anticipates that the landfill MACT air regulation will address the design of landfill gas collection and control systems, the criteria that require their installation, and the timing of their installation to name just a few items. The preamble of the proposed MACT regulation discussed the air issues associated with bioreactors.

2.4 State Agency Perspectives

Workshop presentations provided background on state agency experiences with bioreactors and leachate recirculation from regulatory, operational, and demonstration project perspectives. Section 2.4.1 presents experience in the State of New York regarding bioreactor landfill and leachate recirculation regulation as well as demonstration project experience. Section 2.4.2 summarizes the experiences of 10 states in regulating and operating bioreactors and leachate recirculation under a newly formed Association of State and Territorial Solid Waste Management Officials (ASTSWMO) Bioreactor Landfill Work Group. Section 2.4.3 provides leachate recirculation demonstration project experience of the Delaware Solid Waste Authority (DSWA).

2.4.1 State of New York Bioreactor and Leachate Recirculation Experience

The State of New York solid waste management regulations (6 NYCRR Part 360) have encouraged the use of bioreactor landfill operations since October 9, 1993. These regulatory requirements are "passive" in that they ask landfill operators to consider active landfill management concepts and techniques (bioreactor landfill concepts). These provisions were included in the State's solid waste management regulations as an acknowledgment that there are numerous potential benefits which could result from a properly designed and operated bioreactor landfill, including:

- Optimization of solid waste compaction and increased waste mass densities
- Optimization of landfill disposal capacity and conservation of land resources
- Extension of the operational site life of existing and proposed landfills
- Reduction of the volume and pollution potential of leachate generated from landfills
- Enhanced quality and rate of generation of landfill gases, maximizing the potential energy recovery and associated revenues along with minimizing air emissions
- Minimization of the long-term pollution potential of the wastes being disposed.

It is not the intent of New York State to mandate that all landfills pursue bioreactor operations. The State's regulatory provisions encourage landfill owners to consider promoting rapid waste mass stabilization methods (bioreactor landfill operations) in their operations. These regulations offer the flexibility to landfill operators to pursue landfill bioreactor concepts in a manner which best fits into their landfills' operation.

Overall, the State of New York has conservative regulatory requirements for municipal solid waste (MSW) landfills. The State's regulations require that all MSW landfills be lined with double composite liners with dual leachate collection and removal systems with required upper liner performance monitoring. As of September 2000, there were 38 double-lined landfills operating in the State. New York State's Department of Environmental Conservation (NYSDEC) experience with double-lined landfills has been favorable in that they have been demonstrated to be working as designed, affording a high degree of leachate containment. Based on required liner system performance monitoring and results from groundwater monitoring conducted at these double-lined landfills, it is clear that these double-lined landfills, when properly operated, pose little to no threat to groundwater quality. As confidence grew in the ability of the modern landfill's liner systems to prevent groundwater contamination it was determined appropriate to look ahead to modern/alternative landfill operations that would limit a landfill's long-term pollution potential.

NYSDEC has been involved with six bioreactor landfill projects that have taken place in New York State, lasting in duration from 90 days to approximately 5 years, and there is currently one additional project being proposed. The projects which have taken place have been pilot and/or research, development and demonstration projects which have not been integrated into a permanent form of long-term landfill operation. Four of the bioreactor projects, including the one which is proposed, have used or will use an aerobic decomposition process to help enhance the initial waste mass decomposition process. The other three projects studied the benefits of anaerobic waste mass decomposition and processes.

In general, NYSDEC's experiences with these bioreactor projects were positive. These projects, although they were of limited duration, did establish that the merits of a bioreactor landfill operations are achievable to varying degrees. These demonstrations also established that enhanced odor and landfill gas generation could contribute to operational compliance problems if effective landfill odor and gas control provisions are not applied early upon initiation of leachate recirculation.

NYSDEC considers bioreactor landfill operational methods to be an alternative form of landfill operation. Since NYSDEC experience has been largely with double-lined landfills, the issue of whether the act of leachate recirculation has the potential to generate additional upper liner system leakage during bioreactor landfill operations is of great interest. To date, NYSDEC has not experienced increased upper liner system leakage as a result of leachate recirculation in its demonstration projects. In one instance, leachate generation was shown to have decreased upon leachate recirculation; therefore, the bioreactor landfill operation appeared to consume the recirculated leachate within the decomposing waste mass rather than generating more leachate. Operational experience indicates the importance of not over saturating the waste mass, which could increase the head on the liner system and cause excessive liner system leakage. Over saturation of the waste mass can also diminish the decomposition process and pose waste mass geotechnical stability problems and as such needs to be avoided.

New York State's regulatory perspective on bioreactor landfill operations hinges on the double-lined landfill's ability to demonstrate both acceptable leachate accountability and acceptable overall operational compliance from a bioreactor landfill proposal. It is NYSDEC's belief that neither the State nor federal regulations should stymie innovative advances in modern solid waste management, but rather need to be flexible while maintaining an ability to assert the needed regulatory controls and oversight to ensure adequate protection of public health and the environment. In such a regulatory framework all parties stand to gain.

2.4.2 Association of State and Territorial Solid Waste Management Officials' Experience

ASTSWMO is a national, non-profit organization representing the managers of solid waste, hazardous waste, remediation, recycling/reduction/minimization, and underground storage tank programs of the States and Territories. Among other programs, the Association's membership regulates the implementation of solid waste programs addressed by the 40 CFR Part 258 Solid Waste Disposal Facility Criteria of RCRA Subtitle D.

Due to recent increased interest from its member states on the topic of bioreactor landfills the ASTSWMO Solid Waste Subcommittee assembled a Bioreactor Landfill Work Group to develop comments in response to the April 6, 2000 Federal Register notice, Alternative Liner Performance, Leachate Recirculation, and Bioreactor Landfills Request for Information and Data, and to track EPA's progress on developing regulations and guidance on bioreactor landfills. The Work Group is comprised of 10 state solid waste management officials who have experience with implementing bioreactor landfills and/or leachate recirculation from across the country (CA, DE, FL, IA, KY, NY, TN, VT, VA, WI). These remarks are based on the Work Group's collective experience with bioreactor landfills.

The first Work Group meeting was held on August 17, 2000 with representatives from California, Florida, New York, Tennessee, Virginia, and Wisconsin in attendance. During this initial meeting the

Work Group concluded the following:

- All attendees recognized the merits of bioreactor landfill operations and supported bioreactor landfill operations as a viable alternative to conventional landfill operations. All attendees expressed having had positive experiences with bioreactor landfills in their states.

- With respect to leachate recirculation, each attendee expressed preference for a federal regulatory program that would allow each State to make its own decisions about what is an acceptable minimal liner system.

- Each attendee expressed preference for a federal regulatory program that would allow each State to make its own decisions about whether a landfill can recirculate liquids other than leachate as long as the liquids are aqueous in nature and are found to be compatible with a landfill's microbiology.

- The attendees all agreed that limited data are available from previous bioreactor pilot projects (10 as of September 2000 from the 7 attendee states) and there is uncertainty in what future data will show. The Work Group indicated that another 5 bioreactor landfill projects will be coming into existence among the 10 State members.

- All the attendees agreed that active gas collection and control systems will likely be necessary at bioreactor landfill operations because many of the states had experienced odor problems at their bioreactor landfill projects.

- The concern for the potential for landfill fires was raised by the attendees as being attributed to the increased waste mass temperatures associated with bioreactor landfill operations. It was suggested that monitoring of carbon monoxide (CO) concentrations in bioreactor/ landfill gas could act as a good indicator for subsurface landfill fires. The basis for this recommendation is that literature indicates that CO concentrations in conventional landfill decomposition gases should only be about 2-4 ppm.

- All attendees agreed that recirculation of liquids heightens regulatory concerns about surface seeps, however, all believed that a comprehensive bioreactor operation and contingency plans would be effective in mitigating this concern.

- Geotechnical stability of the waste mass and liner systems associated with bioreactor landfill operations were raised by the Work Group as a regulatory concern. The added loading/weight attributed to leachate recirculation and other associated bioreactor landfill waste mass density increases is the basis for this regulatory concern. The Work Group agrees that all bioreactor proposals should be supported by a geotechnical analysis demonstrating structural integrity of the subgrade, liner and leachate collection and removal system, and that stability analyses demonstrate acceptability for both static and appropriate seismic conditions for the site.

- The Work Group expressed a need for federal guidance regarding proper bioreactor landfill performance monitoring, addressing such issues as how to determine when the waste mass is stabilized, when to reduce long-term monitoring, and whether 30 year minimum post-closure maintenance and monitoring requirements can be reduced.

In general, the Work Group noted the need to avoid developing landfill bioreactor regulations that are so prescriptive that practitioners and regulators are kept from being able to continue to learn from the bioreactor operation experiences which are yet to be gained. The Work Group also suggested the need to proceed cautiously with bioreactor landfill implementation since the bioreactor process is not yet well understood and that a single failure, even on an isolated account, could impair the ability to gain public trust and support for these modern disposal facilities. These concerns for proceeding with caution should not present a barrier to implementation of bioreactor projects, but rather reinforce the need for comprehensive and well thought out operations and contingency plans associated with this alternative form of landfill operation.

The Work Group views the bioreactor landfill as an alternative form of landfill which involves increased sophistication and complexity over traditional municipal solid waste landfill operations and management requirements. As such, the Work Group advocates that specialized bioreactor landfill operator training programs be developed to address this need. Such training could be offered through federal training programs or be incorporated into existing training programs, such as those sponsored by the Solid Waste Association of North America (SWANA).

The Work Group also noted that additional Federal technical guidance is needed. One recommendation is to modify the existing solid waste technical guidance document to add a chapter that specifically addresses bioreactor landfills. Other areas needing additional guidance associated with bioreactor landfills include design, operation, monitoring, closure, and post-closure.

In summary, the Work Group advocates that the federal regulations need to impart flexibility into the current solid waste management regulations. Such flexibility should allow modification of conventional landfill operations while maintaining appropriate regulatory attention/concern for the landfill's liner system design, waste mass stability, and the standard operational criteria as is required for all solid waste landfills necessary to protect water and air resources and public health and safety.

2.4.3 Delaware Solid Waste Authority Experience

The DSWA is the State entity responsible for landfill operations in all three counties of the State of Delaware. Since 1980, there are also 10 locations in Delaware where the DSWA has conducted some type of bioreactor landfill operation. These operations have included recirculation of leachate for 2 or more years at some landfills, use of single- or double-lined landfills, use of one or more types of alternate liners, and use of different capping materials.

Initial regulations for municipal solid waste landfills were promulgated in the 1970s with increased stringency in the 1980s. The regulations became even more restrictive in the 1990s to the extent that it is becoming more difficult for DSWA to explore alternate landfill designs and operations. As a result, there is great interest in making some regulatory changes to allow the flexibility needed to explore bioreactor and leachate recirculation practices; for example, the restrictions against leachate recirculation in RCRA Subtitle D.

The DSWA conducted a Test Cell Program from 1989 to 1998 with EPA participation. This Test Cell Program explored various practices for leachate addition, recirculation, and collection including the following:

- Use of septic pipe leach fields and vertical recharge wells
- Horizontal leachate recirculation in conjunction with landfill gas extraction
- Use of perforated pipe to spray liquids onto landfill cover
- Ponding liquids on landfill cover
- Recharge wells
- Spraying systems to distribute leachate
- Concrete manholes for leachate collection
- Creation of distinct drainage areas with sandy cover material in conjunction with storm water runoff controls
- Use of aboveground and underground tank systems for liquids management.

The majority of these technologies dated to the mid-1980s. Many of the methods for leachate application to the test cells resulted in significant odor problems.

DSWA experience to date offers the following considerations in developing regulations for bioreactor landfills:

- Allow flexibility to conduct research and to test new technologies
- Base the regulatory requirements upon good science
- Favor performance-based requirements rather than prescriptive regulations to provide the necessary flexibility for these systems
- Stay in communication and work together with regulatory partners.

3.0 Bioreactor Theory, Operations, and Expected Benefits

As a result of increased interest, EPA is evaluating the operation of landfills as bioreactors to determine their viability as a solid waste management technique and their environmental impact. This section summarizes Workshop discussions on bioreactor definitions, designs, operations, monitoring, closure, and potential benefits. Section 3.1 presents the definitions and characteristics of bioreactor landfills. Section 3.2 describes the bioreaction process and approaches for determining its completion. Section 3.3 discusses bioreactor landfill systems and their design issues as compared to conventional municipal solid waste landfills. Section 3.4 reviews features of landfill operations specific to bioreactor landfills. Section 3.5 provides an overview of the monitoring systems for landfill performance and release detection and measurement. Section 3.6 identifies performance measures and factors to consider in optimizing bioreactor landfill performance. Section 3.7 considers closure and post-closure issues specific to bioreactor landfills. Section 3.8 summarizes some of the potential benefits that may be achieved from the use of bioreactor landfills and leachate recirculation.

3.1 Definition and Characteristics of Bioreactor Landfills

Bioreactor landfills promote microbial waste mass decomposition, which results in the generation of landfill gas and a decrease in total waste mass and volume. Some Workshop participants suggest that bioreactor landfills are essentially large-scale, in-ground composting operations. Others view bioreactor landfills as providing solid waste treatment and draw similarities to a wastewater treatment facility with the intention of using the landfill space for treatment rather than indefinite future storage.

Various past studies of conventional municipal solid waste landfills developed gas generation curves that show specific changes for internal landfill conditions over time and enable different phases to be defined, as follows:

- Phase I (lasts a few hours to 1 week) – this phase is aerobic in which oxygen in the landfill is depleted, the temperature of the waste mass increases due to biological activity, and CO_2 levels are high initially

- Phase II (lasts 1 to 6 months) – this phase is a transition from aerobic to anaerobic conditions with most of the oxygen being depleted, nitrogen beginning to be displaced, cellulose beginning to be broken down, methane gas beginning to form, and CO_2 levels declining

- Phase III (lasts 3 months to 3 years) – this phase involves anaerobic conditions within the landfill and is a growth period for bacterial formation of methane (via methanogenesis)

- Phase IV (lasts 8 to 40 or more years) – this phase is an ongoing period of gas generation with landfill gases consisting of 50 to 60 percent methane

- Phase V – this phase is marked by the decline in methane generation.

Bioreactor landfills can involve aerobic or anaerobic conditions. Waste mass temperature may be 130 to 150°F or more under aerobic conditions with the moisture content above field capacity. Anaerobic conditions can involve lower temperatures. In both cases, drier areas within the waste mass tend to have the lowest temperatures.

Aerobic bioreactor landfills attempt to sustain the Phase I activity over a longer period of time than is experienced in a conventional municipal solid waste landfill. Anaerobic bioreactor landfills attempt to significantly reduce the time involved for Phase IV activities – to possibly 5 to 10 years (a 75 percent reduction), with 5 to 7 years for Phase IV considered optimum.

Gas generation may vary depending on the moisture and oxygen conditions within the landfill and the effects of moisture and oxygen conditions on waste mass decomposition.

Presenter information also suggest that data in the United States and the United Kingdom indicate that hazardous air pollutants (HAPs) may enter the landfill gas stream very early in the bioreactor process. This may be true for volatile organic compounds (VOCs) as well. One hypothesis for this is the difference in operating temperatures between a conventional municipal solid waste landfill (70 to 80°F) and a bioreactor landfill (150 to 160°F).

Additional discussion proposed that liquid in the form of moisture within the waste mass may be a key factor in sustaining the bioreactor operation. Some bioreactor landfills may operate in a moisture deficit with moisture being consumed in waste mass decomposition and also being removed through air emissions, gas collection/removal, and leachate collection/removal. Therefore, it may be necessary to add water, wastewater, leachate, or other liquids to replace the water loss and to sustain the bioreactor activity. Key to effective liquids movement and distribution of moisture within the landfill waste mass is a system for liquid introduction to the waste mass, open liquid flow within the waste mass, and the leachate collection and removal system.

In addition to gas generation, decomposition of the landfill waste mass and associated volume loss results in the following additional bioreactor landfill attributes:

- Biological generation of humus-like material that acts like a trickling filter to remove some salts and metals as leachate or other liquids pass through
- Partial to complete biological reduction of the organic constituents in the leachate
- Decreases in BOD
- Potential increases in fatty acid production that cause the pH to rise and reduce the metal-carrying capacity in the leachate
- Increased effective density of the waste mass
- Significant settlement of the waste mass.

Workshop participants also observed that bioreactor landfills undergo more waste mass settlement in their lifetimes than is seen in conventional municipal solid waste landfills. Some participants maintain that when the low permeability final cover is applied, both gas generation and the moisture content of the waste mass drop dramatically, which significantly affects continued bioreactor function and gas flow to any co-located beneficial gas reuse projects (e.g., energy recovery). Thus, key areas of concern in full-scale bioreactor landfill operation involve the type and timing of final low permeability cover placement, as well as the use of alternative temporary covers supporting continued bioreactor operations pending installation of the final cover.

The increase in the effective waste mass density and the significant amount of waste mass settlement combine to reduce the volume of material in the landfill. The airspace "recovered" as a result of such settlement has economic value and can extend the useful life of the landfill.

In summary, the workshop discussions indicated that anaerobic bioreactor landfills result in the following, as compared to conventional municipal solid waste landfills:

- Nearer term stabilization of the waste mass within 5 to 10 years of initiating bioreactor operations
- More complete stabilization of leachate within 3 to 5 years
- Rapid settlement

- Earlier gas generation
- Increased gas flow and yield (total and per unit basis)
- Minimized future environmental liability related to gas, settlement, and leachate after achieving a stabilized waste mass through completion of the decomposition process.

Aerobic bioreactors have the same benefits as anaerobic bioreactors, only these benefits seem to be achieved more quickly. Since aerobic bioreactors do not produce such significant quantities of methane, there is no potential to sell methane for energy.

Some cautions about bioreactor landfills were also noted by participants, specifically:

- There may be increased potential for fires, explosions, and stability issues.
- A wet landfill or leachate recirculation does not necessarily mean the landfill is a bioreactor.
- Some bioreactor benefits (such as waste mass/volume reduction) attributable to microbial decomposition may be attributable to settlement/compression from the addition of liquid.
- Even after the majority of the waste mass is digested, there can still be significant quantities of material that can be reduced further over time and the potential exists for continued generation of gases and transport to groundwater.
- Landfill gas emissions may increase if sites are not well controlled soon after liquids addition.

Some Workshop participants speculated that all landfill sites may eventually return to aerobic conditions, but others believed that this might not occur for very long periods of time (several hundred years or more). However, if such landfills are reopened at a future date to mine the waste or degraded waste material, aerobic conditions may be introduced and this should be factored into conceptualization of such operations.

Some websites of interest for more information on bioreactor landfills include the following:

- www.bioreactor.org
- lst.sb.luth.se/bioreactor
- www4.ncsu.edu/~barlaz/.

3.2 BIOREACTOR PROCESS

Microbial activity is the primary process operating in bioreactor landfills and the addition of water helps the microbial system to work more efficiently. However, some bioreactor benefits attributable to microbes may in fact be attributable to settlement from liquid addition.

By understanding the following aspects, bioreactor landfill performance can be influenced as with other microbial-based systems:

- Microbial population dynamics in bioreactor landfills
- Microbe distribution and microbial activity distribution
- Microbial population and activity responses to site-specific parameters such as:
  - redox potential
  - p H
  - soluble nutrients
  - abundance of water.

To date, there is only very general knowledge of the activities and roles of the microbial populations within landfills. There are currently few culturing techniques and few modern molecular techniques applicable to this situation.

The microbe-based decomposition of wastes in the landfill provides many of the end results discussed in Section 3.1 and throughout this document, specifically gas generation, decomposition of organics, and nitrogen cycling.

There are a number of ways to examine gas generation in a bioreactor landfill. Gas production may be correlated with waste type (food, vegetation, paper, other), measured by production rate (rapid, moderate, slow), monitored with respect to landfill age or characterized by methane content. Numerous gas generation curves have been developed for all of these factors, and they all demonstrate that the methane generation rate in bioreactor landfills can be substantially higher than in conventional municipal solid waste landfills.

Studies have been performed regarding the makeup of municipal landfill solid waste and the contribution each type of waste makes to gas generation. Municipal solid waste generally consists of food, vegetation, paper, wood, plastic, rubber, and textiles. Overall, vegetation, food, and paper matter have a greater and more immediate impact on methane generation and leachate strength than plastics and other more inert materials.

Lignin, however, is resistant to breakdown in anaerobic landfill environments and may be similarly resistant under aerobic conditions as well. Previous research has demonstrated that the loss of cellulose/hemicellulose changes (decreases) the ratio of cellulose to lignin over time in the landfill. Soil used for daily cover does not seem to affect these results.

The following sections present additional discussion of the factors affecting the bioreaction process (Section 3.2.1), the behavior of metals in the bioreactor landfill (Section 3.2.2), and potential methods or criteria for determining completion of the bioreactor process (Section 3.2.3).

3.2.1 Factors Affecting the Bioreactor Process

The experience of some Workshop participants was that waste materials in plastic garbage bags did not break down (i.e., dry anaerobic conditions existed in the plastic bag even if wet bioreactor conditions existed in the rest of the waste mass). Other participants had found that plastic garbage bags degraded under bioreactor landfill conditions of at least 122°F for 18 months. Still others suggested that either breaking open plastic bags to expose the contents (by equipment or during emplacement) or use of degradable bags may be necessary for optimum bioreactor performance. Another view was that most plastic bags are ripped or broken.

There are also a number of considerations regarding degradation potential for different redox conditions (aerobic, anaerobic, microaerophilic/facultative/nitrifying) encountered in bioreactor landfill systems, including the following:

- Relationship of waste composition to the choice of bioreactor redox conditions
- Impacts of waste segregation or pre-processing on bioreactor performance (i.e., enhanced gas generation/waste decomposition from waste shredding)
- Changes of process dynamics from introducing new waste into a partially or fully decomposed waste mass.

Moisture content is a factor affecting the bioreaction process as noted in Section 3.1. Participants noted that reactor performance can decline as dry conditions develop within the waste mass. However, oversaturation of the waste mass may achieve negative results; a wet landfill does not necessarily mean the landfill is a bioreactor.

Additional discussion indicated that bacterial decomposition of the waste may result in a layer of humic material forming at the bottom of the landfill (and possibly in other areas as well) that resembles a trickling filter in its behavior. The permeability of this layer can affect the movement of liquids throughout the landfill and the ability of leachate to move through this layer to the leachate collection system at the bottom of the landfill. Better understanding of this layer, its attributes, its permeability, and how these change over time is necessary to identify and mitigate any potential impacts.

3.2.2 Metals

Several Workshop discussions considered the long-term fate of metals in bioreactor systems and impacts of changes in redox/pH conditions in the landfill after stabilization and closure (e.g., potential for remobilization). Workshop participants speculated that since heavy metals may concentrate during wastewater biosolids treatment, similar effects could be anticipated in bioreactor landfills during waste decomposition, and such changes in heavy metal concentrations should be seen in the leachate quality. Workshop participants also noted the challenges in addressing the presence and behavior of metals in the landfill environment, including:

- Microbes may concentrate metals
- pH and sulfides in the landfill may affect mobilization
- Filtration of water samples (leachate, groundwater, etc.) prior to analysis can remove metals entrained in the solids thereby affecting the interpretation of analytical results regarding the presence or absence of metals
- Potential for remobilization of metals if landfill conditions become aerobic (e.g., oxidized humic acids, additional CO_2 that lowers the pH).

Research conducted at Georgia Tech and elsewhere indicates that while there is some potential for mobilization, there are multiple mechanisms for attenuation of all metals and therefore the metals generally precipitate in the waste mass. In addition, a review of data from 12 landfills indicated that heavy metals are not an issue for a fully stabilized anaerobic landfill. In pH conditions of 7 to 9, as are typically encountered in these landfills, the metals are immobilized. While metals are present in the landfill leachate, all of the values are below drinking water standards.

EPA participants at the Workshop requested information on mercury in landfills – its presence, quantities involved, potential for emissions, and any technologies to address mercury treatment/control. Superfund sites were noted to have mercury problems, but representatives from the solid waste industry noted their belief that modern Subtitle D landfills do not seem to have problems with mercury contamination. Ongoing research in Florida has conducted measurements of mercury emissions at a few landfills and these measurements seem to conflict with other reports that had suggested that mercury emissions were not an issue. However the fate of mercury in septic sewage sludge and other landfill materials has not been established.

3.2.3 Completion of the Bioreactor Process

An important issue in any reaction process is how to determine when the reaction is completed. For bioreactor landfills, Workshop participants indicated that this equates to defining when the waste mass is stabilized.

The decomposition process for organic matter produces methane and CO_2 under anaerobic conditions and produces CO_2 under aerobic conditions. Data exist for gas yield per kilogram of cellulose/ hemicellulose. Therefore, gas generation may be a method of determining stabilization of the waste mass. However, a concern expressed by many Workshop participants is the potential to continue generating methane gas after stabilization is accomplished.

Many questions were raised and discussed during the Workshop regarding how to define waste stabilization and the difficulties of selecting an appropriate endpoint. Examples include:

- Is partial or full treatment desirable, i.e., achieving an optimal decrease or an absolute decrease in gas generation?
- Is gas generation really a surrogate to measure organic decomposition? Or to assess how much material is left to decompose?
- Is the landfill stabilized when monitoring shows no more than a specified level, e.g., X cubic feet per minute (cfm), of gas is being generated?
- Is the drop-off in methane production in an anaerobic bioreactor a good measure of stability?
- Since methane is not likely to go to zero at any time, is another measure or some other value more appropriate?
- Is the drop-off in CO_2 production in an aerobic bioreactor a good measure of stability?

- Are there other/better indicators of waste mass stability than gas parameters, such as geochemical stability of leachate?

- Can leachate from different landfill areas be used to determine solids degradation or completion of the waste mass stabilization process since leachate is typically collected from the base of the landfill where the greatest decomposition can be expected?

- Can changes in characteristics of solids provide a better, although more difficult to obtain, method to determine stability?

Research is still ongoing to determine when data show stabilization of the waste mass. Workshop participants also uniformly agreed that it is critical to set performance goals because these in turn establish operational guidelines.

3.3 Bioreactor Landfill Systems

This section addresses Workshop discussions pertaining to systems for containing, managing, and promoting the bioreaction and its byproducts as well as design considerations specific to bioreactor landfills. Section 3.3.1 reviews issues raised pertaining to liners for landfill bioreactors and their performance. Section 3.3.2 addresses leachate collection and internal drainage systems to sustain the bioreaction and manage the liquids from the landfill. Section 3.3.3 focuses on gas collection and management systems. Section 3.3.4 summarizes issues raised pertaining to the physical stability of the landfill and waste mass as compared to conventional municipal solid waste landfills. Section 3.3.5 considers temporary and final cover requirements for bioreactor landfills.

3.3.1 Liners

Landfill liner research to date indicates that landfill liners work well. One study noted by participants addressed the performance of various liners at 91 landfills considering both sand layers and geonet layers for the leak detection system. This study found that the leakage rate was 4 gallons/acre/day, which dropped to 1 gallon/acre/day after closure.

Some Workshop participants suggested that the regulations allow flexibility for use of single composite liners, mixed composite liners, and double liner systems with an interliner detection system. In addition, EPA representatives indicated that alternative liners are being seriously considered in the current regulatory development process. Workshop participants expressed interest in pursuing performance standards rather than prescriptive criteria such as the composite liner specification currently found in the RCRA landfill regulations.

3.3.2 Leachate Collection and Internal Drainage Systems

Leachate collection systems for bioreactor landfills serve to collect, remove, and manage leachate generated in the landfill, but must also support the management of any liquids added to sustain or promote the bioreaction. Some practitioners believe that it is necessary to increase the size of the leachate collection and removal system to support recirculation. However, the Workshop presentations indicate that bioreactors frequently operate with a moisture deficit, which raises design questions regarding the sizing of these systems.

Many Workshop participants indicated that there will always be some leachate generated in a landfill. Others indicated that bioreactor landfills will generate little leachate at the conclusion of their operation.

A number of Workshop participants recommended that the leachate collection system design for wet bioreactor landfills should be flexible. Some considered the 0.01 cm/sec leachate collection system design requirement specified in the regulations to be too low for good liquid discharge. Different opinions were expressed as to the appropriate size of the stones for the drainage collection layer (e.g., AASHTO #3, 1.5 inches, 2 inches). Design recommendations and considerations included the following:

- Use a perforated pipe network within a stone layer
- Stone is preferable to sand, which can promote clogging of the collection pipes
- Avoid wrapping geotextile fabrics around collection pipes to prevent fouling
- More organic material can be expected to move through the landfill and into the drainage system at the early bioreaction stages when the pore space is much higher in the waste mass than at later stages, resulting in a much higher potential for plugging the drainage system earlier in the process.

Leachate collection and removal systems generally involve a pipe network that is difficult to design and maintain because of its location above the landfill liner. Repair, removal, or replacement of these pipes can be very expensive once waste is emplaced in the landfill cell.

Internal moisture distribution is another important aspect of bioreactor design. Building such systems within the waste mass may improve moisture distribution over that achieved by trickling liquids down through the waste from the top of the waste mass. This may also help to avoid mounding and the problems associated with preferential pathways or blockages developing around denser material.

Questions were raised about the potential impacts of high internal bioreactor landfill temperatures on leachate temperatures. Experience presented by the Workshop participants indicated that the leachate temperature does not seem to change from that found in conventional landfills because of the cooling action of the earth and the insulation provided by the depth of the waste (i.e., the distance between the high temperatures within the waste mass and the leachate collection system at the bottom of the landfill).

3.3.3 Gas Collection and Management

Gas collection and management systems for bioreactor landfills need to be installed earlier and designed for larger flow than for conventional municipal solid waste landfills because landfill gas forms earlier and in greater quantities. Workshop discussions indicated that bioreactors can be designed and operated to:

- Maximize landfill gas collection and control
- Minimize occasional landfill fires or appropriate actions are taken should a fire occur.

Issues identified by Workshop participants pertaining to the collection and control of gas generated from bioreactor landfills include the following:

- What is an adequate level of gas collection and control?
- What contingency plans and procedures are needed to respond to failures and fires in landfill gas collection/control systems?
- When will updated models and model input default values be available that reflect bioreactor landfill operations in order to estimate the life-cycle environmental burdens?

A common misconception is that landfill gas collection is not necessary for aerobic landfills because they do not generate methane. However, these types of landfills also generate significant quantities of other gases that may also require control.

3.3.4 Physical Stability of the Landfill and Waste Mass

Physical stability of the landfill and waste mass involve the following considerations:

- Density changes and settlement of the waste mass from compaction and decomposition
- Impacts of liquid addition and recirculation
- Shear strength of the waste.

These stability considerations, their impacts, and design considerations are discussed further in the following sections.

3.3.4.1 Waste Mass Density and Settlement

Settlement of the waste mass in a bioreactor landfill can be significant over time — easily involving 10 to 25 percent of the landfill height. Settlement will also be differential rather than consistent across the landfill surface. Gas collection and other internal landfill cell systems (such as leachate collection/ recirculation) must be able to move with this settlement.

When water is added to paper (a significant component of municipal solid waste) and the wet paper is put under pressure (as would be seen in landfill waste emplacement), the wet paper consolidates. Thus, the 10 percent settlement seen in the early stages of bioreactor landfill operations may in fact be more the result of water addition than microbial degradation.

A wet landfill can produce a 50 percent increase in the total unit weight of the waste and the unit weights increase with height (for example, doubles in the first 150 feet). Addition of water or other liquids to the waste mass to promote the bioreaction will add additional weight. Such changes in waste density may affect seismic and other stability design requirements. For example, increased density of the waste through the decomposition process and settlement may result in the waste mass becoming more unstable with steeper slopes, thereby reducing the designed safety factor.

3.3.4.2 Impacts of Liquid Addition and Recirculation

Another major landfill stability concern is leachate (hydraulic head) buildup on the landfill liner system. Ponding of liquid on the liner can be a significant source of failure as a result of the associated hydrostatic forces. Addressing this in design should be a straightforward issue for bioreactor landfills because liquid levels, shear strengths, and other parameters are generally known.

However, some of the biggest questions facing designers of bioreactor landfills include the following:

- How do changes in the waste mass, hydraulic head, and pore water pressure (resulting from recirculation and liquid addition) affect the design parameters?

- How do these changes affect physical stability factors?

- What safety factors, based on the above changes, need to be addressed in design and operation to prevent landfill failure?

- How will placement of new waste on top of a stabilized waste mass (i.e., reuse of the "recovered" landfill space) affect landfill stability?

One critical area is controlling the hydraulic head/pore water. Pore water pressures remain high in bioreactor landfills for a long period of time, while they decrease in conventional landfills after placement of the final cover.

Of additional note, recirculation of liquid can affect the stability of the perimeter berm in heavy rainfall or hurricane conditions in landfills with steep liner slopes.

3.3.4.3 Waste Mass Shear Strength

A dry waste mass can be tremendously strong as evidenced by stable modern landfills with waste heights of up to 300 feet and slopes steeper than 3:1. However, the addition of water adds weight but no shear strength, which affects traditional landfill design factors such as the waste mass geometry (for stability). Some geometries used for dry landfills may not work with wet or bioreactor landfills because of differences in the shear strength of the waste and elastic displacement caused by water addition.

Some data exist on the shear strength of "new waste", but there do not appear to be any data regarding the shear strength of "old waste" such as might be found in a bioreactor landfill after stabilization of the waste mass is achieved. One Workshop participant noted that there appears to be some data that indicate that "old" wet waste may have the same shear strength as new waste.

Testing shear strength to obtain the necessary data for nonhomogenous waste streams such as municipal solid waste can be difficult. To test shear strength, material samples are needed that are five times bigger than the particle size. For municipal solid waste, particle size can be a telephone book, refrigerator, etc.

Liquid addition and waste shredding prior to emplacement both affect the shear strength of the waste, and can change the waste mass behavior from that experienced with conventional landfills. This raises the question as to whether the decomposed and settled waste mass in a bioreactor landfill will be sufficiently stable to allow new waste to be placed on top.

3.3.4.4 Design Considerations for Landfill and Waste Mass Stability

Factors affecting waste mass stability and their effects include:

- Leachate/liquid mounding has a negative impact
- Increased unit weight/density has a negative impact
- Decreasing slopes over time has a positive impact
- Changes in waste shear strength have an unknown impact
- Changes in waste compressibility have an unknown impact.

Stability concerns were generally not expressed regarding the first waste placement and Workshop participants had not encountered any stability problems with a wet landfill or bioreactor landfill. The stability concerns raised in the Workshop generally focused on reuse of the landfill cell to place new, unreacted waste on top of old, decomposed waste.

One suggested approach was to use a "stabilize as you go" concept. This would involve stabilization of the lower parts of the landfill as waste is emplaced because it is too difficult to go back into the waste mass later to make adjustments.

Overall, Workshop participants recommended following good geotechnical engineering principles when designing a landfill for stability, similar to those followed in building a dam. Good input data are key to good design.

3.3.5 Temporary and Final Covers

As noted in Section 3.3.4.1, bioreactor landfills undergo significantly more waste mass settlement in their lifetimes than conventional municipal solid waste landfills. Thus, the type and timing of the final landfill cover and the potential need for alternative temporary covers, pending installation of the final cover, are key factors in successful bioreactor operation. Decisions regarding the type and timing of landfill covers are important because state regulatory agencies have seen a number of final cover failures in conventional landfill situations as a result of significant or differential settlement.

Workshop participants generally agreed that it is necessary to seek flexibility in the regulations regarding the timing of final cover placement so that landfill operators can continue to manipulate the waste mass. Once a synthetic or other final cover is installed, it is too expensive to remove and reinstall it. As an example, a number of Workshop participants proposed the use of higher permeability temporary covers (so-called alternative covers) for filled landfill cells until the bioreaction process is completed. Only at that time was it considered appropriate to install a final, low-permeability cover. A common argument in support of this approach is the fact that low-permeability covers will change the internal landfill conditions, possibly affecting the bioreaction process. Another argument in support of this approach is that bioreactor landfills operate at elevated temperatures (such as 160°F), and current low-permeability liner materials cannot withstand prolonged exposure to such temperatures without degradation of their performance.

Another strong recommendation was to defer final cover placement until after primary settlement of the waste mass has occurred (5 or more years after bioreaction is initiated). The overall goal in this time period is to allow liquid to enter the waste mass to achieve decomposition and to manage the landfill gas generated from this decomposition. Only after waste mass stabilization and settlement are achieved did Workshop participants feel it was appropriate to conduct final compaction and place the final cover.

One suggestion for alternative final cover design involves the placement of shredded tires at the top of the waste mass; this layer is in turn covered by a geotextile with the top layer consisting of clay. This creates a zone underneath the final cover for continued gas collection and removal.

Other factors to consider with regard to alternate, temporary, and final covers for bioreactor landfills raised in Workshop participant discussions include the following:

- What type of temporary covers can be installed that will withstand the massive total and differential settlement that will occur in a bioreactor landfill?
- What type of cover can keep the gas confined for proper management and extraction yet allow rainwater to penetrate?
- What is the potential for differential settling when using biosolids as cover material?
- How do cover requirements vary depending on the landfill type (e.g., dry tomb vs. bioreactor

vs. landfill types in between the two) and how do regulations need to consider the range of landfills that may be encountered?

The Sandtown, Delaware landfill project examined the impacts of a simulated cover failure on a dry landfill cell (see case studies provided in Appendix C). The chemical oxygen demand (COD) in the leachate for this landfill cell had decreased. The experiment involved opening up an area of the landfill cover and adding several thousand gallons of water over a few weeks. The leachate was monitored during and after the water addition. Results indicated that the added liquid took about 45 days to reach the leachate collection system and the liquid addition caused the COD to increase to 30,000 mg/L. This research experience appeared to indicate that if there is a breach of the cover, liquid addition may re-initiate the bioreaction.

3.4 Operations

This section summarizes Workshop discussions pertaining to bioreactor landfill operations and changes they may have on traditional municipal solid waste landfill practices. Section 3.4.1 discusses the moisture requirements of bioreactor landfills, moisture sources, and methods for liquid introduction. Section 3.4.2 reviews the waste compaction and potential waste preprocessing needs of bioreactor landfills. Section 3.4.3 addresses potential variations for daily cover requirements. Section 3.4.4 summarizes fire hazard concerns and potential mitigation measures. Section 3.4.5 addresses the control of mud on vehicles. Section 3.4.6 reviews Workshop discussions on nitrification and odor control. Section 3.4.7 presents training suggestions provided by Workshop participants.

3.4.1 Liquids Addition

The moisture content of wastes is critical for bioreactor operation; the addition of significant quantities of liquid may be required. Some estimates presented at the Workshop indicated that about 13 million gallons of liquid might be needed for 400,000 tons of waste; others estimated this requirement as 54 gallons of water per cubic yard of waste. Landfills in states with dry conditions will need even larger liquid quantities. Also, more liquid may be needed to sustain bioreactions after a low permeability cover or cap is installed because the landfill moisture may be removed via the gas collection system.

Thus, the leachate generated in the landfill may not be sufficient to support the bioreaction moisture needs, and additional liquid sources may be necessary. Factors raised by Workshop participants for consideration in addressing liquid addition to bioreactor landfills include the following:

- Whether and how to differentiate between the amounts of liquids needed by different types and sizes of landfills
- Use of temperature as a parameter to monitor or to control liquid injection since good wetting of the waste mass seems to result in the most uniform temperature
- Timing of liquid addition, e.g., at time of waste emplacement or emplace dry waste first and add liquid later
- Determination of the desired moisture content and the amount of liquid required is necessary to support design of a distribution system to achieve this.

Workshop participants noted that the moisture needs of a bioreactor landfill will depend on site conditions and will change as stabilization of the waste mass proceeds.

The timing of liquids addition was also discussed. Some projects such as the Worcester County Landfill in Maryland (see case studies in Appendix C) began recirculating leachate once the first lift of waste was emplaced and continued throughout the life of the landfill. Other options were more of a retrofit in nature with recirculation systems added after the landfill cell was filled with waste.

The following sections summarize discussions on alternative liquid sources and techniques for moisture addition.

3.4.1.1 Alternative Liquid Sources

Workshop participants explored alternatives to landfill leachate for liquid addition, including wastewater, biosludges, and biosolids from POTWs. Stormwater runoff and groundwater were other liquid sources suggested by Workshop participants.

Biosolids considered most suitable for bioreactor use are those in liquid form that typically undergo land application rather than the dewatered sludge. Use of this material could avoid dewatering costs, but would involve more trucks to transport the larger volume of the dilute wastewater.

Concerns were expressed regarding the operational health and safety issues raised by this material and this practice. Of particular interest was potential worker exposure to pathogens, risks to workers and nearby residential areas from aerosols resulting from biosolids application to the landfill surface, and risks present after digestion of the biosolids in the landfill. Many participants believe that there would be little risk associated with this practice because (1) there have been a number of studies conducted at wastewater plants indicating that worker safety is not compromised by exposure to this material; (2) large landfills servicing big urban areas typically take sewage sludge (hundreds of tons per day) and mix it with general trash, so worker exposure is well known and does not seem to have an impact on worker health and safety; and (3) RCRA Subtitle D landfills already receive animal carcasses, medical waste, and other pathogen-bearing materials, so the biosolids addition does not pose any new or special risk beyond that experienced in current practices. Some participants suggested that there may not be a pathogen problem in the leachate because the biosolid material will undergo pasteurization as it moves vertically down through the bioreactor landfill waste mass, which is at elevated temperature.

Questions were raised about the best choices in liquids, based on their composition, to augment the liquids already present in the landfill. Of particular note were potential impacts on leachate quality from the application of high BOD wastewater or biosludge to a bioreactor landfill. The following issues were raised:

- Will such wastewater increase the protein content and thereby increase ammonia generation, which is already a concern?
- Will heavy metals from sludges result in accumulation that may be a longer-term problem?
- Will there be compatibility issues between the wastewater and the landfilled waste or with changes to landfill internal conditions from waste addition? For example, will the addition of high BOD wastewater lower the pH of the landfill within a very short period of time and create areas of acidic conditions?
- Is there a potential need for additives to the wastewater in order to have it work in the desired manner?

A Workshop participant cited a research study conducted by EPA that examined the impacts of adding different amounts of biosolids to garbage, and evaluated impacts on leachate and methane generation. This study spiked the biosolids with heavy metals, which appeared to result in better quality leachate.

3.4.1.2 TECHNIQUES FOR MOISTURE ADDITION

Designs and practices for liquid addition to the waste mass cited by Workshop participants include the following:

- Slug injection of liquid followed by continued liquid addition in significant amounts until saturation occurs
- A high initial injection rate to saturate the waste mass followed by continued introduction of liquid at a much reduced rate
- Wetting the waste surface during waste emplacement
- Pooling the liquid on the top of the landfill
- Liquid infiltration trenches
- Nested vertical injection wells to provide liquid to multiple landfill layers at each location
- Pulsed vertical injection.

Some Workshop participants indicated that wetting the waste surface may initiate the bioreaction process, but optimum bioreactor performance is expected to require significantly larger liquid quantities. Others noted that surface application of liquid may be a key factor in the active bioreaction phase. However, the experience of state representatives with such practices raised concerns about vectors and odors. A risk assessment of such a practice may provide useful information, although some Workshop participants noted that odors can be a significant local community/political issue rather than an actual risk. In addition, there may also be worker safety issues to be considered.

Liquid injection can be accomplished through horizontal or vertical injection. Benefits of horizontal systems are that they are less likely to introduce oxygen into the landfill (a potential fire source). Horizontal distribution systems were considered by some Workshop participants to be very expensive and physically unlikely to survive the waste layering process in a large, active landfill. Horizontal systems may have to be abandoned and new systems installed in upper layers as the height of the waste mass rises during active waste emplacement.

In an example of vertical injection, pulsed vertical injection wells achieved significant saturation through overlapping zones of penetration below 20 feet, but above 20 feet there was poor saturation. Such variation did not necessarily impact the bioreaction results. This experience suggested that an important focus for liquid addition may be the economics (cost) of liquid injection methods rather than achieving uniform liquid distribution.

A concern expressed by some Workshop participants regarding the use of vertical injection wells was the potential for higher decomposition rates in the immediate vicinity of the injection wells to result in well plugging. Workshop participants responding to this concern had found somewhat higher decomposition in the immediate injection well vicinity, but noted that preferential pathways exist in the waste mass for injected liquids.

Some aerobic bioreactor programs are looking at closer well spacings. For example, 50 foot well spacings for liquid injection are common, but it is not clear that this is the optimum spacing.

3.4.2 Waste Preprocessing

Two forms of waste preprocessing were discussed: initial waste compaction upon emplacement in the landfill and shredding the waste prior to placement. The goal for this preprocessing is to achieve optimum exposure of waste material to the bioreaction process without creating conditions that preclude or hinder performance.

Some Workshop participants indicated that the method of initial waste compaction appears to have little correlation to the waste density ultimately achieved in the bioreactor landfill waste mass. Others noted demonstrated experience with the absence of decomposition in bioreactor landfills for waste inside plastic garbage bags, which may or may not be broken open during conventional compaction with heavy equipment. Some suggested that either breaking open plastic bags to expose the contents (by equipment or during emplacement) or use of degradable bags was necessary for optimum bioreactor performance.

Some Workshop participants questioned the importance of shredding the waste, raising the following issues:

- Pore size and capillarity in the waste mass influence liquid transport and this can be used to operational advantage in lieu of waste shredding
- Shredding changes the physical stability of the waste mass, and can impact both waste settlement and the potential for landfill failure

- Differential decomposition may be useful; for example, if only the bottom waste layer decomposes it will act as an anaerobic trickling filter for leachate and other liquids from higher layers and this may still be progress over no decomposition at all

- Shredding to achieve uniformity in the waste mass will help to drive the bioreactor process to completeness, but may not be economically feasible.

Workshop participants noted that there are some patents for shredding waste to obtain a more uniform particle size to enhance bioreaction performance. Participants also noted that some pretreatment of lignin in the waste may be necessary so it will decompose more readily.

An example of the compaction and shredding issues involves a landfill in central Florida that shreds waste in a tub grinder prior to waste emplacement. With waste material in this shredded form, the dozers only need to cross the landfill twice to achieve the desired compaction in the active landfill cell. The shredding costs approximately $7 per ton; however, the improved compaction achieved with shredded material may decrease the ability of liquids to penetrate the waste mass. Other Workshop participants noted that a tub grinder is a manual, batch feed process, and that for larger waste quantities, a continuous feed machine that breaks open garbage bags and shreds the waste material may be faster and more cost-effective.

In addition, data from the United States and the United Kingdom indicate that pre-composting waste prior to disposal may significantly increase emissions of HAPs and VOCs. One hypothesis for this is the difference in operating temperatures between a conventional municipal solid waste landfill (70 to 80°F) and a bioreactor landfill (150 to 160°F).

These discussions raised the following questions regarding current compaction and waste shredding activities for bioreactor landfill operation:

- Is initial compaction necessary?

- Is shredding economically and technically possible?

- Should current equipment be replaced with dozers that have shredding tines that break open plastic bags and other materials during initial waste emplacement and compaction?

- Do dry and wet landfills require different compaction for optimum performance?

- Will shredding or composting provide desirable performance improvements?

Workshop participants believed that the shredding and compaction issues ultimately will be determined either by regulation or by economics.

3.4.3 Daily Cover

Daily cover materials should be selected to avoid creation of low permeability layers within the landfill cell. For example, silt and clay can become barriers to leachate drainage and recirculation, while foams, slurries, sludges, or reusable tarps (among other techniques) will provide the benefits of daily cover without preventing infiltration and drainage.

3.4.4 Fires

Active landfill gas collection systems are a common source of fires. Other fire initiators include drilling and lightning strikes. Potential fire hazards during drilling are easily controlled through safe work practices (no smoking around the drilling hole) and use of spark preventing equipment. Note that surface fires are much easier to control and eliminate than underground fires. Landfill fires also pose a hazard because they may generate and emit dioxins and furans.

Fire prevention at composting facilities relies on controlling the waste mass temperature. RCRA Subtitle D landfills commonly see temperatures of 140 to 160°F up to 190°F. For fire prevention in composting operations, intervention is needed in the 170 to 180°F range. Some Workshop participants noted that a whole range of indicators (e.g., carbon sources, oxygen sources, heat) may need to be considered.

Aerobic bioreactor landfills rely on high temperatures as well as the addition of oxygen to sustain the bioreaction. For such operations, good moisture and oxygen control enable control of the waste mass temperature and fire potential. Participants noted that achieving uniform moisture levels at the landfill cell slopes and perimeter can be critical in that they provide an outside buffer. Adding moisture to the waste mass appears to be a simple, straightforward fire hazard prevention method; however, this overlooks the tremendous moisture variation encountered within a landfill and the difficulties created for gas removal with too much moisture present.

3.4.5 Control of Mud on Vehicles

Some Workshop participants anticipated that there would be increased incidence of mud on vehicles and operating equipment as a result of increased liquids use in bioreactor landfills. This situation was anticipated to require increases in the number and frequency of vehicle wheel wash stations, resulting in increased wastewater volumes generated over those encountered in conventional operations. Other Workshop participants noted that the impacts of liquid application at the surface of bioreactor landfills would not differ significantly from conventional landfill operations at a site with heavy rainfall.

3.4.6 Nitrification and Odor Control

A facultative landfill bioreactor may be useful to control nitrogen cycling and may contribute to the control of ammonia — a common odor problem in landfill leachate. Waste Management, Inc. (WMI), is conducting studies of such bioreactors. The described operational technique involves treatment of ammonia-containing leachate by nitrification. The nitrate-enriched leachate will then be introduced to the facultative bioreactor cell, as defined and presented by the speaker, where the nitrate is consumed by facultative bacteria. This approach is expected to reduce the buildup of ammonia in the leachate and is also likely to reduce the production of methane. The research will also assess the nitrogen dynamics in the landfill associated with the nitrate addition.

Other studies have shown that the addition of nitrate-enhanced liquids will enhance performance of a bioreactor landfill. However, these studies also demonstrated that this practice also reduced methane production to nearly zero, but methanogenesis returned in about 30 to 45 days. So while temporary reductions may be seen, the process does not seem to be entirely shut down.

There are laboratory studies currently underway to examine the ability of different materials to remove ammonia from leachate. Materials being tested include wood chips, stable refuse, chipped rubber, and plastic trickling filter media. Results to date indicate that wood chips and stable refuse offer better ammonia removal than rubber or plastic.

3.4.7 Training

Bioreactor landfills are a different mode of landfill operation than previously experienced by solid waste industry practitioners. Workshop participants anticipated that difficulties might be encountered in changing work habits to conduct the necessary operating practices for proper bioreactor performance, and noted that this needs to be considered whenever such changes are contemplated.

There were also a number of suggestions to add certification and training requirements for landfill operators with responsibility for gas collection systems or other active-type landfill operations as is done for wastewater treatment plant operators to help address risks/hazards of these operations.

3.5 Monitoring

Monitoring, in this discussion, includes the acquisition of information on landfill liner performance to assess the potential for failure, acquisition of information to determine compliance with applicable standards for emissions or other releases, and the acquisition of information to assess the status of waste mass decomposition. Current demonstration projects typically involve significant amounts of instrumentation to assess leak detection, hydraulic head, emissions, and other factors of interest. Such monitoring systems may not prove cost-effective in full-scale application. In addition, such approaches may require supervisory control and data acquisition (SCADA) systems to maintain the instrumentation, and to collect and manage the data.

Leak detection can involve detection systems placed between liners in a double liner system to assess performance of the upper liner (Section 3.5.1) or groundwater monitoring in the vicinity of the landfill to detect releases (Section 3.5.2). Section 3.5.3 addresses air and gas monitoring, and Section 3.5.4 summarizes solids monitoring.

3.5.1 Leak Detection Systems

Monitoring the leak detection zone is useful in determining landfill conditions and whether the upper liner is leaking. Experience to date indicates that there will be an increase of flow in the leak detection zone between the upper and lower liners if a problem develops in the landfill or with the upper liner. Specific suggestions regarding leak detection system design and operation include the following:

- Use of sensor-based approaches such as electrical conductivity or pressure measurement with sensors installed at the same time as the liner.

- Include design flexibility in the regulations since legal and financial liability for liner failure rests with the design engineers, not the regulatory agencies.

- Focus on quality assurance during construction and leak detection inspections of the liner after construction, since construction is the phase with the highest probability for liner damage to occur. Examples include using an electronic system to look for leaks after seaming or emplacement of a protective cover prior to waste emplacement as that enables repairs to be completed less expensively than after waste emplacement.

Workshop participants also noted that increases in leakage between liners can occur from increased head on the liner, such as may occur as a result of a major rainfall event. These types of problems have been adequately addressed in the past by changing landfill operations and cleaning out the leachate collection system to reduce the hydraulic head within the landfill. Such methods must be integrated into the operational mode of the landfill to be successful; this is especially true for bioreactor landfills, where there is an increased potential for fouling of these systems from increased biomass.

3.5.2 Groundwater Monitoring

EPA has developed a probabilistic method for estimating monitoring point density for containment system leak detection. Of particular interest is finding leaks through slurry walls that, like landfill liners, provide a barrier to contaminant releases. One approach is to look for a signature event such as pressure head changes across the barrier, which may be applicable to bioreactor landfills. Key to this approach is the ability to quantify the amount of leakage occurring. This can be accomplished through hydraulic head monitoring, water quality monitoring, geophysical methods, or groundwater monitoring. All of these methods build on well-established knowledge of fluid flow and measuring the flux across a plane of water.

Nomographs were developed that scaled the groundwater monitoring grid size and evaluated the probability for missing a leak, which requires knowledge of the site geology. With this information, it is possible to estimate the dimensions of the smallest hydraulic signature detectable for a given monitoring point spacing and a specified level of confidence, enabling data quality objectives (DQOs) to be established. However, all of this information needs to be determined before the liner is installed.

Some Workshop participants noted that slurry walls have been overlooked in their potential application to landfill sites. Slurry walls are much more advanced now, with the ability to combine geomembranes with low permeability materials to create very strong containment systems. However, many issues have been raised regarding the ability of slurry walls to provide the containment anticipated. This can be a significant issue for bioreactor landfills where good containment is important.

Some Workshop participants suggested the use of double liner systems with leak detection between the two liners in lieu of groundwater monitoring. Reasons for this suggestion include:

- Leak detection systems are more likely to identify a problem before contaminants are released into the environment
- The economics of such a system might be more favorable than groundwater monitoring.

Other approaches offered by Workshop participants include the following:

- Consider both an acceptable leachate leakage rate (number of gallons/day/acre) and the groundwater flux beneath the site – large groundwater fluxes will offset leakage from the liner if specific concentration limits must be met
- Require groundwater monitoring only after leakage exceeds some trigger level with groundwater monitoring wells drilled very close to the actual landfill rather than 150 feet away as can currently occur
- Monitor hydraulic head over the upper liner in double-lined systems in addition to having leak detection between the liners; an increase in the hydraulic head will be seen as an increase of liquid in the leak detection system
- Consider introducing inward gradients to induce leachate flow back into the secondary system as long as the head differential is appropriately managed.

Workshop participants noted that a leaking liner with significant waste quantities present (e.g., 30 to 50 feet of waste on top) generally cannot be fixed, and environmental risks attributable to any such leakage must be evaluated.

Some Workshop participants indicated that groundwater flux can be measured, but also noted that there is a preference to regulate based on a drinking water standard or to use concentration-based limits for surface water discharge. Other Workshop participants noted that because groundwater regimes change seasonally and for other reasons, some type of groundwater monitoring will be necessary regardless of whether a bioreactor landfill has a single or double liner. In addition, the presence of monitoring wells demonstrates that landfill activities are being monitored.

Other Workshop participants proposed that the real goal is to prevent the release of contaminants rather than to document through monitoring where contaminants went and who was affected. Many felt that monitoring should be conducted for reasons that make sense; otherwise, it involves expenditure of resources for no environmental benefit.

EPA representatives at the Workshop noted that the RCRA statute requires groundwater monitoring and that previous litigation has established that the total absence of monitoring will never be an acceptable option. However, a different type of groundwater monitoring that meets minimum statutory requirements may be an acceptable option. For example, RCRA Subtitle C regulations allow hazardous waste tanks to operate without groundwater monitoring as long as they have double containment systems with leak detection, among other requirements. This precedent opens an opportunity to consider similar changes to groundwater monitoring requirements for bioreactor landfills.

Suggestions regarding the conduct of groundwater monitoring include the following:

- Knowledge of the site-specific hydrogeology is important in properly siting a groundwater monitoring network.
- Flexibility is necessary in requiring groundwater monitoring because there are instances where groundwater cannot be found to be monitored. While some precedent for this appears to exist in many state programs, actual experience indicates that such waivers are difficult to obtain.
- Examine the plume chasing strategies used at Superfund sites to see if these approaches might apply to the bioreactor landfill situation under RCRA.
- Consider using BOD and conductivity as initial monitoring parameters, and if changes are detected, VOC monitoring would begin.

Some Workshop participants felt that groundwater problems seemed to largely be associated with older sites without liners while modern, lined, Subtitle D landfills seem to have little groundwater contamination problem.

3.5.3 Air and Gas Monitoring

An overall monitoring goal for landfill gas is to ensure long- and short-term protection of the environment. The air emissions regulations discussed in Section 2.3 focus on a surrogate (non-methane organic contaminants) that is representative or indicative of landfill gas and the pollutants it contains.

Landfill emissions vary diurnally with barometric pressure, seasonally, or by the amount/height of the waste mass. Workshop participants suggested that there may need to be a strategy for how to extrapolate from one site to another and between different years of operation in order to fully understand the air emissions at bioreactor landfills.

Some approaches identified as potentially useful to landfill emission monitoring include:

- Avoid reliance on ambient monitoring because it can be expensive and may not be reliable for measuring emissions.

- Apply pressure gradients within the landfill to make the landfill gas move in the desired manner rather than relying on atmospheric pressure at a landfill surface.

- Flux measurements rely on concentration measurements (e.g., light detection and ranging [LIDAR] infrared absorption) and velocity measurements in the atmosphere (typically using a micrometeorological technique). However, wind velocity can vary significantly across the surface of a landfill and wind speed variations cause variations in air pressure, which in turn affect the flux rate.

- Mass flux in time and space is the primary parameter of interest so monitoring may ultimately involve measuring concentrations with some as-yet-unidentified technique and translation of the measurements into mass flux (e.g., quarterly monitoring at spot points with measurement data ultimately converted to flux values).

- The permeability of the landfill cover will vary across the areal surface resulting in variable gas releases across the surface. Such variation can result in (1) hot spots that can skew monitoring results, and (2) a high probability of underestimating the flux.

- The need to address or distinguish between the anaerobic and aerobic conditions that will be encountered at the landfill surface and within the waste mass depending on the type of bioreactor operation.

- Methane is only one of possibly many constituents of landfill gas to be of concern, therefore it is necessary to identify the specific constituents of interest.

One Workshop participant recommended that EPA slightly modify the existing rulemaking for landfills (drawing on industry experience in determining what to address) rather than issuing new rules specific to bioreactor landfills. This was proposed because of the belief that the solid waste industry already has some good experience with landfill gas generation and control, and there is an established regulatory framework already in place. EPA representatives indicated that this approach is how EPA currently plans to proceed in the MACT regulation. In general, the MACT rule will refer to the same NSPS requirements used for conventional landfills, but may require implementing them sooner for bioreactor sites. For example, beginning gas monitoring/control soon after leachate recirculation commences may be required in the final MACT regulation.

Workshop participants also identified some newly emerging monitoring methods that may have potential application to landfill gas emission monitoring, including the following:

- The Department of Energy (DOE) has developed a camera that operates by remote control with 360 degree panning to detect gas and the relative volume generated; this is one idea to collect the necessary data. EPA is interested in evaluating this further with DOE for potential application to Superfund and other sites

- Open-path Fourier Transform InfraRed (FTIR) spectroscopy has been applied to wastes sites for several years. European and Superfund investigators have used a single beam measurement with dispersion modeling to estimate the fugitive emissions from these sources. EPA's Air Pollution Prevention and Control Division initially extended the open-path method to include measured vertical gradients to improve resolution of emission estimates. Recently segmented horizontal baseline measurements have defined the horizontal as well as vertical gradients which allows an emission flux to be measured when combined with wind field data. Fugitive emission measurements are being conducted at a bioreactor site in Kentucky evaluating both the vertical and horizontal plane for helping to measure landfill gas emissions. Open-path FTIR is also routinely used at Superfund sites to help identify what pollutants are being emitted.

3.5.4 Solids Monitoring

Solids monitoring was proposed in the Workshop as a possible method for determining the level of stabilization of the waste mass (i.e., the completeness of the bioreaction). However, Workshop participants noted that it is possible to have a large quantity of material that is not in a biodegradable state within the landfill environment. One Workshop participant noted that the procedures for analysis of cellulose and lignin could affect estimates of the degradable waste fraction because these analysis procedures may render the nondegradable material more available or more responsive than might actually be encountered in the landfill.

Measurement of cellulose and volatile solids for comparison has been proposed as a potential method to assess waste mass stability and completion of the bioreaction. However, the results of some studies suggest that the ratio of cellulose to volatile solids can be affected by inert waste streams placed in the landfill (e.g., sand). This consideration led to proposals to consider other parameters such as the cellulose:lignin ratio.

Workshop participants generally considered solids monitoring to be expensive. If multiple sampling is necessary, then the total cost per waste volume becomes quite expensive for waste with tipping fees that are generally inexpensive. Also, the analyses take a significant amount of time, and increases in these sampling and analysis requirements are speculated to result in additional laboratory capacity needs.

To demonstrate this issue and the complicated nature of the sampling and analysis process, the following example of solids sampling and analysis was provided:

- Auger into the waste with a 3-foot bucket auger and remove in 10-foot increments
- Deposit material on plastic placed in an area isolated from the drilling operations
- Continue piling removed material until the 10-foot increment is obtained
- Mix the material manually, then quarter it until a 10- to 20-pound sample is obtained
- Place the sample into a bag, package it in a drum or box, then ship it to the laboratory
- Obtain preliminary pH estimates in the field by putting some of the sample in water to form a slurry, then use a field meter to measure the pH.

The laboratory then shreds the material (if not already done in the field), dries the material in ovens (takes about 3 days), mixes the dried material, grinds it in a special mill to a fine powder (takes about 1 hour) until it resembles pastry flour, then removes lignin with acid to obtain a liquid that can be analyzed by high pressure liquid chromatography (HPLC).

This approach is very labor intensive and the analysis can run several hundred dollars per sample if a laboratory is already set up to do this. Costs are higher if a laboratory must invest in purchasing the special equipment required. Workshop participants were not aware of any commercial laboratory analysis available; one instance was cited in Wisconsin, but all of the steps up through processing the material in the special mill had to be performed prior to sending the sample to the laboratory for analysis. Another question raised in these discussions was how much solids monitoring will be needed and how much monitoring will be enough. One Workshop participant suggested that such sampling and analysis be deferred until after settlement has occurred to verify how much biodegradable material is left. Others noted that the sampling process is very destructive and costly, and therefore may not be beneficial.

3.6 PERFORMANCE MEASURES AND PERFORMANCE OPTIMIZATION

The Workshop included a number of discussions of the factors that affect bioreactor landfill performance and how to monitor or control them. In particular, bioreactor landfills have certain attributes that distinguish them from conventional municipal solid waste landfills as noted in Sections 3.1 and 3.2. Such attributes may serve to identify appropriate parameters for optimizing bioreactor landfill performance.

Another approach to optimize performance involves staggered landfill cell sizing and design. For example, a cell size could be 20-feet thick and of sufficient dimension for 1 year's worth of waste. The next cell is built while this waste is stabilizing and perhaps a third cell is built after waste is emplaced in the second cell. The next step would be to reuse the space in the first cell generated from waste decomposition.

The need to achieve optimal performance of bioreactor landfills was also discussed. Key questions raised in this discussion include the following:

- What is the benefit of less than optimum bioreactor performance, since it results in a landfill that is a hybrid of both dry tomb and bioreactor landfills?
- Will post-closure care be any shorter than for conventional landfills if the waste mass is not fully degraded?
- How are these decisions influenced by other factors such as a co-located energy recovery project that depends on optimum gas generation to be economically viable?

If optimal bioreactor landfill performance is desirable, then there are a number of operational factors that can be or may need to be manipulated or controlled to assure optimum performance or to augment the bioreaction process. Most Workshop participants considered uniform moisture distribution within the waste mass as the most important factor for optimum bioreactor operation, and also noted that this is not easily achieved. In addition, internal drainage (open drainage) through the waste mass is necessary to achieve uniform moisture distribution.

Other factors considered by Workshop participants in optimizing bioreactor landfill performance include the following:

- What is the ideal compaction goal? Should it be a goal such as 1,800 to 1,900 pounds per cubic yard or less rigorous or none at all?

- Does waste preprocessing provide any additional benefits (for example, can it improve lignin breakdown, promote gas generation for energy recovery projects, promote rapid HAP/VOC removal from the waste mass)?

- Does waste heterogeneity provides any additional benefits?

- Can heterogeneity be achieved through shredding or presorting waste materials?

- What is the impact of increased biosolids volume as a result of biosolids addition or generation in the bioreactor because of their low permeability (e.g., creating blockages or preferential flow paths within the waste mass when open flow is better for the bioreaction)?

- Are nutrients or other materials needed to augment microbial action (e.g., additional nitrogen, phosphate, etc.)?

- If there is insufficient liquid, is it better to apply liquids uniformly or to stabilize one particular portion of the waste mass fully? The choice will depend on the desired end goal (energy recovery might work best by incremental bioreaction of the waste mass, while driving the reaction to completion may work best with uniform distribution).

- Can both anaerobic and aerobic processes be used together (by injecting air into one area and injecting leachate into another, but never into the same area)?

- How do moisture needs depend on site conditions and how do they change as stabilization of the waste mass proceeds?

Workshop participants also noted that it might be necessary to develop a methodology for measuring bioreaction efficiency and to develop quantitative methods to measure waste transformation in the landfill.

3.7 Closure and Post-Closure

Given uncertainties noted previously in achieving uniform decomposition throughout large waste masses, Workshop participants raised concerns about the potential to continue generating methane gas even after stabilization of the waste mass is achieved. Some noted that even small quantities generated over a long time period might be considered unacceptable, while others expected the associated risks to be minimal.

Some Workshop participants suggested that closure times in the regulations may need to be modified to reflect actual state and landfill operator experience. State personnel noted that the 180 days allowed for closure by regulation is not usually a sufficient amount of time and that the regulations already allow for an alternative closure schedule to be set as part of the closure plan process.

Inherent in all of the discussions was how to define closure for a bioreactor landfill. Questions included the following:

- Does closure begin when the cell is full of waste as is done for conventional landfills, or when stabilization of the waste mass is achieved?
- Is closure conducted incrementally (cell-by-cell in a "rolling closure" manner) or conducted for the entire landfill at one time?
- What will be done with any excess leachate or liquid in the bioreactor landfill cell?

Some Workshop participants noted that existing regulatory methods may already address issues such as incremental or "rolling" closure, but were generally opposed to making such an approach an upfront permit condition.

3.8 Benefits

Recovered landfill space, the generation of large quantities of landfill gas, and decreasing the length of time for the environmental liability of the waste are probably the three most significant benefits of bioreactor landfills.

Landfill space is recovered through:

- Volume reduction and increased waste density achieved by solids and gas loss from decomposition of the waste mass

- Rapid settlement of the waste mass.

During the landfill operational period, recovered landfill space may allow placement of more waste tonnage into the same amount of permitted landfill volume. This reuse of landfill space can significantly increase disposal revenues and significantly increase landfill life.

The significant increase in total gas available seen within a relatively short time period (the landfill operating period plus 5 to 10 years after bioreaction initiation) provides for entrepreneurial opportunities. One is to maximize landfill gas capture for energy projects; however, a cost off-set is installation of the gas collection system, and there are significant economy of scale considerations that indicate this may not be viable for small- or medium-sized landfills. Related benefits include greatly reduced greenhouse gas emissions and the potential for fossil fuel emission offsets. When the final cover is applied, both gas generation and the moisture content of the waste mass drop dramatically. These reductions can significantly affect gas flow to support energy projects and continued bioreactor function.

Other potential benefits of this enhanced landfill performance include, but are not limited to, the following:

- Reuse of the land may be possible much earlier after installation of the final cover than with conventional municipal solid waste landfills
- A shorter life cycle that may realize significant reductions in operations, maintenance, and monitoring costs
- Treatment of leachate constituents through recirculation
- Leachate recirculation can eliminate transport, treatment, and disposal costs but this may be offset by the costs associated with leachate collection, management, and reinjection (benefit may be positive but economics may not be proven)
- Beneficial reuse of other waste streams (e.g., biosolids) that may otherwise be land applied, and reduction of their constituents within the bioreaction
- Production of a humus-like material that has potential for use as landfill cover as well as other non-landfill uses
- Reductions in long-term risk to the environment and human health.

4.0 Economics

A number of economic and cost-benefit life cycle analyses of bioreactor landfills are being conducted by EPA and private industry. These are presented in Sections 4.1 and 4.2, respectively. Section 4.3 summarizes economic considerations identified in the course of Workshop discussions.

4.1 Economic Analyses Conducted by EPA OSW

EPA OSW has been evaluating the costs and benefits of bioreactor landfills. The basis of this analysis involves the volumes and estimated components of municipal solid waste. In 1998, there were about 158 million tons of municipal solid waste and construction and demolition (C&D) debris waste placed in municipal solid waste landfills. Over half of this waste (84 million tons) was organic with the following estimated composition:

- Paper – 37.8%
- Food – 16.6%
- Yard trimmings – 11.7%
- Wood – 8.6%.

This analysis did not consider plastics and textiles in the waste volume as was noted in the Section 3.1 waste composition discussions. Approximately 83 percent of the organic waste is estimated to be amenable to decomposition.

Also of note for this economic analysis is that 84 million tons of municipal solid waste generate 6 million tons of methane and take up 85 million cubic yards of landfill space.

In evaluating the economics of bioreactor landfills, EPA OSW is examining the following concerns:

- Do bioreactor landfills pose a disincentive to recycling, reuse, and other options for waste material that may be used in the bioreaction process (i.e., will bioreactors preferentially increase the waste volume that is land disposed)?

- Are there other viable alternatives to manage organic wastestreams, such as composting, so that these wastes can be diverted from land disposal and stabilized in a much smaller amount of time than would occur in a bioreactor?

Section 4.1.1 provides an overview of this economic analysis. Section 4.1.2 presents the preliminary findings.

4.1.1 Economic Study Overview

Data needs for this and other related economic analyses include the following:

- Costs of bioreactor landfill design, construction, and operation
- Cost data to compare the effectiveness of bioreactor landfills against composting of organic materials and against conventional landfills for inorganic materials.

For purposes of this Workshop, presentations of this economic analysis focused on the comparison of bioreactor landfills with composting of organic matter.

This EPA study considers the following additional costs realized by bioreactor landfills over conventional municipal solid waste landfills:

- Construction costs associated with the installation of enhanced leachate recirculation devices and landfill gas collection systems
- Operating costs resulting from increased leachate recirculation, gas generation, permitting fees, and equipment/manpower needs.

Note that the cost per ton estimates used in this economic analysis represent the cost to the local municipality and assume separate collection of materials diverted for composting or other action. These costs were derived from an EPA guidebook published several years ago with estimates of the cost per ton to institute grass recycling and similar programs.

Potential benefits of bioreactor landfills being considered in this economic analysis include the following:

- Reduced leachate treatment/disposal costs
- Saved landfill space
- Extended landfill life
- Deferral of new cell construction
- Post-closure savings from fewer monitoring and financial assurance requirements
- More efficient gas collection with potential for revenues from energy production.

Final cost-benefit criteria for this analysis currently focus on:

- Avoided methane emissions, including revenues from energy production and greenhouse gas credits for avoided emissions

- Landfill space saved, such as additional capacity and quantities of organics diverted from landfills
- Changes in waste management costs, such as comparisons of additional operating costs against savings and incremental costs of diversion against disposal.

Uncertainties affecting the economic analysis include the following:

- How does leachate recirculation affect waste densities, settling, and compaction?
- How much more capacity is actually obtained with bioreactors vs. traditional landfills and what is the value of the "saved" space?
- How much additional methane is generated and how much can reasonably be captured?

4.1.2 Preliminary Results

Preliminary results of EPA's economic research and analysis for the comparison of bioreactor landfills and organic composting indicate that:

- Bioreactor landfills may offer improved performance and cost savings over conventional landfills
- Organic diversion has the potential to save significantly more landfill space than bioreactor landfills
- Improved diversion of organic material could more significantly reduce waste management costs than the use of bioreactor landfills
- 25.6 million cubic yards of landfill space may be saved based on an assumption that 13% additional capacity is generated by bioreactor landfill operations and consideration of different density factors for different wastes in the landfill
- Avoided methane and other gas emissions (through energy recovery or other gas collection/ utilization projects) have the potential to be considered "avoided greenhouse gas emissions" for purposes of economic analyses
- Savings from bioreactor methane are longer-term than those achieved by organics diversion, which tend to be short-term based on greenhouse gas emission credits.

This economic analysis does not currently address gases other than methane (such as CO_2). EPA also anticipates looking at the economics of transportation and other factors in combination with the end results of waste management.

4.2 Modeled Economics of Landfill Bioreactors by Private Industry

Waste Management Incorporated (WMI) is working on a variety of bioreactors and is investigating the life cycle economics of these landfills as compared to more conventional municipal solid waste landfills. WMI is developing a cost model that draws on theoretical data obtained in the United States and Europe to assess the financial investment and returns on investment for various types of landfills to identify the most cost-effective approaches, and to identify the factors that drive the economics of bioreactor landfill implementation and operation.

The economic analysis considers two broad categories: new construction of bioreactor landfills and retrofit of existing landfills to become bioreactors. The analysis also considers 10 landfill types:

- Aerobic, retrofit landfill
- Anaerobic, retrofit landfill
- Facultative, retrofit landfill
- Hybrid aerobic/anaerobic retrofit
- Aerobic, new construction landfill
- Anaerobic, new construction landfill
- Facultative, new construction landfill
- Hybrid aerobic/anaerobic, new construction landfill
- Base case, conventional municipal solid waste landfill.

The economic model considers all construction costs as well as those associated with operations, capping, closing, etc. to determine the investment required. The model also considers all investments necessary such as legal, permitting, and other cost factors.

The following sections provide an overview of the economic model and the initial results of the economic analysis. Section 4.2.1 summarizes general background information on assumptions used in the economic model. Section 4.2.2 presents preliminary findings and conclusions regarding bioreactor landfill functions, cost drivers, and overall economics.

4.2.1 Economic Model Assumptions

The different landfill types were compared to a "base" landfill with the following features:

- 140 acres with 10-acre cells and 800 cubic yards of waste in place
- Operates 275 days per year
- 2,500 tons per day of municipal, construction and demolition (C&D), solidification, and special wastes.

New landfills were similar to the "base" landfill in these features. However, the retrofit landfills involved 30-acre plots.

The economic model considers the use of other clear liquid waste streams in addition to leachate. These included clear aqueous waste streams from lettuce processing, soft drink manufacturing washdown, bakeries, etc., that had high BOD and low solids. Biosolids that could be added in liquid form were also considered and are of particular interest because they are readily available and may be relatively economical to use depending on fees and taxes.

Uncertainty presently exists regarding how leachate and other liquids will be added to the landfill waste mass. For example, there are days when workers may not be on site to conduct liquid addition (e.g., Sundays), and there are also considerations of whether to add liquids on days when it rains or snows.

Assumptions used for gas generation and management in the economic model include the following:

- Aerobic reactors have no recoverable methane (although actual experience is that there are some methane emissions

- Facultative bioreactors will produce methane at 1.5 times the rate of Subtitle D landfills

- Anaerobic and hybrid bioreactors produce methane at 2 times the rate of Subtitle D landfills and produce it very quickly.

Also, in its current form, the economic model does not assume any differences in post-closure care between the nine types of landfills.

4.2.2 Preliminary Findings

Data from the economic analyses have been compiled into tabular form to facilitate comparison of the different landfill scenarios considered in the analysis. Comparisons of all landfill scenarios to the base case determined the following for bioreactor operations:

- Gain in landfill space of 15 to 30 percent.
- Increased density of waste mass.
- Increased landfill life.
- Reduced regulatory and permitting costs over "base" landfill case.
- Significant revenues from gas generation.
- A gas collection system is more expensive to retrofit into an existing landfill (this model assumed no gas collection system for an aerobic landfill).
- Odor control systems that counteract the odor rather than mask it may be necessary. Such systems are not expensive to install, but are expensive to operate and can drive the economic model.
- Some substantial increases in investment with some offsets. For example, new construction costs may be more advantageous than retrofitting.
- Ammonia removal may also be necessary.

The largest changes in estimated costs for various types of bioreactors were found for the following factors:

- Aeration of mass or leachate
- In-situ performance monitoring instrumentation (temperature)
- Reduced leachate disposal
- Health and safety (if liquid used rather than caked biosolids)
- Odor control (significant cost per day)
- Dozer operation
- Increased water truck usage
- Decreased new construction.

WMI examined the factors that drive this economic model based on experience gained at its Metro and Live Oak facilities. These factors include, but are not limited to, the following:

- 15% gain in airspace for retrofit with 30% gain in new landfills

- Increased manpower for gas technicians (retrofit)

- Increased manpower for daily operations (e.g., new landfill requires an additional dozer operator and additional technicians to place pipe/monitor).

Potential bioreactor landfill benefits identified from these analyses include the following:

- Reduced post-closure period

- Reduced heavy equipment usage because there is less need for waste compaction

- Decreased air emissions

- Reuse of old landfill airspace on a full-scale basis — a very critical factor from the perspective of private industry.

Potential risks associated with bioreactor landfills include the following:

- Changes in design and construction to make wider cells allowing for flatter filling lifts, which involve stability and safety issues

- Changes in slope construction from 3:1 to as much as 4:1, which would result in a net loss of airspace and may preclude future reuse of the air space for waste addition

- Personnel hazards from more operating equipment, which increases the opportunity for accidents

- Odor problems.

The following conclusions were offered regarding the results of the economic analyses:

- Airspace recovery drives the economic model because that is the key selling factor to those who run landfills.

- Addition of biosolids may be an important factor and may be especially important to new construction bioreactors.
- Bioreactors do not appear to be viable in dry areas without large water sources.

- Installation of a gas collection system is less expensive for bioreactor landfills if done at the time waste is first placed in a new landfill. Even delays of only 2 years can render this economically nonviable.

- Much of the early work on bioreactors involves retrofit of existing landfills because this is easier than building a new landfill. Efficiencies and ease of applying these techniques to new landfill cells may be significantly more beneficial than retrofitting.

- Retrofitted landfills are easier to operate because of the lack of traffic for new waste and the absence of interferences from the work force that may be encountered at an active landfill.

- Aerobic landfills need to be better defined. Experience to date suggests that retrofit aerobic bioreactors are really anoxic and do not actually have aerobic kinetics.

Based on recovered air space alone, bioreactors appear to make economic sense. However, retrofitting existing landfills for bioreactor operations may not be economically viable. Additional research is needed to determine if this economic model is correct, since many of the assumptions are not yet proven at large scale.

4.3 Decision Support Tools for Estimating Landfill Gas Emissions

There are existing tools that may either be directly applicable or potentially modified to predict landfill gas emissions associated with the operation of landfills as a bioreactor. A tool that has been used to calculate the tradeoffs in environmental burdens is the municipal solid waste decision support tool (MSW-DST). This tool was developed through a cooperative agreement (CR823052) between EPA and the Research Triangle Institute. The methodology incorporates a life-cycle evaluation of the full range of multi-media and multi pollutant tradeoffs in addition to providing the full costs of a solid waste system. All the waste management activities are modeled including collection, transportation, recycling/composting, and treatment (e.g., landfilling and combustion). For those materials that are potentially recoverable and displace virgin resources and/or conserve fossil fuels, offsets are calculated for each of the recoverable materials in municipal solid waste (e.g., aluminum cans, steel cans, corrugated containers, newsprint). This tool took over 6 years to develop and has undergone rigorous stakeholder and program peer review from international experts. The result is a credible, state of the art tool for evaluating different strategies for integrated waste management.

One of the options as part of the landfill process model is operating the landfill as a bioreactor. The defaults are based on expert opinion but there is no long term data to confirm if these are accurate. Data resulting from ongoing field studies will help to determine if these defaults need to be modified.

For more information regarding the MSW-DST, refer to the project website at: www.rti.org/units/ese/p2/lca.cfm#life. This website provides a brochure and a PowerPoint™ presentation of the decision support tool, and will be updated to provide additional outputs and information on the availability of the decision support tool and life-cycle inventory database. The research team is also preparing a series of peer-reviewed journal articles to highlight the different aspects and uses of this tool and to summarize findings from case studies in different communities where this life-cycle tool has been applied.

EPA is seeking the following information to help more reliably quantify the potential burdens and/or benefits associated with bioreactors:

- Long-term bioreactor landfill operating data from operating facilities and/or demonstration projects
- Long-term data to develop or validate model inputs for anaerobic, aerobic or hybrid bioreactors
- Data to evaluate different options in use for landfill gas collection and control including timing of installation, length of time in place, type of material for cover to minimize fugitive emissions, etc.
- Types of operating data needed to support permitting and/or enforcement.

The EPA also has available a tool (i.e., Landfill Gas Emission Model[1], or LandGEM) that is used to develop state and national emission inventories, and determine applicability to CAA regulations. The model is based on a first-order decomposition rate equation. However it is based on conventional landfilling practices and would need modification to reflect bioreactor operations.

In addition to the above needs, data are also needed on:

- The potential for fugitive landfill gas emissions as compared to conventional landfilling practice
- Efficiency of existing methods for detecting landfill gas fires and/or landfill gas collection/control failures

[1] (Thornloe, S.A., A. Reisdorph, M. Laur, R. Pelt, R.L. Bass, and C. Burklin, The U.S. Environmental Protection Agency's Landfill Gas Emissions Model (LandGEM), Sardinia '99, *Seventh International Waste Management and Landfill Symposium*, Published in Proceedings, Volume IV, Pages 11-18, October 4-8,1999.)

- Information regarding contingency plans for landfill fires.

4.4 Economic Aspects Identified by Workshop Participants

Throughout Workshop discussions, participants provided a number of suggestions regarding factors to consider in economic and cost-benefit evaluations of bioreactor landfills. Many of these suggestions are presented throughout other sections of this document in the context of those particular discussions. To briefly summarize, economic and cost-benefit considerations include, but are not limited to, the following:

- Leachate transport, treatment, and disposal costs will be reduced by recirculation of this waste stream in the landfill. Off-setting costs include those associated with leachate recirculation system installation and operation.

- Increased disposal revenues from use of additional landfill capacity realized from the rapid settlement of the waste mass seen in bioreactor operations. During the landfill operational period, this allows placement of more waste tonnage into the same amount of permitted landfill volume.

- Significant increases in landfill operating life realized from the rapid settlement of the waste mass seen in bioreactor operations.

- Potential for gas recovery projects to use the large quantities of methane generated by bioreactor landfills. Economics may vary based on landfill size (smaller may be disadvantageous) and whether greenhouse gas credits can be sold. Cost off-sets also exist for installation and operation of the gas collection and management system as well as investments associated with waste preprocessing (e.g., shredding) that may be necessary for optimum gas generation.

- No energy project potential exists for aerobic bioreactors because they do not produce such significant quantities of methane as are found in anaerobic bioreactors.

- Decreased municipality cost to treat and land apply biosolids from POTWs that are instead used for liquid addition in bioreactor landfills. Off-setting costs include increased transport requirements to move a larger waste volume of liquid waste to the landfill.

- Revenues from recovery and reuse of the humus-like substance resulting from bioreaction.

Workshop participants all agreed that any economic or financial analysis must address specific goals to be achieved. These may be airspace recovery, leachate management cost reduction, methane gas recovery, or others. Thus, the outcome of the economic or financial analyses will vary and may be difficult to compare because the financial benefit depends on the goals.

5.0 Bioreactor Research and Data Needs

This section summarizes ongoing research as well as research needs and data gaps to be filled to support potentially broader use and regulation of bioreactor landfills. Section 5.1 provides an overview of current research directions within the EPA Office of Research and Development (ORD) regarding bioreactor landfills. Section 5.2 summarizes research needs and data gaps for bioreactor design, operation, and monitoring identified by Workshop participants.

5.1 EPA Office of Research and Development Bioreactor Landfill Research Directions

Although research on bioreactor landfills and containment systems in general is a relatively small effort from a funding perspective, there are a number of activities underway or planned to be conducted by EPA. Related research activities include the following:

<u>ORD/National Risk Management Research Laboratory (NRMRL)</u>

- Containment
  - Hydrologic models
  - Alternative covers
  - Superfund Innovative Technology Evaluation (SITE) Program project on asphalt additives
  - Slope stability and leachate interaction impacts on geotextiles
  - Long-term performance of containment systems

- Bioreactors
  - Monitoring requirements
  - Reactor design
  - Field evaluations (ORD and OSW have developed a Cooperative Research and Development Agreement (CRADA) with WMI to conduct a detailed evaluation of the design and monitoring of landfill bioreactors)
  - Model for estimating life cycle environmental burdens, which also evaluates capital and operating costs

- Landfill Emissions
  - Air issues, characterization, and controls for landfills
  - Field tests to characterize municipal solid waste landfill air emissions and to evaluate options for controlling landfill gas emissions through synthetic covers and other approaches to minimize environmental burdens
  - Data to develop and/or verify default values in life-cycle inventory decision support tool for characterizing long-term environmental burdens and/or benefits; however, data over many decades may be needed.

National Center for Environmental Research (NCER)-Supported Research

- Science to Achieve Results (STAR) Grants Program – centralizes much of the research funding within ORD, and involves competitive, peer-reviewed, extramural investigator-initiated research grants for innovative solutions to environmental problems. Solicitations are held four times a year in specific topic areas. The STAR Program has funded proposed projects that cover a wide range of research priorities. Additional information may be found on their website at www.epa.gov/ncerqa.

- Hazardous Substance Research Centers – fund different groups of universities. One proposal (not yet finalized) addresses bioreactors.

- Small Business Innovative Research Program – helps fund small business ideas. This is a potential avenue for bioreactor research.

- University of New Orleans – has a small amount of funding from EPA dedicated to landfill research

eXcellence and Leadership (XL) Program

- A national pilot program allowing state/local governments, businesses, and Federal facilities to work with EPA in developing innovative strategies to test better or more cost-effective ways to achieve environmental and public health protection

- Bioreactor projects under this program include:
  - Yolo County, California
  - Buncombe County, North Carolina
  - Maplewood and King George County Landfills, Virginia
  - Anne Arundel County, Maryland

- Additional information can be obtained from the EPA Office of Reinvention or the EPA website at www.epa.gov/ProjectXL.

5.2 Landfill Bioreactor Research Needs and Data Gaps

The history of bioreactor research involves in the U.S. the following timeline of events:

- 1970s – laboratory- and pilot-scale studies showed that bioreactors worked at small scale

- 1980s – first generation full-scale application in Delaware and California

- Early-mid 1990s – second generation of full-scale applications, yet uncertainties remain about how to design and operate them
- Late 1990s/2000 – tremendous growth in interest in implementing this technology with attempts being made to address how to do this at full scale, how to regulate it, and how to determine the economics issues.

The following sections summarize research needs, data gaps in bioreactor landfill understanding, and other suggestions identified by Workshop participants throughout the Workshop discussions. These suggestions are organized by topic areas consisting of bioreactor landfill design (Section 5.2.1), operation and performance (Section 5.2.2), and monitoring (Section 5.2.3). Section 5.2.4 addresses life-cycle, cost-benefit, impact, and economic analysis suggestions. Section 5.2.5 presents general suggestions for research focuses, information sources, and education. Data needs and Workshop participant recommendations pertaining to regulations and regulatory development activities are addressed in Sections 2 and 6 of this document.

5.2.1 Design

Workshop participants expressed many different views on the definition of a bioreactor landfill:

- Base the definition on the end product?
- Include leachate recirculation in the definition?

Others suggested considering bioreactor landfills as simply an alternative operating/management approach to conventional municipal solid waste landfills.

Criteria may be needed in circumstances where it is or is not appropriate to use bioreactor landfills. For example, some Workshop participants suggested that the use of bioreactors in arid environments may not be appropriate. Some Workshop participants also suggested that identifying all of the criteria that need to be considered may be difficult because the bioreaction process can be so site-specific.

Questions were also raised regarding the performance of aerobic bioreactor landfills. Of specific note was whether aerobic landfills would be capable of achieving the performance that anaerobic landfills are considered capable of achieving..

Currently there is only very general knowledge of the activities and roles of microbial populations in the bioreaction process. Better understanding of that process may lead to techniques to monitor or control the reaction as is done for other types of fermentation processes. This may require the development of culturing techniques or adapting modern molecular techniques to obtain the necessary data.

Data needs pertinent to bioreactor landfill design include the following:

- Techniques to measure head on a liner and whether there are more efficient options than installing large numbers of sensors
- Whether single liners or unlined landfills are appropriate for bioreactor landfill operations
- Whether sufficient information is already available regarding waste properties and actual bioreactor landfill operating conditions to use existing tools for predicting landfill stability and failure
- Methods or techniques to assure slope stability
- Timing and placement of temporary covers
- Appropriate materials for temporary and final covers
- Whether materials exist or can be developed that will let water into the landfill yet keep gas from being emitted to the atmosphere.

The performance benchmark for bioreactor landfills expressed throughout many of the Workshop sessions is the RCRA Subtitle D municipal solid waste landfill. Some Workshop participants raised the following questions regarding the use of this benchmark:

- Is the RCRA Subtitle D landfill the appropriate benchmark?
- Is more research on Subtitle D needed in parallel with bioreactors to enable comparison?
- What are the appropriate performance questions to address in demonstration projects:
  - Are bioreactors superior or environmentally preferable to the RCRA Subtitle D landfills?
  - Can bioreactor landfills be shown to be safe and controllable (i.e., protective of human health and the environment)?

Note that the CAA regulations only require demonstration of "similar" not "superior" performance. "Superior" is only required in the XL Program.

5.2.2 Operation

A major question raised by Workshop participants was whether the bioreaction can be stopped once it is started. Many believed that it cannot be stopped at all or that it cannot be quickly "shut off" (like a valve). Therefore, the ability to control the reaction was identified as an operational research area.

Other significant questions arose as to how to define when the bioreaction is "done" or how and when to stop the reaction so closure or post-closure care can begin. Workshop participants noted the following potential areas requiring research to make those determinations:

- Gas generation
- Settlement
- Waste mass reduction.

Table 5-1 presents research needs and data gaps identified by Workshop participants for the following operational considerations: waste emplacement, settlement, leachate collection system performance, controls for internal landfill environment to promote optimum performance, liquid recirculation, and gas management.

In addition, Workshop participants noted the important need to develop complete material balances and estimates of water consumption to support better understanding of the bioreactor landfills. Quantification of the water balance involves the following at a minimum: incoming waste moisture, preferential flow paths through waste, difficulties in achieving even moisture distribution, runoff, evapotranspiration, infiltration, waste field capacity, and average waste flow.

5.2.3 Monitoring

Workshop participants identified the following research needs or data gaps for monitoring landfill bioreactors:

- Consider research in the early 1990s regarding the disappearance of oxygen (air) and changes in helium to determine respirometry

- Type(s) of monitoring instrumentation needed (requires integration of waste engineers, geotechnical personnel, and biochemical personnel to address)

TABLE 5-1. RESEARCH NEEDS AND DATA GAPS FOR BIOREACTOR LANDFILL OPERATIONS

WASTE EMPLACEMENT	SETTLEMENT
• Whether to compact the waste at the time of emplacement or let the waste mass and overburden do that • Methods to compact waste and prevent side seeps without preventing moisture migration	• How to define volume loss • Collect data on characteristics of old or decomposed waste (such as shear strength) to address potential stability issues
LEACHATE COLLECTION SYSTEM PERFORMANCE	**LIQUID RECIRCULATION**
• Methods for in-situ measurements of pore pressure • Criteria to define performance • Methods to monitor performance • Whether the absence of leachate means that no leachate is being generated or that there is a failure in the collection system • Methods to prevent plugging of the collection system	• Methods to recirculate liquids to acheve a uniformly wet landfill • Methods to control how moisture moves through a landfill • Determining how much water is necessary considering cover, preferential channels, and waste hetereogeneity effects on moisture content • Whether to use other types of liquids (nonindigenous liquids) to supplement nutrients/moisture, dispose of other liquid waste streams, compensate for insufficient waste volumes, and/or to avoid concentration of inorganic contaminants • Methods to measure moisture level
CONTROL OF INTERNAL LANDFILL ENVIRONMENT FOR OPTIMUM PERFORMANCE	**GAS GENERATION AND MANAGEMENT**
• Whether pH or moisture content control are necessary • Whether shredding or other waste pre-processing techniques enhance performance • Methods to assure uniform flow of liquid and gas with consideration of new geosynthetic materials, strip drains, etc. • Whether moisture distribution is more appropriately expressed in terms of thermo dynamic activitiy and matrix potential (for thriving of microbial populations) or more traditional weight fraction? • How waste permeability changes vertically within the landfill • Identifying key factors optimizing this environment and the appropriate indicator methods • Appropriate goals or performance levels and operating conditions that will achieve these as quickly as possible	• More efficient/economical methods for gas capture and use • More efficient/economical methods to avoid or control odors • Whether to recycle methane to aerobic parts of the landfill as an energy source for the microbes • Consider establishing different criteria for explosion hazards and greenhouse gas emissions, for example: -explosion done=measurements show X% of lower explosive limit after Y years -greenhouse done=measurements show X% of lower explosive limit after Y years • Acquire emissions data for bioreactor landfills • Determine appropriate default values for methane generation rate and potential under bioreactor landfill operations

- Methods to package instrumentation to track and display data in a useful way
- The number of groundwater monitoring wells needed
- Parameters, values, or other measures that can be used to define the end of the post-closure monitoring period
- Improved, more accurate measurement methods for landfill gases.

5.2.4 Life-Cycle

A number of Workshop participants suggested that the bioreactor landfill contributes to sustaining the landfill life-cycle. Europeans have a concept of a sustainable landfill with the following features: outputs do no harm, outputs represent no long- or short-term risks, hazard at post-closure is not passed on to future generations, and use of landfill is unimpaired. Workshop participants noted that the ability to apply such an approach requires the following questions to be addressed:

- When is the decomposition completed?
- When is waste within a landfill stabilized?
- How much degradation is needed before the waste and landfill pose little risk?
- What kind of cap or other operating issues are required to control fires, metals, etc. so that such a landfill can pose little risk?

Some Workshop participants consider sustainability to involve complete reaction and stabilization of a bioreactor that is eventually dug up, reclaimed, and landfilled again. Such a scenario does not require post-closure care.

Benefit, impact, and economic analysis research needs, data gaps, and suggestions from Workshop participants include the following:

- Approach a bioreactor landfill as a closed treatment system and evaluate the benefits as compared to traditional management methods involving open treatment systems (e.g., land application of biosolids)
- Post-closure long-term usage options include reuse of the space generated to emplace more waste or use for recreation

- Develop a better definition of bioreactor benefits
- Acceptability of continuing to generate small quantities of landfill gas after the post-closure period
- Develop improved models with defaults reflecting bioreactor operations and emissions
- Consider that waste generation continues to rise when conducting alternatives analysis
- Economic viability of recovering the gases produced in large quantities early in the bioreactor process.
- Define economic impacts by weighing benefits (such as enhanced gas production, recovered space, reduced environmental impacts, reduced post-closure care) and costs
- Whether bioreactor landfills are economically more viable for some waste streams and how the cost per ton may vary; for example, some wastes may be more expensive to treat in a bioreactor landfill than others (e.g., food/organic matter are easiest, and paper/wood is easier than metals)
- Need to identify the point at which gas monitoring is more expensive than installing and operating a gas extraction system
- Cost-effectiveness of opening up an alternative cover to check waste mass degradation or to mine landfill materials.

5.2.5 General Suggestions

A number of general suggestions for research topics, data needs, or other aspects of evaluating bioreactor landfills for broader use and application arose throughout the course of Workshop presentations and discussions. These included the following:

Research

- Commitments to long-term research are important. For example, landfill research was active 20 years ago, then declined significantly, and is now increasing
- Consider focusing research on aerobic environments since this type of landfill may accomplish in 1 to 2 years what an anaerobic bioreactor landfill accomplishes in 5 to 10 years
- Consider what Europe and Japan are doing on a larger scale to avoid duplication of effort

- Develop interfaces with European and Japanese researchers to share information

- Research community needs to collaborate in some manner to leverage the available funding to its best use

- EPA needs to prioritize and focus its research efforts and research priorities so that private industry can focus its research activities to avoid duplication of effort

- Private industry research initiatives encompass gas rates, sampling, mass collection, and leachate collection, among others

- Identify additional funding sources for the background research and testing identified in the Workshop since the collection of such data may be valuable but is also very expensive

Information Sources

- There are many 40- to 60-year-old landfills throughout the United States that might help answer some of the questions raised in this Workshop

- California has both wet and dry landfills that might be able to support some of the proposed research studies

- Consider a formal or informal ongoing dialogue between EPA, academia, regulators, and the solid waste industry, preferably over the long-term, for further information exchange in addition to the state-by-state dialogue already underway

- The Wisconsin Department of Natural Resources will soon publish a report regarding the Metro bioreactor landfill activities

- Re-examine research conducted 10 to 20 years ago to see if it has value to current efforts

- With current research plans, much more will be known about bioreactor landfills over the next 3 years

Education

- Bioreactor landfills involve more sophisticated operations than conventional municipal solid waste landfills, so education programs may be necessary for the companies and individuals considering this alternative to better understand both the basic operations and the ramifications and risks because of the potential for massive failures

- Consider educating solid waste industry and the public about the differences between wet landfills and bioreactor landfills

- Develop some design and operations training for air emissions aspect of bioreactor landfills

- Modify existing training for new air regulations to spend more time on wet landfills and to address landfill fires.

6.0 Regulatory and Rule Change Needs

Workshop sessions covered a wide range of technical, regulatory, and economic discussions pertaining to the definition, design, operation, closure, and overall implementation of bioreactor landfills. Section 6.1 presents the EPA perspectives identified during the Workshop pertaining to areas of potential regulatory areas of focus. Section 6.2 presents the suggestions offered to EPA by Workshop participants to consider in developing regulations for bioreactor landfills.

6.1 EPA Perspectives

EPA is focusing is on what changes can be made to existing landfill criteria to enable the use of bioreactor landfills, especially requirements that ensure such systems are protective of human health and the environment. Bioreactor landfills do involve different operations as compared to conventional municipal solid waste landfills.

Issues EPA identified from Workshop discussions for consideration in developing or modifying regulations include the following:

- What is the timing of regulatory change — while several small, full-scale projects are underway, bioreactor closure has not yet been accomplished. Should work on regulatory changes begin now or when more information from these projects is available?
- Will states view Federal regulatory Subtitle D changes that support/foster bioreactor operation in the near term as creating pressure to develop and issue more bioreactor landfill permits than they are comfortable doing?
- Should waste be shredded?
- If moisture is not applied uniformly to waste in the bioreactor landfill, does this impact the need to provide monitoring long-term or in perpetuity, which may be longer than the 30-year post-closure period under RCRA Subtitle C regulations? This issue is of particular note in the SBREFA comments received to date on the RCRA Subtitle D requirements (as described in Section 2.1).
- What is the appropriate timing of final cover installation to ensure its integrity?
- Should EPA specify certain design standards?
- Should EPA specify control mechanisms and their performance?

- Rather than specifying design standards and/or control mechanisms, should EPA develop technical guidance for state personnel; for example, a series of factors to consider such as monitoring for moisture or temperature and when to install such components?

- What special regulatory provisions, if any, are appropriate only to existing landfills or only to new landfills?

EPA representatives believe that the existing Subtitle D regulations provide sufficient flexibility for states to approve alternative materials for daily cover, and State representatives noted that authority already exists to approve alternative liners as well. However, allowing the addition of liquids to a landfill for the bioreaction to work properly would involve a major regulatory change.

One option identified for the short-term is the potential use of research, development, and demonstration (RD&D) permits under RCRA Subtitle C regulations, pending development of regulations. This option received a significant positive response by many Workshop participants.

Many Workshop attendees felt that bioreactor landfills were not yet ready for any type of prescriptive regulation and that flexibility, such as that offered by RD&D permits, may be most appropriate at this time to enable private industry to develop a better understanding of how to best design and operate such facilities.

6.2 Workshop Participant Suggestions

Other regulatory changes proposed by Workshop participants included the following:

- Adapt the regulatory framework already in existence to include bioreactor landfills

- Approve full-scale bioreactor use with basic performance parameters

- Include "or equivalent" with any prescriptive requirements such as those for liners to provide necessary flexibility

- Use testing and monitoring in lieu of prescriptive requirements; for example, requiring testing at the end of the waste stabilization period to determine if waste stabilization has attained the necessary level

- Draw on other regulatory experiences that involved flexibility in developing site-specific stanWorkshop dards; for example, the development of a standard for cyanide to identify when it was "inert" in waste material from gold mining operations, thus enabling the material to be left in place without capping

- Allow flexibility to use single composite liners, mixed composite liners, and double liner systems with an interliner detection system

- Include regulatory flexibility regarding temporary and final cover selection to avoid a bathtub effect of letting liquid in from the top and precluding its release from the landfill base

- Consider viewing alternative final covers as a partial or incremental closure approach since these covers seem to be a variation of temporary covers

- Consider the range of landfills that may be encountered since cover requirements may vary depending on the landfill type (e.g., dry tomb vs. bioreactor vs. landfill types in between the two)

- If a double liner requirement is imposed for bioreactor landfills, then more liberal operating requirements/flexibility should also be included (trade-offs between prescriptive requirements and flexibility)

- Establish criteria for clean closure

- Establish a threshold for gas monitoring (trigger level requiring action if it is exceeded) and an analytical method that an operator can use to show whether this threshold is exceeded.

- Include regulatory flexibility to allow for new processes in the future that may focus on achieving other goals

- Include emergency cleanup provisions (for hurricanes, tornadoes, etc.) — Federal actions may take place under Federal Emergency Management Agency (FEMA) emergency rules and some states already have such emergency provisions; however, many states already feel the regulations offer sufficient flexibility

- Address solid waste management in a way that is not a burden to future generations to maintain caps and leachate collection systems or to continue groundwater monitoring

- RCRA Subtitle D authorizes the Director of a state agency to authorize variations so the states may be the place where regulatory change to RCRA stardards is needed

Workshop participants regularly noted throughout the Workshop presentations and discussions that not every solution will fit every landfill. This is the basis for many suggestions regarding the need for flexibility in regulations for bioreactor landfills.

Regulatory agency representatives raised the question as to whether there should be minimum prescriptive regulatory criteria for bioreactors and what such criteria might involve. Many workshop participants (industry and state regulatory personnel) expressed a preference for performance standards rather than prescriptive requirements because prescriptive standards can quickly become technologically out-of-date and often do not provide regulatory personnel with the flexibility to approve new technologies and techniques as they develop. Another argument in favor of performance measures is that they may help regulatory agency personnel to interpret information and data provided by landfill owners/operators. State regulatory personnel noted that for performance-based standards to be successful, there needs to be a foundation of guidance and technical input from industry, consultants, researchers, and other knowledgeable personnel. Others raised concerns about potential misuse of performance-based standards, which is one reason prescriptive requirements are often put in place. Workshop participants anticipated that ultimately there will be a combination of performance-based and prescriptive requirements.

Other regulatory issues raised by Workshop participants included the following:

- Life cycle bioreactor landfill economics are strongly influenced by whether or not energy is recovered, and this is largely due to the credits received for lack of fossil fuel emissions from use of the gas generated at the landfill. This is difficult for EPA to address since it has no statutory basis to regulate methane.
- Nitrogen oxide (NOx) emissions from the bioreactor landfill and from leachate management/recirculation may be a concern, and may affect the ability to conduct such activities in nonattainment areas.
- Verify the inputs for existing EPA models that evaluate environmental burdens and also determine the need for new landfill gas models for different types of bioreactors.
- Revise existing EPA models for gas emissions and other aspects to reflect bioreactor landfill operations properly.
- Develop a white paper on health risks and safety issues associated with liquids addition and resulting vectors and odors to obtain uniform acceptance within the regulatory community.

- Develop a working policy on the use of biosolids as the liquid supplement to a bioreactor landfill as well as the potential differential settlement aspects of biosolids use as a cover.

- Conduct additional testing and monitoring to understand the bioreactor landfill better, which in turn will support development of performance-based standards.

- Potential need for more staff at the state level to address permitting and implementation of bioreactor landfills.

Many Workshop participants felt that it was premature to have nationwide regulatory changes but that more technical guidance was needed. Examples include:

- Add a chapter to existing landfill guidance document or develop a new guidance manual to address bioreactor landfills

- Provide guidance on developing the context for large-scale air issues to facilitate issue resolution with local regulatory agencies

- Additional training for regulatory agency decisionmakers to enable broader problem solving in lieu of heavy reliance on prescriptive rules and interpretations

- Consider additional training or guidance for state regulatory personnel to enhance understanding of these nontraditional practices.

7.0 Conclusions and Recommendations

The Workshop presentations involved two days of interactive and wide-ranging discussions on bioreactor landfill design, operation, monitoring, economics, benefits, risks, and regulatory strategies. Throughout these discussions, there arose a number of common themes:

- Bioreactors need to be evaluated to determine their potential environmental burdens and/or benefits for the wide range of bioreactor types under consideration. Data over the long term (several decades) are needed for all pathways including air, ecosystems, water, and land.
- Bioreactors may not be suitable for some geographic areas or some types of landfills.
- Large quantities of aqueous liquids are needed to sustain/optimize the bioreaction process, therefore supplemental liquids may be necessary since the bioreactor landfill may not generate sufficient leachate quantities for good bioreactor performance.
- Consider both methane recovery and reuse of decomposed materials in the landfill.
- Recovered airspace is of great economic interest to solid waste management firms.
- Concerns exist about the physical stability of wet waste within the landfill and the stability of the waste mass if new waste is placed on top of old, decomposed waste.
- Need to set specific goals for research programs, financial analyses, regulations, and performance.
- RD&D permit approach is very promising and is of great interest.
- Not every solution will fit every landfill, therefore state programs need regulatory flexibility and landfill owners/operators want regulatory flexibility.
- Performance-based measures were generally preferred over prescriptive requirements.
- Actively seek out the bioreactor landfill experience and research in Europe and Japan.
- EPA needs to set research priorities so that private industry can focus its research and avoid duplication of effort.
- Education programs are needed to help the regulators, solid waste industry, and public understand these types of landfills, their benefits, their risks, and what is needed for proper operation/performance.

In a summary session, Workshop participants identified the following general research areas:

- Integrated waste management trade-off analyses (i.e., evaluate different management strategies for the same waste stream throughout the entire waste stream life-cycle)
- Understand biodegradation in landfills by microorganisms
- "Completeness" of degradation – when/how to stop
- Functionality:
  - stability of slopes
  - water in/gas out materials
  - moisture distribution
  - instrumentation
  - liner design for containment/monitoring
  - post-closure and long-term usage
- Volume loss and settlement
- Hydraulic conductivity vs. waste depth and degradation status
- Ultimate fate and shutdown
- Sustainability via reclamation
- Monitoring needs
- Landfill gas emissions targets and methods
- Environmental burdens/benefits for the wide range of bioreactor types under consideration
- Long-term burden/benefit data for all pathways including air, ecosystems, water, and land
- Data for inputs to models used to develop state emission inventories and to determine applicable regulatory requirements
- General bioreactor guidance/support

- International collaboration
- Educational outreach
- Bioreactor optimization measures
- Known existing performance baseline
- Application limitations – only for Superfund sites? Unsuitable for arid regions?
- Waste preprocessing
- Designer/operator training.

APPENDIX A

AGENDA
FOR
USEPA WORKSHOP ON LANDFILL BIOREACTORS

US EPA Workshop on Landfill Bioreactors
Hilton Crystal City Hotel, Arlington, VA
September 6 - 7, 2000
Agenda

Purpose and Scope: To assess the state-of-the practice of landfill bioreactors and to identify research needs.

Wednesday, September 6, 2000

9:00 AM - 9:10 AM	Welcome and Introductions - *John Martin, ORD/NRMRL*
9:10 AM - 9:35 AM	US EPA Office of Solid Waste - History and Need - *Robert Dellinger*
9:35 AM - 9:55 AM	US EPA Office of Water - Overview of the Landfills Effluent Limitations Guidelines - *Michael Ebner*
9:55 AM - 10:15 AM	US EPA Office of Air Quality Planning and Standards - MSW Landfill Clean Air Act Regulations and Bioreactor Operation Air Pollution Concerns - *Michele Laur*

10:15 AM - 10:30 AM BREAK

10:30 AM - 11:00 AM	US EPA Office of Research and Development - Research Directions - *Fran Kremer*
11:00 AM - 11:45 AM	State Regulatory Perspectives – *Robert Phaneuf, New York State Dept. of Environmental Conservation and Richard Watson, Delaware Solid Waste Authority*

11:45 AM - 1:00 PM LUNCH

	Session: Theory/Expected Benefits Moderator: *David Carson, US EPA*
1:00 PM - 2:00 PM	Theory/Expected Benefits and Types of Bioreactor Operational Techniques: Anaerobic and Semi-Aerobic - *John Pacey, EMCON*
2:00 PM - 2:10 PM	Economics Introduction - *Scott Palmer, US EPA*
2:10 PM - 2:30 PM	Modeled Economics of Landfill Bioreactors - *Gary Hater, Waste Management, Inc.*

2:30 PM - 2:45 PM BREAK

	Session: Case Studies - Performance Moderator: *David Carson, US EPA*
2:45 PM - 3:10 PM	Sandtown, DE - *Richard Watson, Delaware Solid Waste Authority*
3:10 PM - 3:35 PM	New River, FL - *Debra Reinhart, University of Central Florida*
3:35 PM - 4:00 PM	Yolo County, CA (EPA Project XL) - *Ramin Yazdani, Yolo County Dept. of Public Works*
4:00 PM - 4:25 PM	Worcester Co., MD - *Ken Kilmer, EA Engineering Science & Technology*
4:25 PM - 4:50 PM	Louisville, KY - *Roger Green and Gary Hater, Waste Management, Inc.*
4:50 PM - 5:15 PM	Williamson Co., TN - *Mark Hudgins, Environmental Control Systems, Inc. and Jo House, Civil and Environmental Consultants*

5:15 PM ADJOURN

Thursday, September 7, 2000

8:00 AM - 8:10 AM	Opening Comments - *John Martin, US EPA*
	Session: Design and Operational Issues Topics: Where/When to Employ, Design Options, including facultative, anaerobic / aerobic sequential designs, Operation *Discussion leaders listed below; discussion open to all*
8:10 AM - 9:30 AM	Discussion Leaders: *Debra Reinhart, University of Central Florida and John Pacey, EMCON*
9:30 AM - 9:45 AM	BREAK
	Session: Monitoring Goals Moderators: *Wendy Davis-Hoover, US EPA and Bill Mahaffey, Pelorus EnBiotech Corp.* Topics: What, When and Where do we need to monitor, What are the best methods *Discussion leaders listed below; discussion open to all*
9:45 AM - 10:30 AM	Air/Gas - *Discussion Leaders: Susan Thorneloe and Michele Laur, US EPA*
10:30 AM - 11:15 AM	Groundwater/Leachate - *Discussion Leaders: John Wilson and Michael Ebner, US EPA*
11:15 AM - 12:00 PM	Physical Stability - *Discussion Leaders: Robert Koerner, Geosynthetic Research Institute and Gregory Richardson, G. N. Richardson & Associates, Inc.*
12:00 PM - 1:00 PM	LUNCH
	Session: Monitoring Goals continued Moderators: *Wendy Davis-Hoover, US EPA and Bill Mahaffey, Pelorus EnBiotech Corp.* *Discussion leaders listed below; discussion open to all*
1:00 PM - 1:30 PM	Volume / Solids Degradation - *Discussion Leaders: John Novak, Virginia Tech and Morton Barlaz, NC State University*
1:30 PM - 2:00 PM	Microbial Aspects of Refuse Decomposition - *Discussion Leaders: Don Crawford, University of Idaho and Mary DeFlaun, Envirogen, Inc.*
	Session: Research Needs, Identification of Data Gaps for New Facilities and Retrofits, Remediation Topics: Monitoring, Operational design, e.g. water loading rates, stability, and Operational changes at facilities *Discussion leaders listed below; discussion open to all*
2:00 PM - 3:15 PM	Discussion Leaders: *David Carson, US EPA and Debra Reinhart, University of Central Florida*
3:15 PM - 3:30 PM	BREAK
	Session: Discussion on Landfill Regulations Topics: Regulations and Rule changes Needed Operate Bioreactors *Discussion leaders listed below; discussion open to all*
3:30 PM - 4:30 PM	Discussion Leaders: *Robert Dellinger and Dwight Hlustick, US EPA*
4:30 PM - 5:00 PM	Wrap-Up Session - *John Martin, US EPA*

APPENDIX B

WORKSHOP ATTENDEE LIST

U.S. EPA's WORKSHOP ON LANDFILL BIOREACTORS

September 6 - 7, 2000

Arlington, Virginia

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APPENDIX C

CASE STUDIES
OF
BIOREACTOR LANDFILL PERFORMANCE

APPENDIX C

CASE STUDIES OF BIOREACTOR LANDFILL PERFORMANCE

Six case studies of bioreactor landfill research and demonstration projects were presented in the Workshop by state government, local government, academia, and private industry:

- Sandtown, Delaware – Delaware Solid Waste Authority (DSWA)
- Florida Bioreactor Landfill Demonstration Project, New River Regional Landfill – University of Central Florida
- Environmental Protection Agency (EPA) eXcellence and Leadership (XL) project – Yolo County, California
- Worcester County, Maryland – EA Engineering Science & Technology
- Outer Loop Landfill Bioreactor Studies, Louisville, Kentucky – Waste Management, Inc. (WMI) and the EPA
- Williamson County, Tennessee – Environmental Control Systems, Inc., and Civil and Environmental Consultants.

The following sections briefly describe these case study presentations.

C.1 SANDTOWN, DELAWARE – DELAWARE SOLID WASTE AUTHORITY

The DSWA conducted a Test Cell Program in association with the EPA. This program began in 1987 and tested a number of different liners and landfill systems. Site conditions throughout Delaware consist of high groundwater and sandy soils so locally available cover materials have high permeability.

Two double-lined test cells were constructed and filled with household waste; four different liners were tested. Flumes were constructed for stormwater control and measurement. Groundwater monitoring wells were also installed.

Test Cell 1 was constructed and operated as a wet cell. A leachate recycling field was installed over the first waste lift. The drainage layer consisted of 2 feet of sand. Recirculation lines connected to a storage tank system.

Test Cell 2 was a dry cell. A geotextile was used for the drainage layer. Two collection system types were installed: with and without piping. Results found that the use of piping was preferable.

There were concerns about hydraulic head buildup on the liner system. However, they were unable to measure the hydraulic head, so it was believed to not exceed more than 1 foot.

The goals of this study were to compare dry and wet landfills (i.e., typical landfill and bioreactor), and to conduct a full-scale test of a bioreactor landfill. The following aspects were monitored and compared:

- Leachate generation rates – more leachate was generated during dry cell operation than in the wet cell. This was possibly the result of permeability differences in the daily cover. After the final cover was installed on both cells, leachate generation rates became very similar, but the decomposition rate in the wet cell ended up being twice that experienced in the dry cell.

- Leachate characteristics – leachate from both cells was very similar during the operational period. Chemical oxygen demand (COD) was greater than 10,000 mg/L in the first year. After the final cover was installed 5 to 6 years later, COD significantly decreased to 500 to 700 mg/L in the wet landfill, and to approximately 200 mg/L in the dry cell.

- Moisture levels in the test cells – this proved difficult to measure. Lysimeters were installed in the waste and in the wells, but the data obtained may be questionable. This points to the need for a reliable technique to measure moisture level.

- Landfill gas generation rates – the sandy nature of the cover materials made it difficult to measure gas generation rates as well as was desired. However, results indicated that gas generation in the wet cell was about an order of magnitude higher than in the dry cell.

- Landfill gas characteristics were very similar between the two cells with methane consisting of about 50 percent of the gas.

- Leachate recirculation system performance – limited data were available because such a small leachfield was used (50 feet by 50 feet) on top of the cell. These tests relied on horizontal rather than vertical liquid addition.

- Liner performance – four types of liners were studied. These liners were tested before and after use in the test cells. No significant deterioration of any kind was found.

- Capping system performance – first a soil cap was tried, then a partial cap was placed on top, and finally side slopes were capped with polyethylene. Only a few inches of settlement were seen. However, the scale of the test was not large enough to draw conclusions from the data.

The test included a simulated cap failure on the dry test cell. Once leachate characteristics demonstrated decreased COD, an area of the cap was opened and several thousand gallons of water were added over a few weeks. Leachate changes were monitored during and after water addition. The study found that the added water took about 45 days to reach the collection system, at which time the leachate COD increased to about 30,000 mg/L. This result indicated that a real concern for future performance of a landfill includes re-initiation of the bioreaction process following cap failure.

Types of alternative daily covers tested included tarps and spray foam.

The final soil cover had a permeability of $1x10^{-4}$ cm/sec. After placement, there was a significant amount of leachate generated; in some cases, more leachate was generated than could be used for recirculation.

Other cover types tested included:

- Astroturf placed over used carpet with tires used to hold down the material resulted in a slight, insignificant reduction in leachate production. Significant side slope penetration by liquids was experienced with this approach.

- Polypropylene (black) was laid on the side slopes and reduced leachate generation by an order of magnitude.

Late in the study, the test cells were opened and the waste excavated to determine the results of decomposition. The organic decomposed material represented more than 50% of the waste mass (by weight) in the wet cell, while the same material was less than 50% of the waste mass (by weight) in the dry cell.

Landfill mining was also examined in another study. The leachate collection system in another wet landfill (built in 1980) experienced a decline in leachate removal requiring excavation into the cell to determine the nature of the problem and make repairs. This landfill had a polyvinyl chloride (PVC) liner and the leachate collection system consisted of septic pipe wrapped with geotextile. Upon excavation, it was determined that the septic pipe was crushed by the weight of the landfill waste and the geotextile had severe biofouling.

Upon excavation, the waste mass was found to be very moist in some areas and dry in others, but no gushing liquid was encountered. A crude vertical recirculation system was found within the waste mass that contributed to the moisture differences encountered.

Waste material was screened upon excavation. The fines were used for daily cover. Instances were encountered where waste within plastic bags showed no decomposition whatsoever (e.g., 10 year old green grass). This finding indicated that leachate was not distributed within the landfill as well as was desired.

The decomposed waste resembled soil or compost. The nondecomposed material was contaminated by leachate and was therefore unsuitable for recycling or other reuse.

Test program conclusions included the following:

- If properly designed and constructed, bioreactor landfills are attractive alternatives to conventional landfills

- Use of tarps or foam for daily cover is promising

- Use of polypropylene for capping and liner is promising

- Geonets are preferable for leachate collection systems

- Trommeling is the preferred processing method for landfill mining

- The most useful recycled product mined from the landfills is daily cover, which has high costs but may be appropriate for certain applications.

C.2 FLORIDA BIOREACTOR LANDFILL DEMONSTRATION PROJECT, NEW RIVER, FLORIDA – UNIVERSITY OF CENTRAL FLORIDA

The Florida Bioreactor Landfill Demonstration Project has the following objectives:

- Demonstrate full-scale use of bioreactor technology
- Evaluate aerobic bioreactor technology
- Compare aerobic and anaerobic processes
- Control and measure all inputs and outputs.

The Florida Department of Environmental Protection is the primary funding source for this project.

The landfill for this demonstration consists of the following:

- Three cells with a composite liner

- Leachate collection in one cell consists of sloped geomembranes; no piping is used

- Recirculation of leachate and air in two of the cells

- Leachate/air injection conducted through well clusters on 50 foot spacings and drilled to various depths

- Permeable daily cover (10^{-5} cm/sec).

This is a retrofit because 75 feet of waste are already in place. Wells will be installed into the existing waste mass using direct push technology as well as a new version of air-driven rotary drill. This latter technique drilled very rapidly, but it was harder to take samples.

Gas will be collected from the leachate collection system and from beneath the landfill cap using positive displacement blowers to create a vacuum. Trenches will be placed below the cap to assist with gas collection. Collected gas will be brought to a flare and burned.

This study will measure the following:

- Leachate quantity and quality
- Landfill gas quantity and quality
- Waste properties
- Settlement.

Instrumentation will be placed to measure:

- Head on liner (using 128 pressure transducers outside the waste area)
- Leachate flow
- Landfill temperature
- Moisture content (through measured resistance).

Upon receipt of the final permit (estimated to be December 2000), construction should begin with recirculation beginning in 2001. A large quantity of liquid will be added, followed by addition of sufficient water over time to sustain the reaction. Groundwater and possibly stormwater runoff will be used to supplement leachate for water addition as insufficient leachate is anticipated to be generated. However, the State of Florida has put a ceiling on the amount of water allowed to be added.

C.3 EPA PROJECT XL – YOLO COUNTY, CALIFORNIA

Yolo County has a bioreactor landfill demonstration project under the EPA Project XL. This project involves a 725-acre landfill with a 25-million cubic yard capacity, a single composite liner system, leachate collection and removal, gas collection (with a co-located 2-megawatt power plant), and a 15-acre storage pond for water/leachate. The landfill opened in 1975 and closure is anticipated in 2021.

Previous research at this site addressed the following objectives:

- Demonstrate that water addition can substantially accelerate waste decomposition and landfill gas generation

- Monitor biological conditions in the landfill

- Estimate the potential for landfill life extension

- Better understand moisture movement in the landfill

- Assess performance of shredded tires as drainage material

- Provide data to EPA and the private sector

The landfill cells used in this early research had the following characteristics:

- Two test cells (control and enhanced)
- Double composite liner with leak detection
- Compacted clay sidewalls
- Manholes to collect leachate
- Vertical gas collection system.

Instrumentation was installed on 20- to 30-foot centers during waste mass emplacement. Clay levees are placed around the cells to isolate the gas collection and leachate systems from the rest of the landfill.

The cover consists of shredded tires placed on top of a geotextile layer with a clay layer over the tires. This technique creates a gas collection zone beneath the clay cover.

Approximately 470,000 gallons of water were added in a manner similar to drip irrigation over a two-year period. Injection points were on 20-foot centers and were each surrounded by shredded tires.

Waste samples were obtained by coring. Results indicated that good moisture distribution was achieved. However, the bottom portions of the landfill cells were generally found to be drier, which indicated that more water could have been added.

Gas generation was higher over time in the wet cell. Within one year, substantial decreases were seen in COD, total dissolved solids (TDS), and biological oxygen demand (BOD).

Findings from these earlier studies indicated that:

- Addition of water does promote the bioreaction resulting in accelerated decomposition and methane recovery

- Significant settlement and leachate chemistry improvement can be seen after a short time (within 6 months)

- Shredded tires perform well in support of landfill gas transfer and leachate injection.

Under EPA Project XL, Yolo County will be conducting a full-scale demonstration that builds on efforts conducted over the past 5 years involving many different funding sources. This demonstration project has the following goals:

- Accelerate waste decomposition
- Accelerate methane production and improve energy recovery
- Verify improvement in leachate quality
- Verify hydraulic head on the liner
- Look at both aerobic and anaerobic conditions

- Look at post-closure implications.

For this demonstration, groundwater will be used to supplement the leachate used to increase the moisture content of the waste mass. The liquid application rate will be about the same as for previous efforts – approximately 10 gallons per minute on a 100-foot by 100-foot area. This is roughly 13 million gallons of water for 400 tons of waste.

The daily cover will consist of shredded green waste and a tarp rather than soil.

The measurement system is quite extensive involving over 320 monitoring points in each landfill cell. A supervisory control and data acquisition (SCADA) system will be installed to manage the instrumentation and the data collection. Such an extensive instrumentation system is necessary to obtain the desired research data and to address concerns raised by regulatory agencies (such as potential head on liner). This can be very expensive – for example, 10 acres cost about $2 million to construct.

Yolo County hopes to demonstrate the following in this project:

- Extended use of current site and reduced need for a new site
- Amount of gas that can actually be recovered for economical energy use
- Landfill mining opportunities and landfill cell reuse
- Improved leachate quality and reduced risk of groundwater contamination
- More rapid biodegradation and earlier stabilization of the waste.

The methane generation is a particular issue for this site. The production of electricity using the methane generated by the landfill results in higher NOx emissions. This is a concern because the landfill is located in a nonattainment area for air emissions regulation and control.

Federal approval to begin water addition is anticipated to occur in November 2000 with cover system installation completed by February 2001 and liquid and air injection beginning April 2001. Data collection and reporting is expected to continue from July 2000 to July 2004.

C.4 WORCESTER COUNTY, MARYLAND – EA ENGINEERING SCIENCE & TECHNOLOGY

This demonstration project has been ongoing for about 9 years at an operating county landfill that receives approximately 300 tons per day of municipal solid waste. Recirculation began once the first lift of waste was emplaced and has continued throughout the life of the landfill.

Such bioreactor landfills represent solid waste treatment rather than disposal, and involve the following:

- Long-term risk reduction
- Leachate treatment through recirculation
- Maximization of airspace through accelerated decomposition

- Long-term risk reduction through source treatment
- Closure and post-closure cost savings.

In addition, landfill mining in conjunction with the above can offer significant benefits.

This location receives 41 inches of rain a year so there is no lack of liquid. The landfill consists of four cells, each about 17 acres with a 400,000-gallon aboveground storage tank to support recirculation through vertical recharge wells placed on 150-foot centers. This approach to liquid injection was selected to keep these activities out of the way of daily operations. Leachate was recirculated without any additional treatment or modification.

Data collected between January 1991 and July 1997 showed the following:

- BOD dropped briefly after liquid addition, then peaked, then sharply declined to achieve baseline levels in about 18 months

- New waste addition resulted in BOD variation (increases)

- Fatty acid production increased and caused the pH to rise

- pH changes significantly reduced the metal-carrying capacity of the leachate with iron and chromium no longer coming out into solution

- Chlorinated volatile organic compounds (VOCs) significantly declined from 17 times the maximum contaminant level (MCL) to below the levels specified in the Safe Drinking Water Act, becoming nondetectable after about 3 years

- Certain gasoline constituents did not disappear and had variable but consistent presence, possibly from household hazardous waste and equipment operation in the landfill cell.

These data indicate the following measures of the process rate for bioreaction completion:

- From BOD data – reaction completed in 4 years
- From the generation of insoluble metal complexes – reaction completed in 3 years
- From the chlorinated VOCs reaching baseline levels – reaction completed in 3 years.

This project involved constant recirculation resulting in approximately two-thirds of the leachate generated over 8 years being recirculated. In western and southwestern United States areas, possibly all leachate can be recirculated.

Quantification of the overall water balance was conducted including consideration of the following:

- All incoming waste moisture
- Preferential flow paths through the waste

- Difficulties achieving even moisture distribution
- Runoff
- Evapotranspiration
- Infiltration
- Waste field capacity
- Average waste receipt.

The water balance indicated the potential for 100 percent recycle of the leachate.

This recirculation process has been operated since 1990. Recently, the feasibility of landfill mining was examined and the utility of the remaining materials was evaluated for on-site and off-site uses. This investigation was conducted using a rotary trommel with 1-inch holes. The material removed resembled soil fines and represented approximately 75% of the material removed except in the top 25 feet of the waste mass. Little degradation was encountered in that zone and is believed to be due to uneven waste wetting.

The humus-like material recovered in this excavation appeared suitable for use as a landfill cover and nonlandfill uses might be possible. The reclaimed material had hazardous constituents present at two to three orders of magnitude below the levels that would trigger classification of the material as a hazardous waste. The reclaimed material met all human health risk-based limits for industrial use, and met all requirements for residential reuse except for arsenic limits.

A life cycle cost analysis was also developed. The scenario used in this analysis was to build one cell to hold unusable residuals from material recovered out of six original cells. All undegraded materials would go back into an active landfill cell. No caps are used because each cell keeps getting reworked. This analysis estimated a landfill life of 50 to 60 years.

Key conclusions drawn from this study are:

- There is potential for long-term savings in reduced monitoring

- Significant reduction of long-term risk to the environment

- Offsite use of recovered, decomposed material can double the landfill site life if properly operated.

C.5 OUTER LOOP LANDFILL BIOREACTOR STUDIES, LOUISVILLE, KENTUCKY – WMI AND EPA

WMI has been evaluating landfill bioreactor technology at sites across the United States. WMI and EPA have developed a Cooperative Research and Development Agreement (CRADA) for joint bioreactor landfill research. Bioreactor research studies planned for the Outer Loop Landfill are anticipated to be among the first studies under this agreement.

Over the next 2 years, WMI will be looking at aerobic, anaerobic, and facultative bioreactor landfills as compared to conventional municipal solid waste landfills. This research effort is anticipated to be large enough and long enough to evaluate the economic and operational issues, especially the health and safety aspects of bioreactor operations. This effort involves statistically based studies to generate credible data.

The waste area at the Outer Loop Landfill is 400 acres. Each test and control cell involves about 6 acres.

The operation of an aerobic-anaerobic landfill bioreactor will cause rapid biological decomposition of easily degradable waste in the aerobic stage. This bioreactor landfill will be constructed during waste placement and will have separate, dedicated leachate and gas collection systems.

The objectives of the aerobic-anaerobic bioreactor study are to:

- Evaluate waste stabilization enhancement resulting from sequential establishment of aerobic and anaerobic conditions relative to waste stabilization in the control cells

- Demonstrate the feasibility of implementing this technique in a commercially viable operating scale.

The facultative landfill bioreactor study intends to demonstrate control of nitrogen cycling in the landfill. Ammonia-containing leachate will be treated external to the landfill by nitrification to convert the ammonia to nitrate. The treated leachate will be introduced to a landfill cell where the nitrate will be used by facultative bacteria. This approach is expected to reduce the buildup of ammonia in the leachate, but may also reduce methane production. Trenches will be used for liquid infiltration and there will be separate leachate and gas collection systems.

The objectives of the facultative bioreactor study are to:

- Evaluate stabilization enhancement resulting from nitrate-enriched leachate application
- Assess commercial viability of the operation.

Both studies will include replicate sampling and analysis. The studies will characterize:

- Landfill gas and emissions
- Leachate head on liner
- Leachate production rates
- Waste temperature (daily)
- Waste settlement (quarterly)
- Volatile solids (annual)
- Biochemical methane potential (annual)
- Moisture content (annual)
- Waste density (annual)

- pH (annual).

Critical measures will be:

- Continuous gas production rates
- CO_2, CH_4, O_2, and balance concentrations (daily).

Noncritical measures include:

- Nonmethane organic compounds (NMOCs) (quarterly)
- Hazardous air pollutants (HAPs) (quarterly)
- Surface emissions (twice per quarter)
- Cellulose:lignin ratio (annually)
- Carbon:nitrogen ratio (annually).

Project startup is anticipated for October 2000.

C.6 WILLIAMSON COUNTY, TENNESSEE - ENVIRONMENTAL CONTROL SYSTEMS, INC., AND CIVIL AND ENVIRONMENTAL CONSULTANTS

The Williamson County landfill has a 6-acre footprint, a waste depth of approximately 40 feet, and nearly 70,000 tons of solid waste. This landfill is located in a rural site without access to a publicly owned treatment works (POTW). The cell shape resembles a truncated pyramid with steep slopes and is lined with Subtitle D composite liner and an underdrain leachate collection system. Current head on the landfill liner averages less than one inch. The landfill cover consists of 12 to 24 inches of highly compacted cover soil and 6 to 24 inches of mulch.

The waste mass had the following characteristics (based on initial characterization and sampling data):

- 29.7 percent average in-situ moisture content
- 71°F average temperature
- Average oxygen content of the gases ranging from 6 percent to 11.9 percent by volume
- Estimated biodegradable organic fraction of 6,900 tons
- 15:1 carbon to nitrogen ratio.

The objectives of this study include evaluation of the following:

- Changes in waste characteristics following operation of the bioreactor
- Effectiveness of proposed air and leachate delivery systems
- Overall trend in leachate quality and quantity
- Variations in methane gas production
- Overall economic costs versus benefits
- Site water balance
- Impacts of bioreactor operation on stability of waste fill.

Lysimeters, tensiometers, and other instrumentation were installed to collect the data needed to develop a full site water balance. The estimated water balance indicated that 3.8 million gallons of water were needed to achieve a 40% moisture content; this represents approximately 54 gallons of water per cubic yard of waste. There is an on-site weather station including a data logger to continuously collect weather data, which can be compared with water level studies.

Liquid is added at 30 gallons per minute. Wells (over 200 with over 190 thermocouples) were placed on a 50-foot grid and nested at 10, 20, and 30 feet. Because this was a retrofit to an existing landfill, a 10-foot safety factor was included in the drilling operations to avoid penetrating the lower liner. Water sources include leachate from the landfill and storm water. Other water sources may be necessary to obtain sufficient quantities.

The liquids are aerated in an aboveground mixing tank prior to circulation in the landfill via an aboveground pipe network.

Air is added to the waste mass. When blowers are operating, three readings of CO2, O2, and methane are taken weekly from each of 12 monitoring wells.

Waste cellulose:lignin ratio readings are taken quarterly. Biochemical Methane Potential (BMP) testing is currently underway to further examine the biodegradation process.

Other measurements include:

- Quarterly sampling of solid waste and leachate
- Nutrient content within the waste (with supplemental nutrients added as necessary)
- Air injection amounts and and leachate quantities injected and collected;
- Weekly inspection of leachate head on liner.

The initial theoretical water balance calculations indicate that biological processes, especially in zones that become aerobic, should biochemically produce a significant amount of the water to help support the bioreaction process. Data collected from lysimeters during heavy rainfall events indicated that infiltration is slope dependent. Good saturation was found in flat areas—the greater the slope, the less inflow.

The following geotechnical research is planned using data collected from this landfill:

- Whether failure planes are created in the waste mass from injection of so much liquid?
- What is the settlement rate?
- Temporal and spatial changes in head on liner.

There are also plans to conduct slope stability analysis and to use this data to develop estimates of waste mass strength.

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