ENVIRONMENTAL PROTECTION AT THE MANAGED SOLID WASTE LANDFILL

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Document No. MD10186

29 MARCH 2010

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TABLE OF CONTENTS

ACKNOWLEDGEMENTS AND DISCLAIMER 1

DEFINITIONS AND LIST OF ACRONYMS 2

EXECUTIVE SUMMARY 4

1. OVERVIEW OF A MANAGED SOLID WASTE LANDFILL 15

1.1 What is a Managed Solid Waste Landfill? 17
1.2 Key Elements of a Managed Solid Waste Landfill 17
1.3 How is Environmental Performance Monitored? 19
1.4 What Happens Inside a Managed Solid Waste Landfill? 21
1.4.1 Treatment (Biodegradation) of Solid Waste 21
1.4.2 Permanent Storage of Biogenic Carbon in Landfills (Sequestration) 24
1.4.3 Development of a Leachate Biofilter in Bottom-Most Waste Layers 24
1.4.4 Physical and Biogenic Settlement 25

2. REGULATORY OVERSIGHT OF MANAGED SOLID WASTE LANDFILLS 26

2.1 Overview of Solid Waste Landfill Regulations 27
2.2 Regulatory Obligations though the Life of a Landfill 27
2.2.1 Siting Considerations 28
2.2.2 Planning and Design 28
2.2.3 Construction 29
2.2.4 Operation and Maintenance 30
2.2.5 Environmental and Performance Monitoring and Reporting 30
2.2.6 Closure 31
2.2.7 Long-Term Maintenance and Post-Closure Care 32
2.3 Public Involvement in the Permitting Process 33

3. DESIGN COMPONENT SYSTEMS OF A MANAGED SOLID WASTE LANDFILL 34

3.1 Containment of Waste in Landfills 34
3.2 Liner System 36
3.2.1 Liner System Components 37
3.2.2 Key Environmentally Protective Features of Liner Systems 38
3.2.3 Long-Term Performance of Liner Systems 38
3.3 Leachate Management System 39
3.3.1 Leachate Collection and Recovery System 39

TABLE OF CONTENTS
(continued)

3.3.2 Key Environmentally Protective Features of Leachate Collection Systems 40
3.3.3 Long-Term Performance and Longevity of Leachate Collection Systems 41
3.3.4 Leachate Management Options....41
3.4 Landfill Cover Systems....44
3.4.1 Design of Final Cover Systems....45
3.4.2 Key Environmentally Protective Features of Final Cover Systems....47
3.4.3 Long-Term Performance of Final Cover Systems....47
3.5 Gas Management System....50
3.5.1 Active Landfill Gas Management....50
3.5.2 Passive Landfill Gas Management....51
3.5.3 Key Environmentally Protective Features of Gas Control Systems....53
3.5.4 Long-Term Performance of Gas Management Systems....53
3.6 The Role of Managed Landfills in Controlling Greenhouse Gases....54
3.6.1 Landfill Gas Collection Efficiency....55
3.6.2 Methane Oxidation in Cover Soils....56
3.6.3 Carbon Sequestration....56

4. OPERATION AND MAINTENANCE OF A MANAGED SOLID WASTE LANDFILL 58

4.1 Management of Landfill Operations....59
4.1.1 Landfill Infrastructure and Equipment....59
4.1.2 Landfill Supervision and Operator Training....59
4.2 Landfill Operation under Permit Conditions....60
4.2.1 Compliance with the Facility Operating Plan....61
4.2.2 Waste Screening....62
4.2.3 Daily Operation at the Working Face....62
4.2.4 Stormwater Management....63
4.3 Maintenance of Landfill Systems....65
4.3.1 Preventative and Response Maintenance during Active Operations....65
4.3.2 Post-Closure Maintenance....67

5. ENVIRONMENTAL MONITORING AT MANAGED SOLID WASTE LANDFILLS.... 68

5.1 Why Monitor for Potential Releases from a Landfill to the Environment?....69

TABLE OF CONTENTS
(continued)

5.2 Components of an Environmental Monitoring Program 69
5.2.1 Groundwater Monitoring System 70
5.2.2 Surface Water Monitoring Program 71
5.2.3 Subsurface Gas Migration Monitoring System 71
5.2.4 Surface Emissions Monitoring 72
5.2.5 Monitoring the Performance of Landfill Operational Systems 73

6. THE SAFETY OF THE MODERN LANDFILL 75

6.1 Performance-Based Landfill Design and Management 76
6.1.1 Overlapping Systems for Landfill Operation 76
6.1.2 Predictability in Landfill Performance Trends 77
6.2 Providing Long-Term Landfill Integrity 78
6.2.1 Responding to Minor Upsets of Landfill Operational Systems 78
6.2.2 The Potential for Extensive Landfill Failure 78
6.2.3 Performance-Based Maintenance and Ending Care at Closed Landfills 80
6.3 Environmentally Protective Landfill Designs 81

7. BEYOND WASTE CONTAINMENT – LANDFILLS AS A RESOURCE 89

7.1 Landfill Gas-to-Energy and Other Proactive Green Energy Opportunities 89
7.2 Effective Sequestration of Carbon in Landfills 91
7.3 Enhanced Waste Treatment vs. Waste Containment 92
7.4 Increased Beneficial End Use Options for Closed Landfill Properties 94

8. REFERENCES 96

APPENDICES

APPENDIX A: LONG-TERM BEHAVIOR OF MANAGED LANDFILLS

A1. OVERVIEW 105

A1.1 Degradation of Waste in Landfills 105
A1.2 Regulatory Background 107
A1.3 Organization of this Appendix 107

A2. LONG-TERM TRENDS IN LEACHATE GENERATION AND QUALITY 108

TABLE OF CONTENTS
(continued)

A2.1 Technical Synopsis 108
A2.1 Summary of Supporting Body of Knowledge 109
A2.1.1 Long-Term MSW Leachate Generation 109
A2.1.2 Characterization of MSW Leachate 109
A2.1.3 Mechanisms Affecting MSW Leachate Quality 110
A2.1.4 Long-Term Trends in MSW Leachate Quality 110
A2.1.5 Development of a "Biofilter" in the Bottom-Most Refuse Layer 112
A3. POTENTIAL HEALTH IMPACTS OF MSW LANDFILL LEACHATE 113
A3.1 Technical Synopsis 113
A3.2 Summary of Supporting Body of Knowledge 113
A4. LONG-TERM TRENDS IN LANDFILL GAS GENERATION AND COMPOSITION 115
A4.1 Technical Synopsis 115
A4.2 Summary of Supporting Body of Knowledge 115
REFERENCES 116

APPENDIX B: LANDFILL CONTAINMENT SYSTEM PERFORMANCE AND LONGEVITY
B1. OVERVIEW 123
B1.1 Containment System Design and Performance 123
B1.2 Organization of this Appendix 123
B2. LONG-TERM PERFORMANCE OF LINER SYSTEMS 124
B2.1 Technical Synopsis 124
B2.2 Summary of Supporting Body of Knowledge 124
B3. LONG-TERM PERFORMANCE OF LEACHATE COLLECTION SYSTEMS 128
B3.1 Technical Synopsis 128
B3.2 Summary of Supporting Body of Knowledge 128
B4. FINAL COVER SYSTEM PERFORMANCE AND LONGEVITY 130
B4.1 Technical Synopsis 130
B4.2 Summary of Supporting Body of Knowledge 130
B4.2.1 Final Cover System Components and Specifications 130
B4.2.2 Maintenance of Final Cover Systems 131

TABLE OF CONTENTS
(continued)

B4.2.3 Estimating Air Emissions from Landfills 132
B4.2.4 Gas Collection Efficiency 134
B4.2.5 Methane Oxidation in Landfill Covers 135
B4.2.6 Carbon Sequestration in Landfills 136

REFERENCES 138

APPENDIX C: POST-CLOSURE CARE AND LONG-TERM LANDFILL INTEGRITY

C1. OVERVIEW 143

C1.1 Factors Affecting Landfill Performance during Post-Closure Care 143
C1.2 Organization of this Appendix 143

C2. LANDFILL PERFORMANCE DURING POST-CLOSURE CARE 144

C2.1 Technical Synopsis 144
C2.2 Summary of Supporting Body of Knowledge 144

C3. POST-CLOSURE CARE MONITORING SYSTEMS 146

C3.1 Technical Synopsis 146
C3.2 Summary of Supporting Body of Knowledge 146

C4. LONG-TERM INTEGRITY OF LANDFILLS 148

C4.1 Technical Synopsis 148
C4.2 Summary of Supporting Body of Knowledge 148

REFERENCES 150

ACKNOWLEDGEMENTS AND DISCLAIMER

This detailed technical report was prepared by Geosyntec Consultants and funded by Waste Management, the largest waste management company in North America. Geosyntec Consultants would like to acknowledge the assistance of Waste Management in providing access to their databases, landfill information, and technical personnel.

Geosyntec comprehensively reviewed the technical and peer-reviewed literature in order to provide an up to date evaluation of the regulatory oversight, engineering design, active management, routine maintenance, and long-term monitoring requirements associated with the modern managed solid waste landfill. The findings and conclusions of this report characterize the state-of-practice in terms of the systems and controls routinely implemented by the solid waste industry to protect the environment. However, this report is not intended as a substitute for thorough engineering and technical research with respect to any specific site and may not be relied upon for that purpose.

DEFINITIONS AND LIST OF ACRONYMS

ACAP	Alternative Cover Assessment Program
BAT	best available technology
BOD	biochemical oxygen demand
BCT	best conventional technology
BMP	best management practice
BPT	best practical technology
CAA	Clean Air Act
CCL	compacted clay liner
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CQA	construction quality assurance
CWA	Clean Water Act
COD	chemical oxygen demand
C&H	cellulose and hemicellulose
DSWA	Delaware Solid Waste Authority
EMP	environmental monitoring program
EREF	Environmental Research and Education Foundation
ET	evapotranspirative
FML	flexible membrane liner
GC	geocomposite
GCCS	gas collection and control system
GCL	geosynthetic clay liner
GEC	geosynthetic erosion control
GHG	greenhouse gas
GM	geomembrane
GMS	gas management system
GN	geonet
GT	geotextile
GWMS	groundwater monitoring system
HDPE	high density polyethylene

HHE	human health and the environment
IPCC	Intergovernmental Panel on Climate Control
ITRC	Interstate Technology and Regulatory Council
LCRS	leachate collection and removal system
LEL	lower explosive limit
LFG	landfill gas
LMS	leachate management system
LRS	leachate recirculation system
MBR	membrane bioreactor
MSW	municipal solid waste
NSPS	New Source Performance Standards
NSWMA	National Solid Waste Management Association
PCC	post-closure care
POTW	publicly owned treatment works
PVC	polyvinyl chloride
SBR	sequencing batch reactor
SDWA	Safe Drinking Water Act
SEM	surface emissions monitoring
SOP	standard operating procedure
SWANA	Solid Waste Association of North America
SWM	stormwater management
SWMS	stormwater management system
SWMP	surface water monitoring program
RCRA	Resource Conservation and Recovery Act
USEPA	United States Environmental Protection Agency

EXECUTIVE SUMMARY

Geosyntec Consultants, an independent consulting firm, prepared a detailed technical report discussing the protectiveness of modern managed landfills, specifically landfills that receive non-hazardous municipal solid waste (MSW). This executive summary provides an overview of the detailed technical report.

What is The Purpose of the Detailed Technical Report?

The report is intended as an independent treatise on solid waste landfills that describes liner and cover performance, landfill gas generation and collection efficiency, and long-term protection of groundwater and other environmental media in a single document. It includes supporting references to more than 200 peer-reviewed technical papers addressing how a modern managed MSW landfill is protective of human health and the environment.

What is The Main Message?

The report concludes that no one single element is relied on to maintain long-term environmental protection; rather, it is the overlapping function of the landfill containment systems, operations, and maintenance procedures, combined with independent regulatory oversight and on-going system performance monitoring, that protect human health and the environment for the very long term.

Who is the Intended Audience?

The report provides a compendium of information regarding the protective features, processes, and regulatory and community oversight of modern landfills that should be useful to both technical professionals and the general public.

What Principal Questions Does it Seek to Answer?

The report answers many typical questions asked about landfills such as, "Are landfills safe?", "How are landfills protective of groundwater, surface water, soil, and air?", "Are landfills still protective after a natural disaster?", and "Are landfill failures common?"

The conclusions presented in the report are supported by peer-reviewed research and practical field studies on landfill performance and their ability to provide long-term protection of human health and the environment. Technical references are provided at the end of the report, and additional technical details are provided in three appendices. Each chapter of the report is intended to be self-contained for readers interested in particular elements of a landfill; as a result, there is a necessary level of repetition of key points. Symbols are used to simplify for the reader where to find information on a specific topic. As illustrated below, the most commonly used symbols relate to the key elements of modern managed landfills – containment, treatment (biodegradation), operation, maintenance, and monitoring.

KEY ELEMENTS OF MODERN MANAGED LANDFILLS

Introduction

The modern, managed municipal solid waste (MSW) landfill consists of a combination of regulatory, design, operational, maintenance, and monitoring features. The permitting, design, construction, and regulation of MSW landfills are intended to protect human health and the environment both during their active operating phase and after they stop receiving waste and are closed. MSW landfills are engineered to provide overlapping measures for environmental, health, and safety protection. These measures include monitors and back-up systems that help protect the integrity of landfills in the event of emergencies or natural disasters.

In preparing the report, Geosyntec Consultants conducted a comprehensive study to summarize the state-of-the-practice of the modern managed landfill. Primary findings include:

- **Landfill Design and Operation is Highly Regulated ➔** Location and site characterization requirements combined with professional design standards and prescriptive best management operating standards for waste acceptance and operations serve to uphold the physical integrity of MSW landfills.

- **Containment Systems are Scientifically Engineered ➔** Scientific research and testing shows that engineered and natural liners and cover systems can likely provide effective containment in excess of 1,000 years.

- **Landfills are Actively Maintained ➔** Active management through the operating, closure, and post-closure stages helps to prevent system breakdowns, enabling engineered containment systems to operate as designed.

- **Generation of Waste Byproducts Decreases Over Time ➔** Predictable and decreasing trends in the generation and concentration of non-hazardous waste liquids generated in the landfill (termed "leachate") and biologically generated landfill gas mean that, over time, the landfill unit can progress to a relatively inert state that does not require active management.

- **Landfills are Actively Monitored ➔** Monitoring systems are designed to detect signs of system malfunction or a potential release of solid waste or byproducts from the landfill, and allow for a timely response prior to potential off-site impact.

Lastly, with effective end-use planning, the managed landfill can also provide beneficial land use options to support renewable energy projects, sustain wildlife habitats and parks, or offer "green space solutions" (such as golf courses or walking trails).

Each of these findings is summarized in more depth in the following sections. Further details are provided in the report.

Regulatory Requirements for Landfill Design and Operation

Modern MSW landfills are designed and operated pursuant to strictly enforced regulatory standards established by the U.S. Environmental Protection Agency (USEPA) and implemented by State environmental regulatory agencies. Under the provisions of Subtitle D of the Resource Conservation and Recovery Act (RCRA), owner/operators of MSW landfills are required, by permit, to characterize site geology and develop plans for operation, maintenance, and monitoring prior to constructing a landfill unit that will accept waste. In addition, landfills must operate in compliance with regulations governing waste screening and inspection, daily waste disposal and cover operations, odor control, and storm water control and monitoring. State and local laws also govern the safety of landfill operations and stipulate a list of wastes prohibited from being disposed of in an MSW facility.

The **regulatory requirements** imposed at the modern MSW landfill to assure protection of human health and the environment are summarized below.

- **Permitting ➔** Advanced planning and regulatory approvals, including:
  - **Siting Considerations** such as surface and subsurface characterization to avoid siting landfills in unsuitable locations such as floodplains, wetlands, or locally unstable areas; and
  - **Planning and Design**, including engineer-certified calculations and plans regarding geotechnical stability, proper management of waste by-products (gas and leachate), effective control of stormwater runoff, and prevention of environmental and community impact and nuisance.
- **Construction ➔** Implementation of engineered plans for containment and monitoring, including independent certification by Construction Quality Control (CQA) technicians and engineers that the landfill is built as designed.
- **Operation and Maintenance (O&M) ➔** Performance of disposal, prevention, compliance, and response actions, including system maintenance by trained professionals to avoid

breakdown or failure of containment features as well as planning to protect worker and public safety.

- **Environmental Monitoring** ➔ Establishment of scientifically-developed monitoring plans implemented to measure system performance and provide early warning of operational upsets (such as a leachate spill or other release) prior to potential off site impact.

- **Closure and Post-Closure Care Maintenance and Monitoring** ➔ Planning and implementation of long-term managed care, including:
    - **Closure** in accordance with approved engineered plans for the landfill to remain in compliance with state and federal regulations; and
    - **Post-Closure Care**, a regulatory-required period of maintenance and monitoring with the objective of demonstrating that landfill containment systems are performing as designed after active landfill operations cease.

From the above, it is clear that there are many regulatory compliance requirements that must be achieved during design, construction, operation, and maintenance of a MSW landfill. Furthermore, the scientifically engineered systems and components of the modern managed MSW landfill also meet long-term performance criteria as described below.

Performance of Scientifically Engineered Landfill Containment Systems

A cornerstone of the modern managed landfill is containment of waste and waste by-products. The materials and construction methods used in Subtitle D landfill containment systems are well known and have been comprehensively tested, and their performance has been documented through more than three decades of research and field observation.

The modern managed MSW landfill is comprised of **engineered systems and components** functioning together with natural geologic conditions to optimize overall landfill environmental performance. These systems and components must meet strict design standards and receive approval from the governing regulatory authority prior to construction. Once approved for construction, component systems are designed to meet long-term performance goals. Component systems include:

- **Liner system** ➔ An engineered barrier system designed to contain the byproducts of MSW stored in landfills. In particular, liner systems are designed to prevent leachate (liquids present in the disposed waste) from migrating into subsoil, groundwater, and surface water.

Long-Term Liner System Performance

Scientific studies and testing have shown that the service life of typical synthetic materials used in liner construction (most commonly, high-density polyethylene membranes) is estimated to exceed a thousand years. Composite liner systems consisting of a synthetic membrane liner overlying a compacted clay layer, similar to those used at Subtitle D landfills, have been designed for radioactive waste depositories requiring the highest standards of containment for tens of thousands of years.

- **Leachate management system** ➔ A system of drains, pumps, pipes and hoses designed and operated to remove leachate from above the liner and convey it away for treatment and/or disposal. The leachate collection and removal system controls leachate build-up on the liner, working in conjunction with the liner's barrier systems to minimize the potential for seepage to groundwater and other environmental media.
- **Cover system** ➔ An engineered system used to control moisture and percolation from entering the landfill, promote surface water runoff, minimize erosion, prevent direct exposure to waste, control animal or plant intrusion, control gas emissions, control odors, and meet aesthetic and other end use purposes.

Long-Term Cover System Performance

Regulatory compliant cover system types are designed to have service lives in excess of a thousand years. The service life can be further maximized by ensuring a diverse native plant community is established on the cover, which will be more resilient to natural and man-induced catastrophes and the anticipated unpredictable changes in environmental conditions (such as overgrazing or fires) and climatic fluctuations that can occur over time.

- **Landfill gas management system** ➔ An engineered system of wells, surface and subsurface pipes, gas extraction pumps (termed "blowers"), and flares. Use of gas management systems adds to the control of gas migration from the landfill as emission to the atmosphere or laterally into the unsaturated soil (or vadose zone) and groundwater. At many modern managed MSW facilities, landfill gas is used to generate green energy.

- **Stormwater management system** ➔ An engineered system designed to divert rainwater and snowmelt away from the landfill to control potential contact of surface water with waste. Stormwater runoff is monitored in accordance with the Clean Water Act standards and compliance is overseen by the applicable Federal or State agency.

Although each of the systems described above provides an element of environmental protection, it is the overlapping integration of all systems that provides for comprehensive protection of human health and the environment over the long term.

<u>Landfills Are Actively Maintained</u>

Active and responsible operation provides for regulatory compliance and environmental protection at the managed landfill. Key elements of responsible landfill operation include:

- Incoming waste screening, documentation, and waste load inspections (to prevent disposal of hazardous or unacceptable waste);
- Safe operations at the working face (to protect site workers and waste haulers);
- Daily covering of the waste (to avoid litter and access by rodents, birds, or other vectors);
- Odor and nuisance control;
- Leachate and landfill gas management (to control potential environmental impacts); and
- Routine inspection, repair, and replacement of equipment, structures, and systems.

Maintenance and monitoring activities continue after landfill closure, when the landfill no longer accepts waste. Post-closure care activities include regular inspections, maintenance, and optimization of principal post-closure care elements, including the leachate management system, final cover system, landfill gas management system, and environmental monitoring programs.

Like any complex engineered system, operation and maintenance of a modern managed MSW landfill requires a skilled workforce trained in system operation, safety, and environmental regulatory compliance. A key responsibility of the site operations team is waste screening. All trucks entering an MSW landfill must check in with the gatehouse attendant. Waste loads are visually inspected to prevent acceptance of non-compliant wastes at the landfill. Site operators are trained in visual recognition of potentially unacceptable wastes when placed at the working face and follow strict procedures to return unacceptable waste to its originator for proper handling and disposal.

<u>Generation of Waste Byproducts Decreases over Time</u>

The chemistry of leachate from MSW landfills is well documented, understood, largely predictable, and has been shown to improve with time after capping. Similarly, LFG generation is predictable over time and is based primarily upon waste type and moisture. LFG generation has also been documented to decrease with time after capping. Because leachate and landfill gas have predictable and decreasing trends in their generation and concentration over time, potential emissions of leachate and landfill gas from a landfill unit can progress to a relatively inert state that ultimately does not require active management.

A large number of scientific studies have been conducted on closed landfills. The results of these studies support the following broad conclusions:

- MSW landfill leachate is a non-hazardous liquid that predictably decreases in volume and concentration after landfill closure;
- As waste material in a landfill degrades, the bottom-most layers decompose fastest and can act as an effective biological filter that reduces the concentration of leachate as it passes from upper waste layers to the leachate collection system;
- Landfill gas generation declines in a predictable manner after closure; and
- Future quantities and concentrations of landfill gas and leachate can be estimated based on current and historic measurements.

Active Landfill Monitoring

Environmental monitoring systems are used to monitor landfill system performance and environmental compliance. Because a comprehensive environmental monitoring program (EMP) is implemented to confirm that containment and control systems are performing as designed to protect groundwater, surface water, land, and air, an EMP serves as an early warning system for potential environmental impacts.

The principal EMP components include:

- **Groundwater** monitoring for a potential release from the landfill to the uppermost aquifer;
- Monitoring of **surface water** quality onsite and in the local vicinity of the landfill where rainwater or snowmelt may have potentially come in contact with waste;
- Monitoring the **vadose zone** (unsaturated shallow subsurface above groundwater) for potential landfill gas migration;
- Cover system monitoring to detect and quantify low-level **landfill gas** emissions and potentially indicate the need to restore an area of the cover system to optimize its integrity and ability to control landfill gas emissions; and
- Performance monitoring of permit compliance conditions such as confirming no build-up of **leachate** on the engineered liner.

Effective environmental monitoring can readily detect potential upsets to control systems and/or releases of leachate or gas, allowing necessary response actions to be implemented expeditiously before long-term damage or potential offsite migration occurs. Monitoring data can also help predict future landfill performance based on trends in past and current data.

Control of Greenhouse Gas Emissions at Landfills

Landfill gas, which is comprised mostly of methane and carbon dioxide, is generated from the decomposition of organic constituents in the waste mass. If released into the atmosphere, methane is considered a greenhouse gas (GHG). Managed MSW landfills are designed and operated to control emissions of landfill gas.

Three primary mechanisms combine to directly control the emission of landfill gas from a landfill:

- The efficiency of landfill gas collection;
- Natural oxidation, a process by which specialized bacteria living in landfill cover soils consume methane in the presence of air; and
- Permanent storage of non-decomposed organic constituents within the landfill itself (termed "carbon sequestration" in the context of controlling greenhouse gas emissions).

Landfill gas collection efficiency is the percentage of the total amount of landfill gas generated that a collection system is effective in collecting. According to the USEPA's "Compilation of Air Pollutant Emission Factors" (commonly referred to in the industry as the "AP-42 document"), estimated efficiencies of landfill gas collection systems typically range from 60 to 85 percent. A default value of 75 percent is often assumed, although the USEPA notes that well-operated systems may achieve collection efficiencies in excess of 90 percent. Other researchers and practitioners have observed that collection efficiencies at well-designed and operated landfills can be even higher. For example, at landfills that contain a final soil and/or geomembrane cover system, gas collection efficiencies are reported to range from 90 to 99 percent. Climatic conditions also play a role in gas generation rates and collection efficiencies achieved. In arid regions such as southern California, for example, gas collection systems are reportedly capable of close to 100 percent control efficiencies.

A portion of the landfill gas that is not captured by the gas collection system can migrate into the landfill cover soils. A fraction of the methane in that gas is converted (oxidized) into carbon dioxide by bacteria within the cover soil. This transformation further reduces the amount of methane that can potentially escape into the atmosphere. Based on a review of recently published literature, the percent of methane oxidized in landfill cover soils ranges from 22 to 55 percent of the gas not collected, with a reported average of 35 percent. The percent of methane controlled via active gas collection or oxidation in cover soils is dependent on the type of cover system in place. Gas collection efficiencies at landfills with low-permeability covers have been reported to range from 90 to 99 percent, leaving little uncollected methane available for oxidation. On the other hand, the gas collection efficiency is generally less where thicker all-soil cover systems using more permeable, organic material is in place. This is because these covers allow more air to come in contact with methane within the cover, which in turn facilitates greater methane oxidation. Landfill engineers are able to take advantage of the dual benefits provided by gas collection systems and final cover designs to maximize the level of landfill gas control.

Research has shown that MSW landfills permanently store a significant amount of carbon. This storage, or "sequestration," is important because it permanently removes carbon from the natural carbon cycle. The USEPA, the United Nation's Inter-governmental Panel on Climate Change (IPCC), the Oregon Climate Trust, and the California Air Resources Board (CARB) all recognize that when organic wastes are deposited in landfills and do not completely decompose, the carbon that remains is effectively removed from the global carbon cycle. In other words, although landfills produce methane, they also play an important role in sequestering carbon that would otherwise contribute to the accumulation of GHGs in the atmosphere. Taken together, responsible landfill design and operation, active gas collection systems, oxidation of methane in cover systems, and the permanent storage of carbon in landfills all combine to produce low net methane (GHG) emissions.

Long Term Landfill Integrity – How Safe are Landfills?

Modern landfill designs are very safe and significant failures at managed landfills are extremely rare. A large number of scientific studies have been conducted on closed landfills to predict long-term environmental protection at modern landfill sites. The results of these studies support the following conclusions:

- The containment features of the modern landfill are designed, constructed, and maintained as necessary to protect human health and the environment throughout the operational and post-operational life of the facility; and
- Where natural catastrophic events have occurred at modern landfills (even after closure), the facility's environmentally protective features have not been found to be significantly compromised.

In addition to design, construction, operation and monitoring objectives, the physical integrity of the landfill is a key focus for engineers before and after closure. Factors that can affect the integrity of the landfill before closure or during post closure care are well understood and can be accounted for during the design of modern landfills. There is nothing in the literature identifying major structural failures at closed, modern landfills, and no significant impacts have been caused by catastrophic events (e.g., hurricanes, earthquakes, or wildfires). The few significant problems that have occurred at operating landfills are well documented and, following investigation, have been found to be the result of a specific operational failure or poor construction practice. Forensic studies on the performance of landfills during catastrophic events have found that landfills are highly resistant to damage from such events and that environmental protection systems remain intact. Of the studied events, only surface features (e.g., vegetation and landfill gas vents) showed signs of significant damage.

Integrated Systems for Overlapping Protection: Managed MSW landfills may have differences in designs and in operational methods to reflect local climate, geology, and adjacent land use. However, effective landfill designs consider these site-specific differences and appropriately incorporate the systems necessary to optimize landfill performance and provide integrated waste containment, leachate management, and landfill gas control. In this way, no single element is relied upon to protect human health and the environment. It is the combination of multiple systems and active management (including monitoring) that provides a comprehensive level of protection.

Empirical studies of liner quality and impacts to groundwater downstream of Subtitle D-lined landfills using site-specific data indicate that properly installed liner systems and effectively maintained leachate collection systems can prevent leachate impacts to groundwater. For example, a recent study that included more than 60,000 data records collected from some 740 monitoring wells installed at over 100 landfills showed no evidence of leachate impacts to groundwater from Subtitle D-lined cells. These results are consistent with earlier USEPA studies on the effectiveness of engineered liners to contain MSW leachate.

Planning for Care After Closure: There is considerable empirical evidence that the modern managed MSW landfill is a safe and responsible long-term waste management solution. Tools exist to evaluate appropriate levels of care after closure, and monitoring can confirm that any changes made are protective of human health and the environment. Because leachate and landfill gas concentrations and volumes decrease during the post closure period, a performance-based evaluation of threat after closure can represent not only current conditions but future conditions as well. Regulations stipulate that post closure care be provided for a period of 30 years, unless it is demonstrated to the regulatory agency that any change would not harm human health and the environment. As summarized in the post-closure care guidance document published by the Interstate Technology and Regulatory Council (ITRC) in 2006, enhanced landfill management has the potential to end regulated post-closure care activities earlier than the traditional 30 years. ITRC is a coalition of state environmental regulators working with the USEPA and other federal partners, industry, and stakeholders to advance innovative environmental decision making (see www.itrcweb.org for more information regarding the work of ITRC).

Planning for Care after Closure

Quote from the Interstate Technology and Regulatory Council (ITRC) Technical Regulatory Guidance document on **Post-Closure Care** (September 2006):

"Ongoing evaluation of MSW leachate quality and landfill gas production indicates that leachate quality improves and landfill gas production decreases from the time of closure in a manner that makes the 30-year prescriptive post-closure care term reasonable for financial planning purposes."

Beyond Waste Containment – Landfills as a Resource

The science of waste containment, degradation, and treatment continues to evolve in response to industry and socio-economic needs. Three areas of study and advanced use of MSW landfills as a resource beyond providing a responsible means of waste disposal include the following.

- Landfill gas-to-energy (LFGE), in which the methane contained in landfill gas is utilized to provide renewable **green energy** and further optimize greenhouse gas emission reductions through replacement of fossil-fuel derived energy.

- Enhanced waste treatment through wet landfill operation (that is, where the landfill is operated as a waste treatment vessel rather than a storage unit and generally cited in industry references as "**bioreactor operation**"). Enhanced waste treatment landfills are engineered to degrade the waste faster, speeding up landfill gas production, and facilitating more efficient energy use (thus decreasing the time for which that active landfill gas management is needed).

- **Carbon sequestration**, in which carbon is permanently stored in the landfill and removed from the global carbon cycle, leading to more accurate inventories of greenhouse gas emissions from solid waste management activities.

With effective end-use planning, the managed landfill can also provide beneficial use of the land to sustain wildlife habitats and parks and offer "green space solutions" (such as golf courses or walking trails).

In summary, the technical, regulatory, and operations sectors of the solid waste management industry continue to study the science of landfill systems and waste degradation in order to improve landfill efficiency, environmental compliance, and responsiveness to public needs. Peer-reviewed studies have concluded that actively managed modern MSW landfills are effective in containing and treating solid waste, and preventing impact to the environment. Moreover, they can be used as a source of renewable green energy for local communities and industries.

1. OVERVIEW OF A MANAGED SOLID WASTE LANDFILL

The last few decades have seen tremendous advances in land disposal technology and regulation. These advances have resulted in the modern managed landfill, which include:

*Scientifically Engineered **Containment***

*Highly Regulated **Operations***

*Preventative and Response **Maintenance***

*Active Environmental **Monitoring***

*Enhanced Waste **Treatment***

These elements, in combination, provide effective and overlapping protection of human health and the environment. Further, the evolution of the modern managed landfill to a valuable community asset includes renewable energy, wildlife habitat, and "green space" solutions.

Beneficial uses of closed landfill sites include children's playgrounds such as this soccer field
(Photo courtesy of NSWMA)

This report assesses the modern managed landfill and its ability to protect human health and the environment. The report is organized as follows:

- Section 1 describes the integrated elements and core attributes of the modern managed landfill (see Figure 1-1), explains the format for the report, and introduces the body of knowledge from research on landfill and waste processes;
- Section 2 presents the overarching framework for **Regulatory Oversight** and the broad foundation of **Design and Planning** that governs the life cycle of modern, managed municipal solid waste (MSW) landfills;

- Section 3 presents the primary engineered physical **Containment** components of a managed landfill;
- Section 4 describes the requirements for landfill **Operation** and **Maintenance;**
- Section 5 presents the types of regulated environmental **Monitoring** activities that underlie the other elements to provide for compliance and measure performance at the modern managed landfill;
- Section 6 describes how the elements of design, operation, maintenance, and monitoring are integrated to provide back-up protection of the environment;
- Section 7 outlines operational practices that go beyond containment to include enhanced **Treatment** and green energy solutions; and
- Section 8 provides a comprehensive list of key references that provide the technical and regulatory basis of this report.

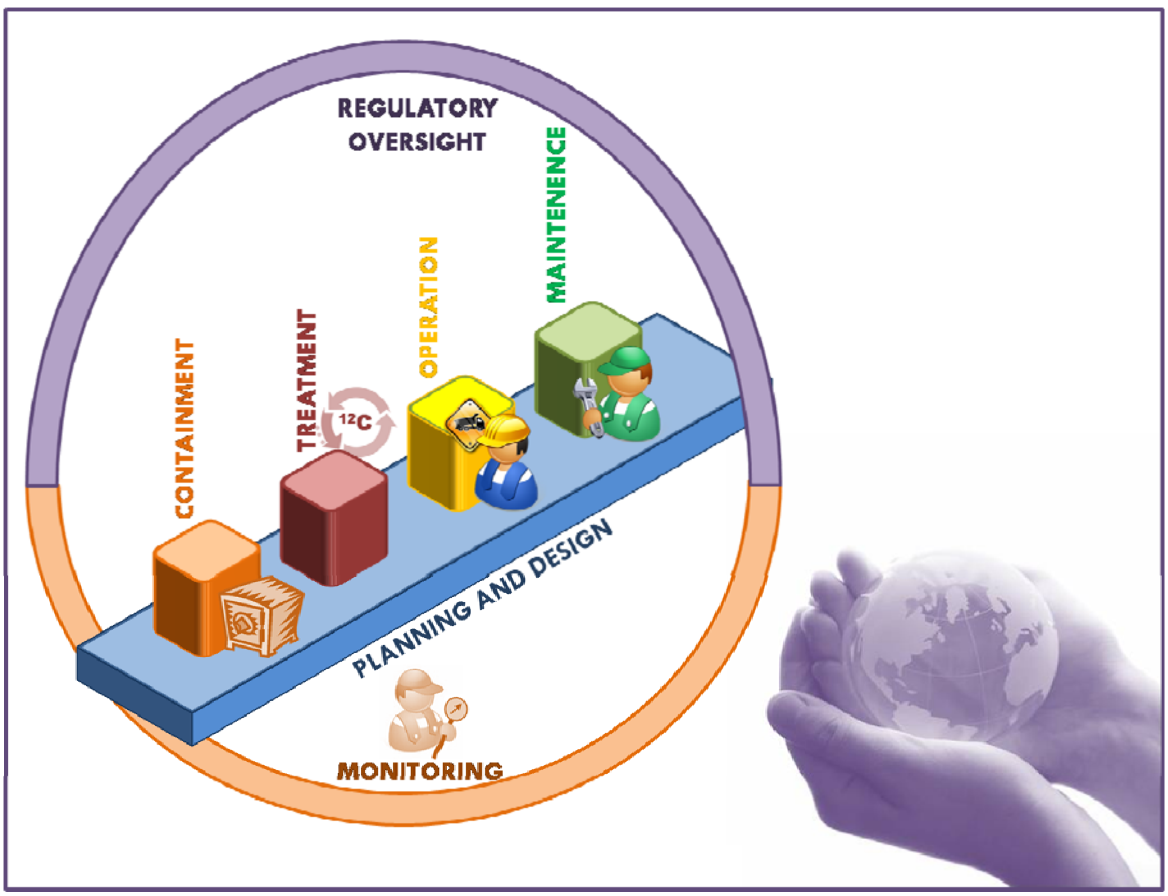


Figure 1-1: Integrated Elements of the Modern Managed Solid Waste Landfill – Protecting Human Health and the Environment

The reader is encouraged to review the references presented in Section 8. This report attempts to condense a large volume of information into an easy-to-understand document, with source materials for further reference consolidated into technical appendices. For the user's easy reference, in some sections a list of seminal references is included in a footer to support specific technical conclusions in the text.

1.1 What is a Managed Solid Waste Landfill?

The foundation of the modern, managed municipal solid waste (MSW) landfill is the combination of regulatory, design, construction, operational, maintenance, and monitoring features to create an inter-dependant, overlapping system for protection of human health and the environment. This document describes municipal solid waste landfills regulated by the United States Environmental Protection Agency (USEPA) under Subtitle D of the Resource Conservation and Recovery Act (RCRA) and does not cover landfills classified as a hazardous and which are regulated under RCRA Subtitle C.

The modern RCRA Subtitle D or "sanitary" landfill is an environmentally protective means to manage non-hazardous waste. As defined by the USEPA, landfills are *"land-based waste management cells that contain solid wastes. Waste containment systems for landfills consist of liner systems that underlay the wastes placed on them and final cover systems constructed over the wastes."*

What is a Landfill?

Landfills are engineered waste disposal structures designed, constructed, operated, and monitored to protect human health and the environment, and minimize receptor exposure to waste materials, potentially impacted groundwater, landfill gas, and leachate.

The Interstate Technology Regulatory Council (ITRC) has expanded upon this definition to provide a performance-based description, provided in the adjacent call-out box.

1.2 Key Elements of a Managed Solid Waste Landfill

Modern MSW landfills are designed and operated to strict regulatory standards, established by USEPA to be implemented by state environmental agencies, and effectively managed to prevent potential adverse environmental impacts. The key attributes of a modern managed MSW landfill include:

- Scientifically Engineered **Containment**;
- Strictly Regulated Facility Siting, Construction, and **Operations**;
- Preventative and Response **Maintenance**;
- Waste Degradation and **Treatment**; and
- Multi-functional environmental performance **Monitoring**.

Required by regulation, monitoring is not only an important compliance tool to see whether component systems are functioning as designed, but it also provides a means to measure system performance over time. The performance objective for these systems and monitoring functions is protection of sensitive media (such as groundwater) through the life cycle of the landfill (i.e., operation, closure, and post-closure).

To achieve the performance objective of protecting the environment, the modern, managed landfill employs multiple systems acting together throughout the landfill's life. The managed landfill exhibits five primary attributes – engineered containment of waste and by-products of waste degradation, passive and active waste treatment (in the form of natural as well as enhanced biodegradation), regulatory controlled operations, proactive systems and equipment maintenance, and active environmental monitoring. Together, these core attributes comprise the site-specific features of a modern landfill operation as illustrated in Figure 1-2.

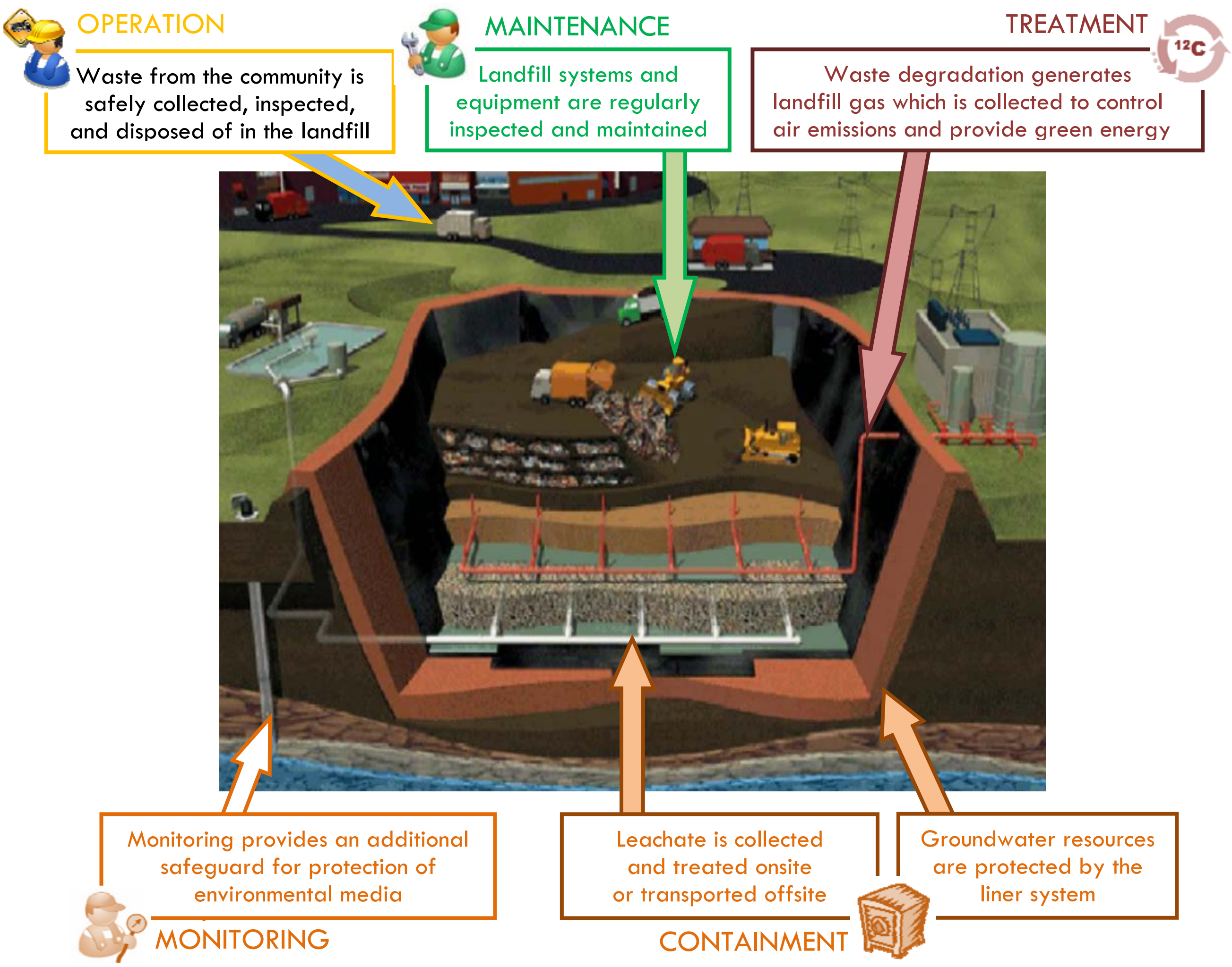


Figure 1-2: Primary Environmentally Protective Attributes of a Managed Landfill

The components (or systems) of the managed landfill, and their role in the landfill meeting its required performance standards, are detailed in Section 3. Briefly, these components include the:

- Liner system, which provides underlying containment of wastes for protection of groundwater;
- Leachate management system (LMS), which collects leachate (i.e., liquid that has passed through or emerged from the solid waste and contains soluble or suspended materials removed from the waste). The typical LMS has one or both of the following elements:
  - Leachate collection and recovery system (LCRS), which provides containment and protection of groundwater in addition to facilitating treatment and performance monitoring;
  - Leachate recirculation system (LRS), which reduces the quantity of leachate requiring disposal by recycling it back into the landfill, which in turn provides for enhanced (active) treatment (degradation) of the waste as described in Section 1.4.1.
- Gas management system (GMS), which collects the gas produced from the degradation of waste by biological processes inside the landfill, thereby allowing for landfill performance monitoring, gas destruction, and/or renewable energy production; and
- Final cover system, which provides containment, controls the rate of water entering the landfill as a result of rainfall or snowmelt (thus facilitating treatment of the waste within the landfill), provides stormwater management (SWM) and protection of surface water quality, and can provide suitable wildlife habitat.

1.3 How is Environmental Performance Monitored?

The environmental performance of the key components of the modern, managed landfill are evaluated routinely over time by means of systematic, inter-related programs measuring compliance with regulatory standards and confirming proper functioning of the landfill components. The environmental monitoring program (EMP) typically comprises some or all of the following components:

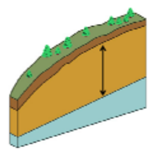
- **Groundwater** monitoring;
- **Surface water** monitoring;
- Lateral (outside the landfill) gas (methane) migration monitoring in the shallow unsaturated subsurface (known as the **vadose zone**);
- Head-on-liner monitoring (i.e., monitoring the amount of liquid build-up on the base liner system);
- Leachate (liquids collected from the base liner system) quality monitoring;

- Landfill gas system monitoring (i.e., within the landfill); and
- Surface emissions monitoring (SEM) to detect and evaluate migration of methane through the cover system to ambient **air** – performed on the landfill surface.

EMP activities are typically performed in conjunction with other inspection and maintenance programs such as those for the cover and stormwater management systems. An EMP monitors media (e.g., air, water) as a means to measure system performance of the individual components of the landfill, as well as the landfill as an integrated whole. The USEPA requires monitoring of four primary environmental media:

groundwater,

surface water,



unsaturated zone,

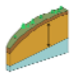
and air/atmosphere.

The media icons shown above will be used throughout this report to signify the role of design and/or operational elements in protecting the environment. By understanding the nature of these media, how they are monitored by the landfill operator, and how they could be affected by a potential landfill upset, it is possible for the landfill operator to predict potential environmental impacts and to rapidly develop response plans to prevent an impact before it can occur.

The following are examples of landfill features designed to protect each of the four environmental media:

- **Groundwater**: Engineered liner and leachate management systems are designed and constructed to contain leachate for collection and disposal/recirculation, thus preventing its seepage from the landfill into groundwater. In addition, groundwater is protected by gas management systems, which are designed and operated to control migration of landfill gas (LFG) out of the landfill through the surrounding soil (vadose zone) to groundwater.

- **Surface Water**: Operational surface flow controls such as berms, engineered let-down structures, and perimeter conveyance ditches and ponds are designed and maintained to prevent impacts to surface water by diverting and controlling storm water flow away from exposed waste. The placement of daily, interim, and then final cover and the operation of leachate management and LFG management systems effectively aid in this prevention.



- **Vadose Zone**: Engineered liner and LFG management systems are designed and operated to minimize the potential for the offsite migration of LFG in the vadose zone.

- **Air**: Engineered cover and LFG management systems are constructed and operated to minimize the emissions of LFG to ambient air.

While each of the containment, treatment, control and monitoring elements of managed landfills introduced above is individually designed to meet regulatory standards for care and protection of human health and the environment, it is the integration of these elements that produces a "design-review/build-monitor/maintain-monitor" form of long-term environmental protection. Sections 3 through 6 show how these elements are integrated to protect the four primary environmental media.

1.4 <u>What Happens Inside a Managed Solid Waste Landfill?</u>

The modern managed landfill is essentially a treatment vessel. The MSW landfill promotes natural organic waste decomposition and conversion of the by-products from solid to more mobile liquid and gaseous phases, which can be captured and treated or beneficially used. The degree and rate of degradation is dependent on many factors, including the moisture content of incoming waste, waste exposure to climate conditions, and site-specific operational practices such as leachate recirculation. The by-products of the degradation process include landfill gas (LFG) and leachate (i.e., the liquid that has passed through or emerged from the solid waste and contains soluble or suspended materials removed from the waste). This section will discuss the processes that promote biodegradation and how the by-products of this process are managed in the modern managed landfill.

1.4.1 Treatment (Biodegradation) of Solid Waste

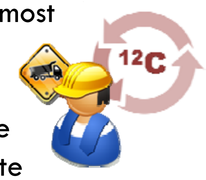
The conversion of a solid organic waste fraction to a gaseous or liquid phase is a natural process that involves either biodegradation or physical leaching of the waste. Waste treatment occurs because MSW has physical, chemical, and biochemical properties that change over time as it degrades. Biological transformation of the organic fraction of MSW in the presence of sufficient moisture reduces the volume and mass of the material, yielding compost-like material once the degradable material has been consumed. The by-products of biodegradation are biogas and leachate. Waste degradation under aerobic conditions (in the presence of oxygen) is rapid, generating biogas that is primarily comprised of carbon dioxide (CO_2). Under anaerobic conditions (in the absence of oxygen), waste degradation is slower but yields energy-rich biogas comprising roughly equal measures of methane and CO_2. Because landfills are operated anaerobically, methane-producing biochemical transformation processes are typically of most significance.

An extensive and growing body of research and practical knowledge exists to demonstrate the long-term performance of landfills under different design, operating, and closure conditions.[1] Reviews of LFG[2] and leachate[3] composition from multiple sites have been published and appear on Figure 1-3. These studies show that the most significant control on long-term leachate generation rates is regulating how much liquid is permitted to enter the landfill. This is usually associated with the installation of the final cover system. It is well documented that LFG generation from MSW landfills decreases with waste age (i.e., after closure). Under normal conditions, LFG generation rates typically reach a peak about one year after cessation of waste placement, before tapering off in exponential form.

A number of factors affect the rate of waste decomposition in landfills and hence the rate and quality of LFG and leachate production, including:

- Waste properties (e.g., composition, biodegradability, and physical state);
- Environmental factors (e.g., pH and alkalinity, availability of nutrients, and the presence of inhibitors to microbial activity); and
- Operational and process-based factors (e.g., addition of degradation-enhancing additives, and practices that optimize the high moisture content necessary for enhanced waste degradation).

Biodegradability is mostly affected by the cellulose and hemicellulose content of the waste as these two biogenic carbon sources contribute most significantly to waste decomposition.



Of the above, operational factors are the most controllable and arguably the most important from the perspective of managing a landfill. By controlling or promoting the processes of waste biodegradation, landfills can be managed to enhance waste degradation to promote in-situ waste treatment, accelerate exhaustion of LFG production, more rapidly reduce concentrations of leachate parameters of concern, and reduce long-term potential environmental impacts. As discussed in detail in Section 7.1, enhancing biodegradation within a modern managed landfill in this way is most commonly achieved through use of bioreactor technology. This kind of proactive operation of the landfill will likely diminish the need for containment (and reduction of infiltration through the cover system) over the long term since LFG production will be reduced and leachate quality improved to levels that protect the environment even in the absence of a tight landfill cover.

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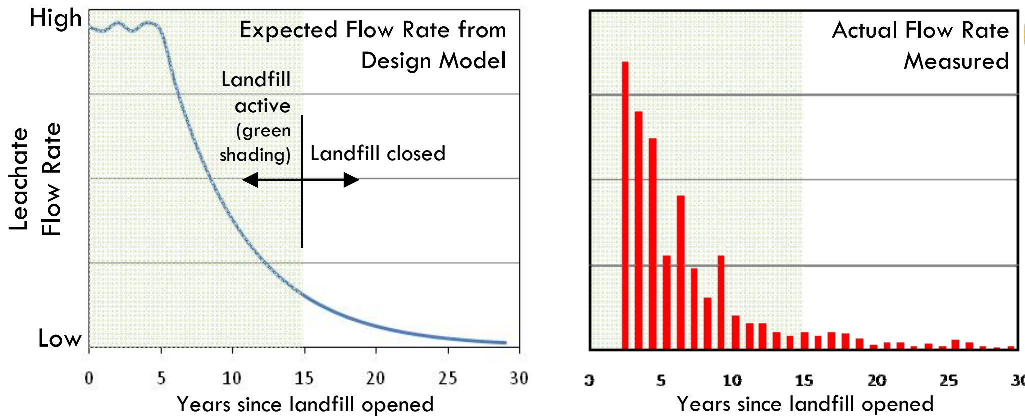
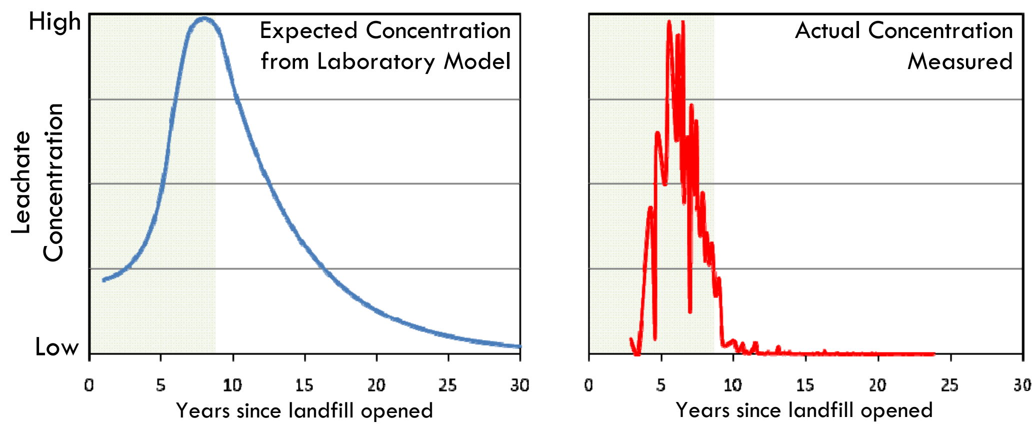
[1] As documented by several noted peer-reviewed journal articles including Farquhar & Rovers (1973), Rees (1980), Pohland & Harper (1986), Christensen & Kjeldsen (1989), Barlaz, et al (1990), Christensen, et al (1992), Bozkurt, et al (1999 and 2000), Revans, et al. (1999) and Kjeldsen, et al (2003). See Appendix A for detailed discussion.

[2] Including van Zanten & Sheepers (1995), Huitric (1999), Hsin-Mei & Kuo (2000), Green, et al (2000), Sullivan & Michels (2000), Sullivan & Stege (2000), Barlaz, et al (2004a), and Sullivan, et al (2004).

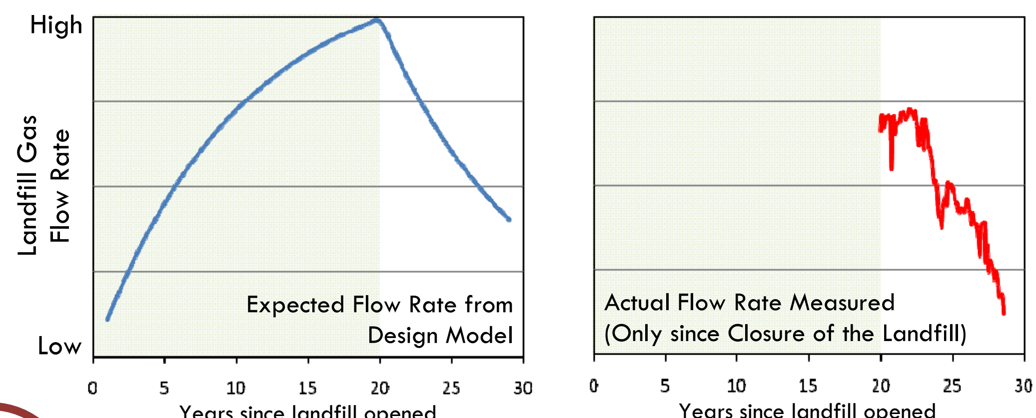
[3] Including Farquhar (1989), Christensen, et al (1994), Robinson (1995), Rowe (1995), Reinhart & Grosh (1998), Knox, et al (2000), Christensen, et al (2001), Ehrig & Kruempelbeck (2001), Bonaparte, et al (2002a), Robinson & Knox (2001 and 2003), and Gibbons, et al (2007).



(a) Expected Flow (left, blue line) and Measured Flow (right, red bars) in a Leachate Collection System (based on data from Bonaparte, et al, 2002a)



(b) Expected Concentration (left, blue line) and Measured Concentration (right, red line) of Organic Indicators in Leachate (based on data from Morris, et al, 2003)



(c) Expected Flow (left, blue line) and Measured Flow (right, red line) in a Gas Collection System (based on data from Geosyntec, 2001)

Figure 1-3: Long-Term Characteristics of Leachate and Landfill Gas

1.4.2 Permanent Storage of Biogenic Carbon in Landfills (Sequestration)

Carbon sequestration is the permanent removal of biogenic carbon (i.e., carbon of recent plant origin rather than the fossil carbon found in coal, natural gas, or oil) from the atmosphere. The major biodegradable (i.e., biogenic carbon) components of MSW are cellulose and hemicelluloses (C&H), which are complex carbohydrates that form the main structural components of cells in all green plants. C&H are thus the most common organic compounds on Earth. However, although C&H will decompose anaerobically to methane and CO_2, the complete decomposition of C&H within a landfill is not expected. In addition, many common components of the waste mass are wood-based and contain lignin. Lignin is highly recalcitrant to anaerobic biodegradation under landfill conditions, and will not undergo any significant decomposition.[4]

Given these conditions, "carbon sequestration" as applied to landfills refers to carbon that is of plant origin (including wood, paper, cardboard, food waste, and green yard waste) that does not degrade after disposal, but rather is permanently stored in the landfill in a stable form that cannot be emitted as a greenhouse gas (GHG) such as methane or CO_2. As discussed further in Section 7.2, the degree of biodegradation that may be achieved in a landfill, combined with the carbon that is sequestered and permanently stored in the landfill, are important factors in understanding the potential for landfills to emit greenhouse gases to the atmosphere.

1.4.3 Development of a Leachate Biofilter in Bottom-Most Waste Layers

Researchers have noted that leachate strength (in terms of organic indicators, primarily the measured biological oxygen demand or BOD, and chemical oxygen demand or COD) from the upper waste layers of a landfill is invariably higher than that in leachate collected from lower waste layers. Independent studies in the U.S., Japan, and China have demonstrated the capacity of lower layers of MSW to accelerate improvement in leachate quality. This suggests that the bottom-most layers of the waste are well decomposed due to moist conditions and the presence of efficient biodegradation in this environment. These degraded waste layers act as a biofilter, with an attenuating capacity for consuming degradable organics in leachate. Moreover, a landfill does not have to be operated under conditions of enhanced degradation to realize the benefits of a basal biofilter layer because moisture will tend to accumulate in the bottommost waste layers of landfills, except at the very driest sites. This is of immense value in effectively evaluating long-term leachate conditions because it allows organic indicator parameters such as BOD and COD to be used as a primary measure of overall leachate quality. Existing research demonstrates that if an improving trend in the concentration of such indicators in leachate can be demonstrated and leachate continues to be

[4] Carbon sequestration in landfills is discussed by Barlaz (1998 and 2006), Barlaz, et al (2007), and is recognized in two seminal reports: (i) USEPA (2006) "*Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks (3rd Edition),*" and (ii) Intergovernmental Panel on Climate Change (IPCC, 2006) "*Guidelines for National Greenhouse Gas Inventories; the National Greenhouse Gas Inventories Programme*." A number of state GHG inventories have been conducted, such as the California Greenhouse Gas Inventory (developed by the California Air Resources Board in response to Assembly Bill 32, 2006), and include landfills as sink for sequestered carbon (for additional information see www.arb.ca.gov/cc/inventory/inventory.htm).

generated, the concentration of degradable leachate organics will continue to decline or remain steady. This attenuating condition is also conducive to the continued immobilization of heavy metals and other persistent constituents that may be present.[5]

1.4.4 Physical and Biogenic Settlement

Settlement of a MSW landfill results from the complex interaction of many processes, including mechanical settlement due to self-weight, superimposed loads (i.e., additional waste layers and cover soil), physiochemical changes such as corrosion and oxidation, and biochemical decomposition under aerobic and anaerobic conditions. The rate of settlement is important in determining the nature and timing for beneficial end uses of the landfill property. Several factors affect waste settlement processes,[6] including:

- Method and rate of waste placement;
- Landfill thickness, method and rate of compaction, and waste density;
- Waste composition and organics content; and
- Temperature, moisture availability, and other operational factors.

Waste settlement behavior in many ways is similar to that of other highly organic materials such as peat, and is generally considered to occur in three stages:

- **Immediate settlement** is due to the application of a superimposed load, under which voids and particles in the waste are compacted, and is often considerable. Landfill operators take advantage of immediate settlement to maximize use of landfill airspace by compacting waste at the working face.
- Thereafter, **primary settlement** is principally due to dissipation of pore water and gas present in waste voids at placement. It has been estimated that primary settlement is usually completed within 30 days and accounts for up to 10 percent of total settlement.
- Finally, although both inorganic and organic wastes settle due to decomposition (inorganic waste decomposes through corrosion, oxidation, or other means), **secondary settlement** of MSW under landfill conditions occurs primarily due to biodegradation of the organic components of MSW. Depending on the thickness of the waste mass, mechanical settlement may occur concurrently with processes that cause secondary settlement. Secondary settlement may result in a reduction of up to 25 percent of the total original landfill thickness. The most significant control on long-term settlement is the availability of moisture within the waste mass (which effectively controls the rate of biodegradation).

[5] This phenomenon is well reviewed and elaborated on in some detail in EREF (2006). See also Appendix A.

[6] Waste settlement in landfills is discussed in numerous seminal studies, including Sowers (1973), Wardwell & Nelson (1981), Edil, et al. (1990), Gordon, et al. (1986), Morris & Woods (1990), Watts & Charles (1990 and 1999), Wall & Zeiss (1995), Park & Lee (1997 and 2002), and Leonard, et al. (2000).

2. REGULATORY OVERSIGHT OF MANAGED SOLID WASTE LANDFILLS

Permits are required to construct, operate, and close a MSW landfill. The permitting process requires ongoing regulatory compliance to protect human health and the environment through all stages of landfill development, operation, and post closure:

***Permitting**:*
Detailed Site Characterization and Landfill Design
Compliance with Regulatory Standards
End Use Considerations & Planning
Public Comment
Regulatory Approval

***Construction**:*
Construct to Designed Specifications
Independent Third Party QA/QC and Certification
Landfill Gas and Liquid Management Systems

***Operation**:*
Compliance with Permit Requirements
Fill/Cover Sequencing
Waste Treatment/Compaction
Performance and Compliance Monitoring

***Closure**:*
Compliance with Permit Requirements
Certification

***Post-Closure Care**:*
Performance and Compliance Monitoring
Financial Assurance
Site Security

Enacted in 1976, the Resource Conservation and Recovery Act (RCRA) put an end to the historical patchwork of highly variable and insufficient state regulation of waste management. Under the statutory mandate of the RCRA chapter devoted to municipal solid waste (MSW), Subtitle D of RCRA (codified at 40 CFR Part 258), USEPA created a national baseline for MSW facility siting, design, operation, monitoring and closure. These federal baseline standards, implemented by the states, were expanded dramatically with regulations published in 1991, which established rigorous mandates for waste acceptance, facility assessment, liner design, groundwater monitoring and corrective action in the event of a potential release from the landfill unit, site closure, and post-closure care (PCC).

2.1 Overview of Solid Waste Landfill Regulations

The USEPA's Subtitle D regulations ushered in the modern era of solid waste landfill regulatory oversight, including prescriptive liner and cover systems (generally, low permeability soil plus geosynthetic membranes), prohibition of liquid waste disposal (although leachate recirculation is permitted), installation of leachate collection systems, control of explosive gas migration, monitoring of groundwater and other media, financial assurance for long-term care, and guaranteed public input into the permitting process. State permitting programs must, at a minimum, comply with the provisions of Subtitle D, and most states have developed additional, more stringent requirements reflecting local conditions.

Moreover, MSW landfills are subject to additional regulation Federally mandated by the Clean Air Act (CAA), which provides additional standards for control of landfill gas and other emissions, the Clean Water Act (CWA), which mandates controls to protect water from potential impact due to activities at the landfill, and the Safe Drinking Water Act (SDWA), which provides standards of safety for groundwater in the vicinity of the site. These federal standards are supplemented by state and local regulations controlling the specific location of landfills, their hours of operation, the kinds of wastes that can be accepted, and other features of local concern.

2.2 Regulatory Obligations though the Life of a Landfill

Under the provisions of Subtitle D, MSW landfills are required by permit to comprehensively assess the site and all aspects of its operation prior to accepting any waste. A permit applicant must conduct extensive characterization of the proposed site's geologic/hydrogeologic and environmental conditions, develop plans for operation, maintenance, and monitoring, and implement these plans throughout the operating, closure, and post-closure phases of the landfill's life. The primary objective of the required engineering controls, physical siting restrictions, and ongoing management obligations is to protect human health and the environment now and far into the future.

The Subtitle D program is based upon:

- Established design and management practices that include good site selection, thorough understanding of the landfill's surrounding environment, principles of engineering and planning, and overlapping systems for waste containment and performance control; and

- Defined post closure care control systems, routine monitoring and response to conditions that occur, and end-use assessment to allow future use of the property to be consistent with environmental security and beneficial use of property.

Regulatory oversight by Federal and State agencies through all stages of the landfill life cycle is intended to ensure that these objectives and performance standards are achieved.

2.2.1 Siting Considerations

Where possible, today's modern landfills are built in locations that provide additional natural buffer between the engineered containment features and potential surface or subsurface migration pathways and receptors. For example, areas with deep groundwater, low permeability in-situ soils, and/or large buffer distances (to surface water bodies, other potential natural receptors, residential communities, and other human receptors) will augment the effectiveness of engineered containment and control systems. In addition, the Subtitle D regulations generally restrict landfills from being constructed in:

- Floodplains, unless engineering measures are in place to prevent a flood from washing MSW out of the landfill into local streams or rivers;
- In or near wetlands, unless the landfill will not cause significant degradation of the wetland or the loss of wetlands is avoided or mitigated through construction or preservation of alternative wetlands;
- Fault areas or seismic impact zones; or
- Other potentially geologically unstable areas, unless the landfill is designed to maintain structural integrity during a geologic event.

Before a landfill can receive a permit to begin operation, its property must be characterized by investigative activities such as drilling and sampling shallow and deep soil borings, installing and sampling wells and piezometers, identifying geologically active faults that may intersect the waste disposal footprint, and other site characterization activities. This characterization is typically certified by an independent engineer, geologist, and/or groundwater scientist that site conditions are suitable for development of a landfill and can be effectively monitored. The adequacy of the site characterization will be discussed in public permit proceedings. In addition to these RCRA requirements, the property must comply with local zoning ordinances governing appropriate land uses.

2.2.2 Planning and Design

The Subtitle D regulations require approval of the design of the landfill's proposed containment, treatment, operations, maintenance, and monitoring plans prior to obtaining a permit to operate. Furthermore, the regulations require the verification of construction as per the design plans be included in the site operating record. There is some flexibility in designing some of the components of the MSW landfill as long as performance standards are met (e.g., an alternative liner or cover system design must demonstrate equivalent levels of performance and effectiveness to the standard Subtitle D design). In making this equivalency determination for an alternative landfill liner, for example, climate conditions, hydrogeologic characteristics beneath the facility and surrounding land, groundwater flow regime, proximity and withdrawal rate of groundwater users, and existing groundwater quality are considered.

Leachate is liquid that drains through the disposed waste as the waste compresses in the landfill. When designing leachate management systems, the potential for leachate formation is assessed through the preparation of a water balance for the landfill. This involves summing inputs (the amount of water entering the landfill) and subtracting other outputs (the amount of water consumed in chemical reactions and the quantity leaving as water vapor). A water balance study at a landfill helps identify the significance of these various water components. This is important to leachate management in terms of determining needed storage, treatment, and disposal capacities and configuration.[7] Peak leachate flow rates generally decrease over time as active landfill areas are closed and improved infiltration control is achieved by the final cover system.

An active gas management system (GMS) is designed and sized to collect generated LFG and to maintain appropriate negative pressures within the landfill to optimize gas collection efficiency and to reduce the potential of landfill gas migration or surface emissions. Design factors include current and future MSW intake, corresponding LFG generation and yield potential, field observations and testing, the size and characteristics of the permitted landfill area, surrounding terrain, and subsurface conditions. These factors will determine system performance and the means to control LFG migration and emissions.

As with any civil engineering structure, consideration of the long-term geotechnical stability of the landfill is a key focus during the design process. Demonstrating both short- and long-term landfill stability are components of the design calculations and modeling performed during preparation of a permit application.

2.2.3 Construction

Following state agency approval of the landfill's planning and design specifications, a permit is issued to begin construction, starting with the base liner, leachate collection and recovery system (LCRS), site access roads, and accessory operations facilities. Leachate is contained and recovered for proper disposal from the earliest phases of landfill use, thus supporting the effectiveness of the liner system. Liner systems are designed and constructed to contain leachate and gas within the landfill as well as to direct leachate and gas to their controls systems.

Liner systems are typically constructed as a composite system of low permeability materials, including natural soils (compacted clay), geomembranes, and/or geosynthetic clay liners (materials used in construction of containment systems are discussed in more detail in Section 3.1). Both the liner system and LCRS are installed in accordance with a construction quality assurance (CQA) program. An independent program of third party CQA is required to inspect, test, document, and certify that the liner system is installed in accordance with design specifications and regulatory requirements.

[7] Estimates of leachate generation rates can be performed using several computer programs of which the USEPA's Hydrogeologic Evaluation of Landfill Performance (HELP) model is the best known and most widely used. Seminal references on leachate generation include Peyton & Schroeder (1993) and Schroeder, et al (1994).

The LCRS is installed along with the liner system, before any placement of waste. Although the design of the landfill's gas management system is planned before construction of the landfill begins, it is installed after a sufficient volume of waste has been disposed that can optimally support the GMS. Pumps, piping, and electronics used for the LCRS and GMS are designed to manage the projected volume of liquids and gas to be collected, conveyed, stored, and transported. The LCRS and GMS equipment and appurtenances must be appropriate for their intended use, with confirmation from the manufacturer that the specifications on proper operation, use, and maintenance of the equipment have been respected. An independent third party CQA program is required to certify that all LCRS and GMS components are installed in accordance with design specifications and regulatory requirements.

2.2.4 Operation and Maintenance

After construction but prior to commencing operations, the landfill operator must obtain an operating permit. This permit prescribes the operating and maintenance criteria and procedures for the operating life of the landfill. The operating permit must be adhered to and includes various details including operating hours, waste inspection requirements, procedures to enforce restrictions on receipt of non-MSW (i.e., hazardous or radioactive waste, regulated medical waste, state-designated "special" wastes, bulk liquid wastes), designation of specific operating equipment, staff responsibilities, daily operational requirements, inclement weather operation, and litter and nuisance control. Procedures for control of potential emissions to air, water and groundwater must be detailed. All State programs regulating MSW landfills must include these baseline protections, and State agencies are free to add restrictions necessary to address local conditions.

2.2.5 Environmental and Performance Monitoring and Reporting

Monitoring must be planned and executed to verify protection of environmental media. Performance monitoring for the landfill includes:

- LCRS monitoring (e.g., recording of leachate flow rates, head on the liner, etc.);
- Monitoring leachate quality at the LCRS sumps and/or storage tanks; and
- GMS monitoring to comply with the requirements of the Clean Air Act (e.g., wellhead monitoring, surface emissions monitoring of the cover), as well as to address RCRA obligations controlling the explosive potential of methane.

Landfills must demonstrate that leachate accumulation is minimized by maintaining a maximum one-foot head (i.e., height of liquid level) above the liner system. This restriction prevents leachate volumes from accumulating on the liner at a volume that could compromise liner effectiveness. Maintaining a minimal head on the liner system significantly reduces the possibility of leachate seepage to the environment. Any deviations from this restriction must be corrected immediately and documented in site operational records. Significant deviations may be reportable to the state regulatory agency.

Active environmental monitoring is required at key locations around the landfill. Four types of monitoring systems are designed to detect a system upset from either LFG or leachate into the four primary media:

- **Groundwater** monitoring;
- **Surface water** monitoring;
- Lateral gas migration monitoring in the shallow unsaturated subsurface (known as the **vadose zone**); and
- Surface emissions monitoring (SEM) to detect migration of gas through the cover system to ambient **air**.

To assure accuracy, monitoring and sampling at Subtitle D landfills is performed by qualified field personnel following strict chain-of-custody procedures for sample collection and data tracking. Sample analyses are conducted at certified independent laboratories under high quality standards. Where on-site monitoring is required, samples are collected using appropriate outdoor monitoring equipment following well-defined protocols, including requirements for routine equipment calibration, collection of several scanning measurements in real time, and other conditions specified in the facility's permit.

Data are evaluated using statistical approaches and other scientific techniques as mandated by the state regulatory authority, employing evaluation techniques specifically developed for performing quantitative, technically-defensible evaluations of monitoring data. These evaluations are important because they can provide reliable predictions of future concentrations based on past and current data, and afford a baseline from which to identify inconsistent results. The results of environmental monitoring are used to confirm the predictions of future trends in leachate or LFG quality and quantity, and to confirm that changes in landfill operation or maintenance have not resulted in an unexpected outcome or upset of the landfill containment system. Monitoring data and evaluations must be reported to the overseeing regulatory agency in a timely manner in accordance with permit conditions.

2.2.6 Closure

Once the landfill has reached its final permitted waste capacity and active operations have ceased, the landfill is closed consistent with detailed regulations and in compliance with the facility's approved closure/post-closure plan. A final cover system is constructed to perform the following functions:

- Control moisture and percolation;
- Promote surface water runoff and minimizing erosion;
- Prevent direct exposure to or contact with the waste;
- Control landfill gas emissions and odors; and
- Provide aesthetic enhancement to the property.

The engineered final cover system is designed to protect the environment and provides flexibility for end use of the landfill property (e.g., generation of renewable energy through landfill gas collection and use of appropriate areas for natural habitat). Once closure construction activities are complete, the operator must obtain a closure certificate and permit specifying ongoing PCC activities and obligations.

2.2.7 Long-Term Maintenance and Post-Closure Care

Under Subtitle D, an operator is required to monitor and maintain the landfill after the landfill is closed such that measures required for protection of human health and the environment are continued. Subtitle D requirements for PCC at MSW landfills include four principal elements:

- Groundwater monitoring;
- Final cover maintenance and monitoring;
- Leachate management and monitoring; and
- Vadose zone monitoring for LFG migration.

The final cover system is designed to limit exposure to leachate, LFG, or waste via direct contact, and to limit liquid infiltration into the landfill. Technical issues that are addressed in the final cover design include the magnitude and rate of post-closure settlement and the stresses that settlement impose on containment system components, the durability of the cover system, waste decomposition and its impact on LFG and leachate generation, and the overall performance of the combined liner and final cover system (i.e., the waste containment system).

In addition to the Subtitle D requirements, there are other federal, state and local requirements to control site access, manage stormwater, comply with applicable Clean Air Act control requirements until those performance standards are met, and generally maintain the site. Maintenance of these systems during PCC is verified through environmental monitoring around the landfill. Subtitle D requires PCC for a baseline period of 30 years following closure, although the PCC duration may be modified as the State regulatory authority deems appropriate and protective of human health and the environment.

2.3 Public Involvement in the Permitting Process

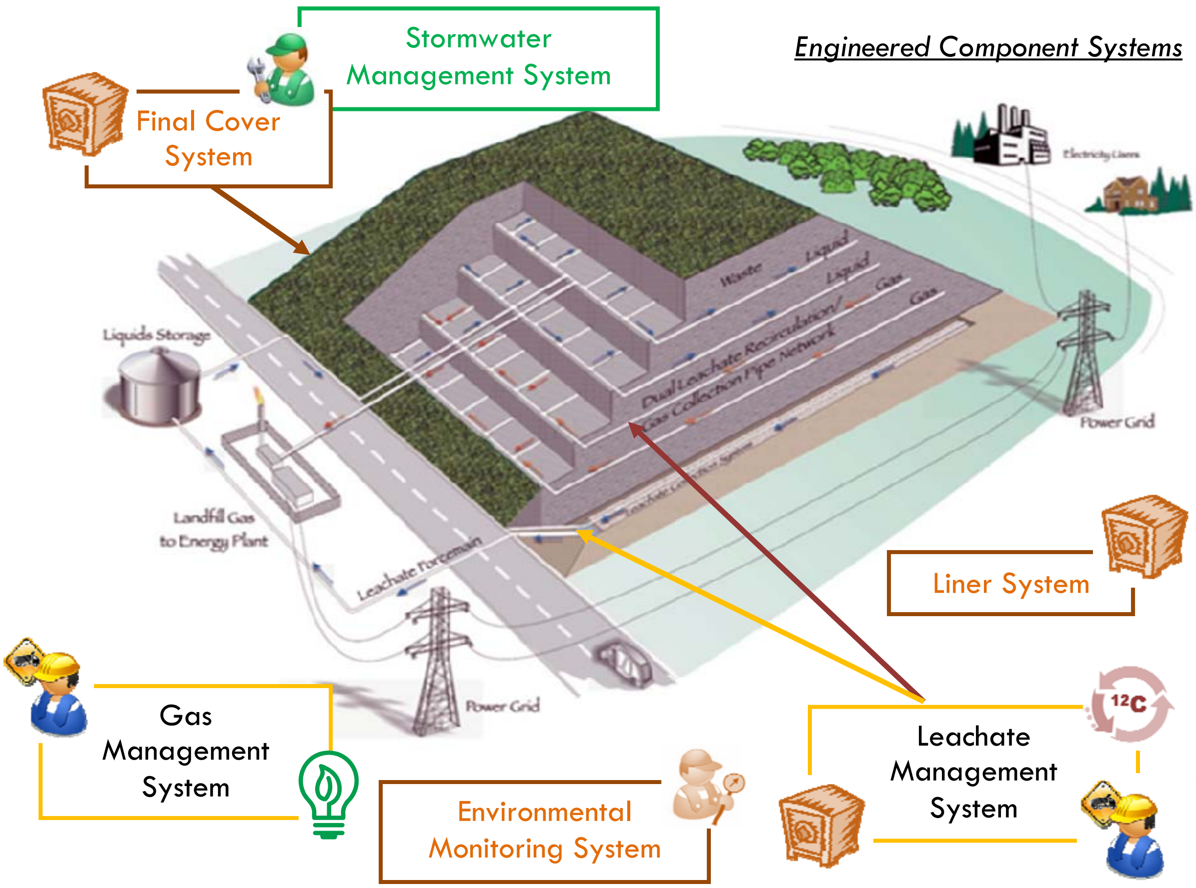
Informational meetings during the landfill permitting process provide for active public participation in the decision making process

Throughout the entire landfill permitting process, the public is encouraged to become involved and offer comment. Once the overseeing regulatory agency determines that a permit application to construct and operate a landfill site meets all regulatory requirements, the agency prepares a draft permit and submits it to the public for comment, often holding a public meeting to answer questions and accept additional comments. Permit applicants are encouraged to interact with interested members of the public even before a draft permit is available.

The agency solicits, collects, and carefully reviews and considers the comments received prior to making a final decision on a permit application. In making a final decision, the agency takes into account public concerns voiced at meetings and as outlined in written comments received. A written summary is usually prepared by the agency responding to public comments and concerns. Where appropriate, specific design criteria may be amended to mitigate potential impacts, or conditions added to the permit to improve the landfill's overall performance.

3. DESIGN COMPONENT SYSTEMS OF A MANAGED SOLID WASTE LANDFILL

The anatomy of a modern managed landfill includes numerous engineered systems and components that function together with natural conditions and buffers. Combined, these engineered and natural components provide overlapping environmental safeguards throughout the operating and post closure life of the landfill.



The waste containment, treatment, and monitoring systems are designed, constructed, operated, and maintained to provide long-term environmental protection.

Modern managed landfills are designed and operated to prevent human or vector (e.g., insects, rodents, birds, etc.) contact with disposed waste. Additionally, modern landfill designs use engineered liners of low permeability to contain waste, leachate, and landfill gas and protect groundwater.

3.1 Containment of Waste in Landfills

The environmentally safe and secure containment of solid waste in landfills has been a major goal of the USEPA since the agency's founding in 1970. Modern waste containment systems consist of the base liner or barrier system, the leachate control and recovery system (LCRS), and the cover system. Modern waste containment systems are the cornerstone of landfill performance, and consist primarily of the liner system, leachate management system, and the cover system. Figure 3-1 shows the principal components of a landfill's overall containment system. As will be discussed in Section 3, the individual components work together as a containment system for waste, liquid, and gas. Landfill containment systems are discussed in detail in Appendix B.

There are three primary materials in use today as low permeability hydraulic barriers for liner systems: compacted clay liners (CCLs), geomembranes (GMs), and geosynthetic clay liners (GCLs).[8] As discussed throughout Section 3, these components are generally combined to create a multi-layer barrier to fluid flow (e.g., a CCL and GM are often combined in a composite liner system). GMs, also known as flexible membrane liners (FMLs), are thin, factory-manufactured polymeric materials that have been the most widely used for liners and final covers (where a low permeable cover is desired) due to their non-porous structure, excellent resistance to degradation by a wide range of chemicals, flexibility, ease of installation, extremely low rates of water and gas permeation, and resistance to tearing. GCLs are thin liners, generally comprised of sodium bentonite sandwiched between two geotextile layers for support. The hydraulic conductivity of a GCL is extremely low, on the order of 1×10^{-9} cm/s. To put this in context, it would take over 30 years for a single drop of water to travel through a ½-in. thick GCL. The hydraulic conductivity of a well-constructed CCL is also extremely low, on the order of 1×10^{-7} cm/s. CCLs are constructed far thicker than their GCL counterparts, typically in a 2-ft thick layer. Again, to put this in context, it would take over 20 years for a single drop of water to travel through a 2-ft thick CCL. GCLs and CCLs therefore provide similar very long-term restriction of water movement through the liner system. Moreover, GCL and CCL liner systems do not function alone as containment barriers but in combination with associated cover and leachate collection systems.

Safe Containment of Waste in Landfills

Waste containment systems at managed landfills include a liner system, final cover system, and typically natural subsurface barriers. Comprehensive multi-media environmental monitoring programs enable demonstration of system performance. The monitoring programs are also designed such that necessary response actions are implemented in a timely manner, before upsets can cause an environmental impact.

[8] The general characteristics of each of these materials are well presented and discussed in a number of seminal references, including Koerner, et al (1990), Bonaparte et al (2002a), Othman et al (2002), and Rowe (2005). See also Appendix B.

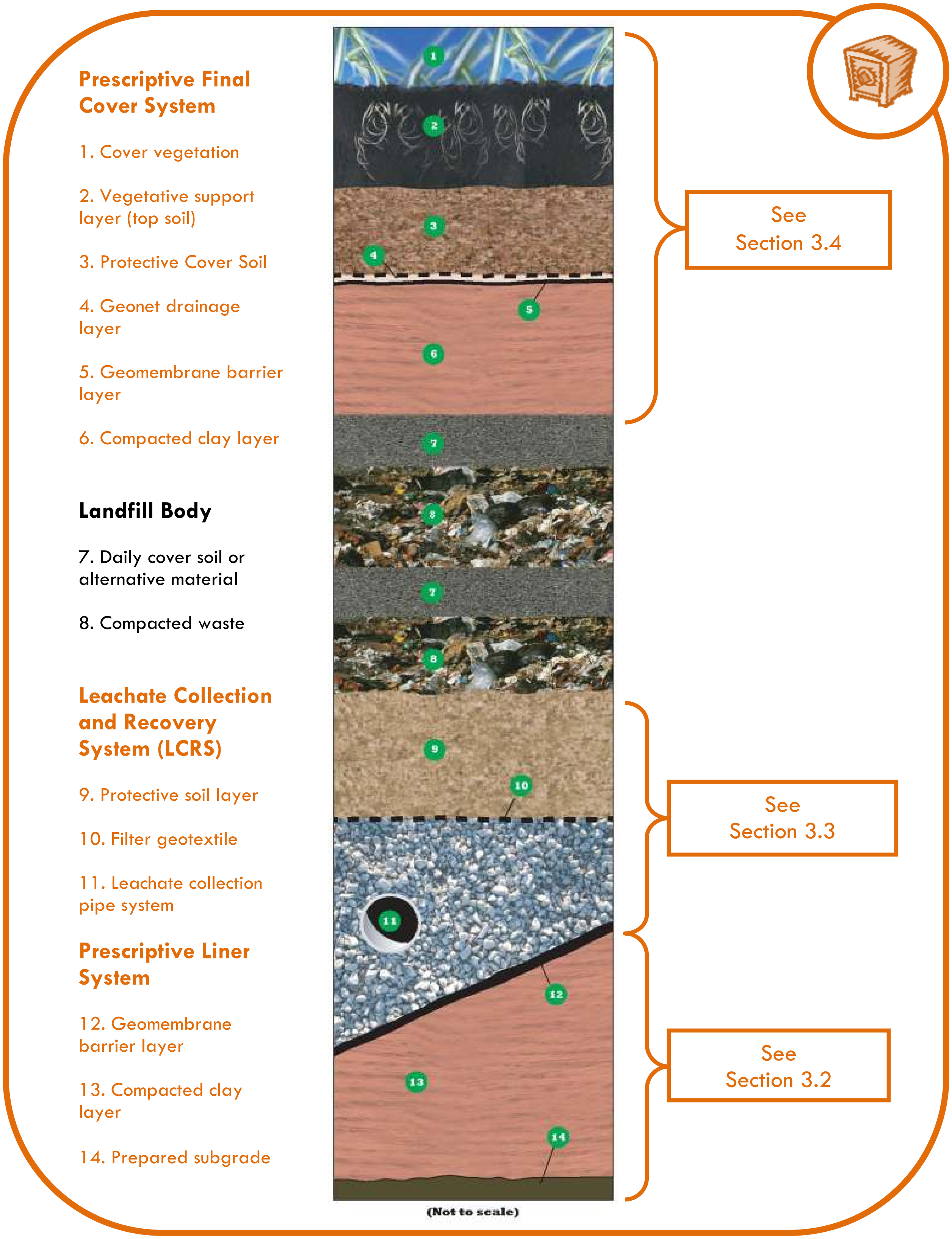


Figure 3-1: Typical Anatomy of a Closed RCRA Subtitle D Landfill

3.2 Liner System

The primary function of base liner systems in modern landfills is to protect groundwater from contamination by landfill leachate. Liners are engineered low-permeability barrier systems that, depending on local hydrogeological and climate conditions, use natural in-situ soils above the groundwater table in conjunction with single, double, or composite soil and/or geosynthetic materials. Beyond protecting groundwater, liner systems serve a number of important secondary functions, including providing containment of waste, controlling landfill gas migration (i.e., protecting the local unsaturated zone and groundwater from gas impacts), and serving as a long-term structurally stable base for overlying facility components. A composite liner system also has a built-in back-up structure (the leachate collection system) to control downward movement of liquid.

3.2.1 Liner System Components

Historically, compacting native (natural in-situ) or borrow-source clay or clay-rich soils has been the favored method of containing leachate within the landfill. The use of clay soils can be effective as a natural liner system and can exceed minimum performance standards. However, where climatic and geologic conditions preclude the use of in-situ soils as an effective natural barrier system, modern landfill designs also feature single or multiple layer liner systems.

Supervised installation of a HDPE geomembrane as part of a composite liner system.

Multiple layered (or composite) liners feature one or more liner components that comprise the composite barrier system. The most common geosynthetic liner material in use today is a geomembrane (GM), or flexible membrane liner (FML), which is manufactured and installed by independent, third party contractors in accordance with protocols for quality control and quality assurance. Due to its resistance to degradation by a wide range of chemicals, among other factors, high density polyethylene (HDPE) geomembrane is the most common type of GM barrier used in landfill liners. However, other GM materials include polyvinyl chloride (PVC), butyl rubber, and hypalon. In a typical installed composite liner, a GM forms the upper component, with compacted in-situ soils, compacted clay liner (CCL), or a geosynthetic clay liner (GCL) as the lower component(s).

3.2.2 Key Environmentally Protective Features of Liner Systems

Not only do liner systems serve as an engineered barrier, they are often constructed with a leachate collection and recovery system (LCRS). The LCRS protects the GM from being damaged through direct contact with overlying waste and prevents leachate accumulation on the liner. In addition to a liner system and LCRS, modern landfills also feature a cover system and a gas management system (GMS). Leachate is contained by the liner system and removed from the landfill via the LCRS. Similarly, LFG is contained by the liner and cover systems and removed via the GMS. Therefore, not only do composite liner systems directly serve to protect groundwater and the unsaturated subsurface interval between ground surface and groundwater (also known as the vadose zone) by containing leachate and LFG, they have built-in back-up systems when it comes to protecting these media by providing a reliable supplement to the LCRS and GMS. Liner systems also indirectly protect surface water by controlling potential leachate leakage to groundwater for recharge to a surface water system.

Engineered Liners are Effective at Protecting Groundwater

Engineered liner systems work in conjunction with natural buffers and barriers and are proven effective at protecting groundwater and the unsaturated subsurface by containing leachate and gas. In a recent study reported by Caldwell & Wallis (2006), more than 60,000 data records were collected from about 740 monitoring wells installed at over 100 landfills. All showed no evidence of leachate impacts to groundwater as a result of leakage of leachate from Subtitle D-lined cells. These results are consistent with earlier USEPA studies on the effectiveness of engineered liners to contain MSW leachate.

Long-Term Liner System Performance

In a recent USEPA-sponsored study (Bonaparte, et al., 2002a), the service life of a HDPE GM was estimated to be on the order of 1,000 years. Liners consisting of a geomembrane overlying a compacted clay layer have been used for radioactive waste depositories required to provide safe containment for tens of thousands of years.

3.2.3 Long-Term Performance of Liner Systems

Because the materials and construction methods used in Subtitle D landfill liner systems are well known and their performance documented through more than three decades of scientific research and observation, they can be expected to be environmentally protective over the very long term. A GCL designed and installed under Subtitle D criteria should meet its performance criterion for hundreds to thousands of years. For a CCL under these same design and construction constraints, the service life is even longer, on the order of thousands of years[9]. This is the reason that CCLs are used in the encapsulation liner systems of more "critical" waste management units (e.g., radioactive waste), and that a well maintained liner can be protective in a MSW landfill far beyond the time the contained waste would be of potential environmental concern.[10]

3.3 Leachate Management System

The purpose of a leachate management system (LMS) is to collect leachate from the base of a landfill and convey the leachate away for safe discharge or disposal. In general, a LMS includes the following three major components:

- A leachate collection and recovery system (LCRS) directly above the liner system, which is sloped and graded to provide positive leachate drainage under gravity to a sump fitted with a riser pipe (see Figure 3-2);
- A leachate transmission and storage system featuring a pipeline network, pumps, and storage tanks, sumps, or lagoons; and
- A treatment and/or disposal system.

These components are integrated and serve complementary functions for environmentally protective leachate management at a modern landfill. The type and complexity of each component system is dependent on local climate conditions and operational design, as well as other site-specific factors. Selection of an appropriate LMS is discussed in Section 3.3.4.

3.3.1 Leachate Collection and Recovery System

In most cases, the LCRS overlies the low permeability liner system in a modern managed landfill. The LCRS normally comprises a 12 to 24 inch layer of porous sand or gravel, the purpose of which is to collect and remove leachate generated in the landfill, although the sand/gravel layer also serves to protect the liner system from damage during initial waste placement. A specifically designed open-weave plastic mesh termed a geonet (GN) or synthetic drainage material termed a geocomposite (GC) is sometimes installed above the liner instead of, or in conjunction with, a sand/gravel drainage layer to improve LCRS drainage performance. The LCRS is overlain by a geotextile (GT) fabric or similar permeable barrier to minimize intermixing of overlying waste and protective soil layers. The first two to four feet of waste disposed of in the landfill are carefully

[9] The service life of HDPE geomembranes and composite liner systems has received significant attention in the technical literature (e.g., Koerner, et al, 1990; Hsuan & Koerner, 1998; Rowe, 1998; Rowe & Sangam, 2002; Sangam & Rowe, 2002; Hsuan & Koerner, 2005; Rowe, 2005) and has been the focus of a recent USEPA-sponsored study (Koerner & Hsuan, 2002). See also Appendix B.

[10] Discussion of the use of geosynthetic and natural soil systems for very long term waste encapsulation is beyond the scope of this document. However, seminal references include Reith & Caldwell (1993) and Bechai, et al (1986).

selected and placed to form a protective "fluff layer" above the LCRS. This fluff layer also serves to provide the perfect "seeding" conditions for a biofilter to develop in the bottom-most waste. As previously described in Section 1.4.3, research has shown that this biofilter layer has the capacity to provide very long-term treatment of leachate before it could emerge from the landfill.

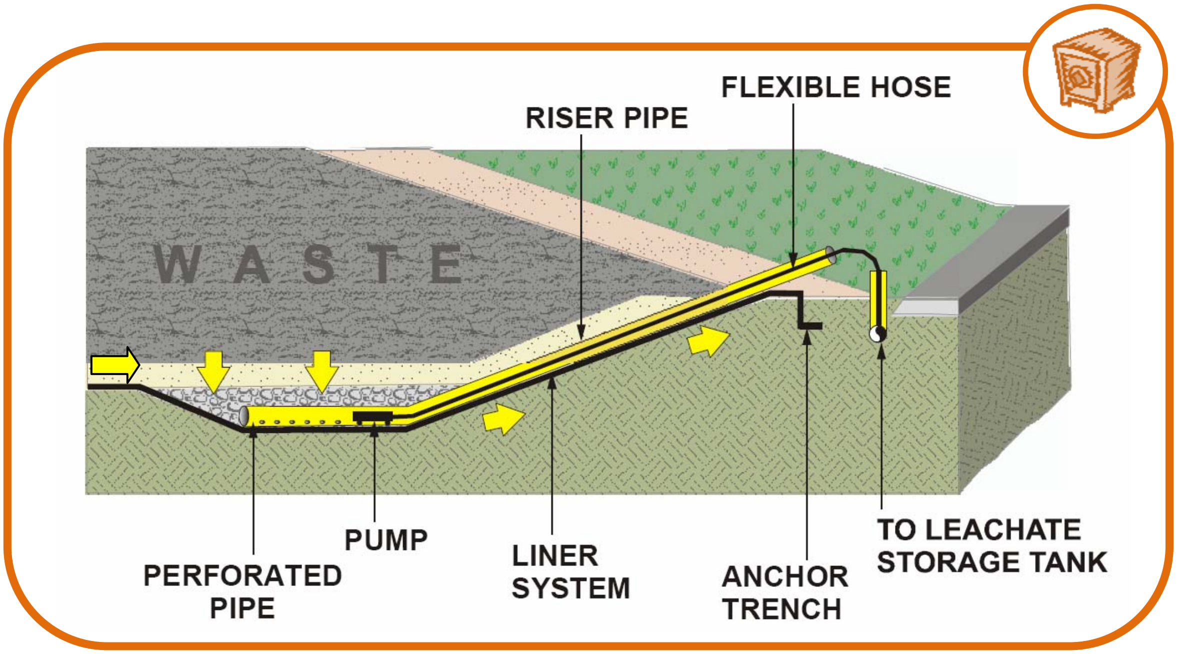


Figure 3-2: Some Typical Features of a Leachate Collection System

3.3.2 Key Environmentally Protective Features of Leachate Collection Systems

To enhance liner system performance, leachate is collected and removed through the operation of a LCRS to prevent it accumulating above the liner. This minimizes potential liquid head build-up on the liner, which provides an additional safeguard for leachate containment within the landfill. Leachate management activities typically consist of:

- Monitoring and managing liquid levels through operation of a LCRS and, in some cases, modified with a leachate recirculation/liquids injection system;
- Leachate quality monitoring for recirculation or disposal purposes; and
- Monitoring and maintaining the overall performance of the leachate management infrastructure.

Although progressively reduced levels of leachate generation occur after a landfill closes, the LCRS is designed to rapidly convey the maximum quantity of leachate expected to collection sumps for final management. The LCRS is also designed to control accumulation of leachate in the drainage layer consistent with the regulatory requirement of no more than 12 inches of head on the liner. Cleanout pipes that connect directly to the main leachate collection pipes in the landfill are incorporated into the design. This allows landfill operators to clear debris from the LCRS if necessary to maintain design flow specifications, thereby reducing the potential for the LCRS to have sustained periods of saturation and decreasing the potential for development of biological fouling within leachate pipes.

3.3.3 Long-Term Performance and Longevity of Leachate Collection Systems

Leachate generated by a landfill will need to be collected during its active life and post closure care (PCC) period until such time as active management is not required to protect human health and the environment. The geosynthetic products (GNs, GCs, and/or GTs) and pipes used in a modern managed LCRS are designed to accommodate the maximum anticipated loads of waste and to be structurally stable for periods well beyond the combined duration of active landfill operations and subsequent PCC period.[11]

LCRS maintenance conditions specified in landfill facility permits issued by most states require regular pipe inspections and cleanout as a means to demonstrate that the piping system remains functional. Documentation of proper LCRS operation is also required to demonstrate compliance with the site operating permit (e.g., transmission pump performance and flow, head-on-liner measurements, storage tank flow balance, recirculation volumes, and quality control criteria for onsite treatment and/or offsite discharge or disposal of leachate as specifically permitted to a surface water outlet or sewer connection to a public wastewater treatment plant).

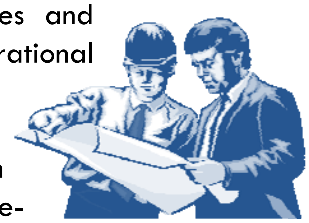
3.3.4 Leachate Management Options

Effective leachate management can vary from site to site based on factors including climate, size of the landfill, waste treatment goals, and location. The determinants include:

- Climate (e.g., annual rainfall, moisture content of incoming waste, volume of leachate generated);
- Site-specific conditions (e.g., site size, landfill geometry, cover system design specifications, and proximity to natural habitats);
- Siting considerations (e.g., distance to a publicly-owned treatment works, or POTW) and the nature of the receiving environment (e.g., proximity and size of surface water bodies, hydrogeologic conditions, and ecological sensitivity); and,

[11] There is extensive information in the technical literature on LCRS design and performance (e.g., Rowe, 1998; Othman, et al, 2002; and Bonaparte, et al, 2002a) as well as the design and selection of sand and geotextile filter components (e.g., Giroud, 1982 and 1996; Lafleur, et al, 1989; Luettich, et al, 1992; and Koerner, 1998). See Appendix B for further details.

- Leachate treatment options (i.e., recirculation into waste, pre-treatment systems, direct POTW discharge, use in existing natural wetlands, creation of new natural or man-made wetlands, or tree-farming).



Climate conditions have a direct effect on leachate generation rates and quantities, and indirectly affect available treatment options or operational performance of the leachate treatment systems (e.g., some treatment systems are efficient for treating small quantities of leachate but are not economical for large volumes, while many treatment systems are reliant on biological processes which may not perform well in cold climates). Site-specific conditions and location of a landfill affect layout restrictions (e.g., if little space is available for leachate management/treatment features, then systems requiring large areas are obviously not suitable) and effluent (treated leachate) discharge options and permit limitations (e.g., small, low-flow surface water systems with highly sensitive or pristine ecosystems will impose stringent limits on effluent quality). Effective leachate management requires assessment of the operational and post closure lifetime of a landfill, taking account of expected changes in leachate quantity and quality over time.

While leachate management strategies are critically important during the operational life of a landfill, sustainable leachate management strategies at the managed modern landfill consider long-term solutions that have added benefits like the production of "green energy" (i.e., gas to energy plant) or development of wetlands or tree farms that provide community benefits and provide for ongoing protection of human health and the environment long after the landfill closes.

Available leachate management alternatives can be broadly categorized as follows:

- Store untreated leachate in onsite tanks, then:
  - Truck offsite for disposal at a POTW for treatment with municipal wastewater; or
  - Direct discharge to a sewer connection to a POTW;

- Recirculate untreated leachate back into the landfill;

- Use untreated leachate for application in natural or constructed wetlands, tree farming, etc.; or

- Provide onsite leachate treatment prior to disposal or discharge consistent with the above options.

The first alternative has historically been the most widespread approach adopted at Subtitle D landfills, although other options are becoming increasingly common. It should be noted that, although the primary objective of recirculation is generally provision of cost-effective onsite management and treatment of leachate, a secondary objective is often accelerated biodegradation of the waste mass and LFG generation (as discussed in Section 7). Leachate can be delivered back into the waste mass through a variety of methods, primarily spraying at the active face, surface infiltration ponds, vertical injection wells, horizontal gravity drainage (infiltration) or injection trenches, or horizontal injection blankets. Currently, subsurface horizontal infiltration trenches are the most common method used. Achieving an even distribution of moisture throughout the waste mass is the most important operational factor as this avoids potential problems with leachate seeps and lateral breakouts.

Based on the various site conditions and surrounding land uses, an effective and long-term LMS can be variable and include different system features. Prior to generating a reasonable design for the LMS, several questions need to be answered:

- Is leachate recirculation planned (e.g., to enhance degradation of the waste, maximize landfill gas generation, and develop "green energy" through methane collection and conversion to electricity)?
- Is there a POTW located near the landfill that is permitted to accept leachate, or are only on-site treatment options available?
- If only on-site options are available, is pre-treatment required prior to discharge, or is re-introduction back into the waste mass preferable?
- Are nearby wetlands available that could be used for natural treatment of the leachate?

The answers to these and other questions will influence the final LMS design at the managed landfill. If on-site treatment is selected as part of the LMS, there are a number of widely adopted options for treatment of leachate, used either alone or in combination. The treatment options can be divided into three general categories:

- **Physical treatment**, including evaporation/concentration, solids removal (e.g., sedimentation/settlement, filtration, or air flotation), and specialized techniques (e.g., air stripping, activated carbon adsorption, ion exchange, or reverse osmosis);
- **Chemical treatment**, including chemical oxidation, precipitation, coagulation, and flocculation; and
- **Biological treatment**, including aerobic (i.e., "with air") systems such as aerated lagoons, sequencing batch reactors (SBRs), membrane bioreactors (MBRs), and percolating filters; anaerobic (i.e., "without air") systems such as digesters and sludge blankets; and combined aerobic/anaerobic systems such as engineered wetlands.

Use of these technologies for leachate treatment is based upon well documented success in treating municipal and industrial wastewaters similar in characteristics to solid waste landfill leachate. In many instances, effective treatment of landfill leachate may involve the adoption of more than one treatment process. A site-specific treatment plan may involve the use of primary, secondary, and tertiary processes.[12] Approaches that are sufficient as primary treatment in one case may be appropriate as a tertiary stage for "polishing" of pretreated effluent prior to discharge at another site.

For example, at an older closed landfill, an engineered wetland or reed bed in which leachate is physically and biologically treated may be capable of providing effective treatment of leachate to achieve surface water discharge standards. A sustainable LMS strategy at a newer active landfill might involve the use of wetlands for effluent polishing; however, in this application, pre-treatment using a more active treatment system is typically required if influent leachate constituent concentrations are well above surface water quality standards. As previously discussed, untreated leachate or treated effluent may be recirculated back into the landfill depending on the waste degradation strategy or other potential beneficial use strategy of the landfill (e.g., gas-to-energy plant). Most treated effluent also has other beneficial uses (e.g., use for dust suppression on access roads within the landfill footprint or as flush water for toilet facilities).

Constructed vertical wetlands provide a passive method by which leachate can be treated prior to discharge. The system design also offers added value as a potential wildlife habitat.

Because the characteristics of MSW leachate at a landfill are well understood and are predictable in terms of both their expected quantity and quality over time (see Section 1.4 and discussion in Appendix A), it is becoming standard practice to design a LMS that considers changes in long-term leachate management obligations in defining goals for sustainable landfill operation at the managed modern landfill.

3.4 Landfill Cover Systems

The landfill cover system is designed to promote surface water runoff, minimize erosion, prevent direct exposure to waste, and control gas emissions and odors. A secondary objective is to provide an aesthetically pleasing final appearance for the landfill. In this regard, the cover can be designed to be compatible with the local ecosystem to broaden the potential end uses of the property. The landfill cover system provides ongoing protection of human health and the environment, improves the collection efficiency of the gas management system, and serves an important function in onsite liquids management.

[12] A number of technical publications deal extensively with leachate treatment technologies, including USEPA (1995a), and U.K. Environment Agency (2007), as well as Robinson (1999), Robinson, et al. (2003), and Robinson & Olufsen (2004).

The structure of the landfill cover varies through the different stages of landfill operations. The initial phase of waste cover is ***daily cover***, a layer (usually about six inches thick) that is placed on top of the active fill area at the end of each working day. Soil is typically used as daily cover, but other types of materials may be used, such as textile covers (manmade fabrics or tarps rolled over the top of the fill area) or stabilized organic materials such as wood chips, shredded green waste, and compost. ***Intermediate cover*** is a thicker layer of soil (typically 12 inches) that is applied to inactive areas of a landfill that will not be used for an extended period of time (e.g., several months or years) but are not ready to be permanently closed. The ***final cover system*** is a more structurally complex, engineered cover system installed once a landfill or portion of a landfill has been completed and permanently closed. Under Subtitle D, the final cover system must meet a prescriptive low permeability cover design or an alternative cover design that complies with performance-based goals. The final cover system is engineered to tie into the liner system around the perimeter of the landfill, providing effective containment of the waste. This section focuses on the containment attributes and environmentally protective management components of final cover systems.

3.4.1 Design of Final Cover Systems

Cover construction will reflect climatic and site-specific performance goals, but all engineered cover systems are designed with components to fulfill the following three primary functions:

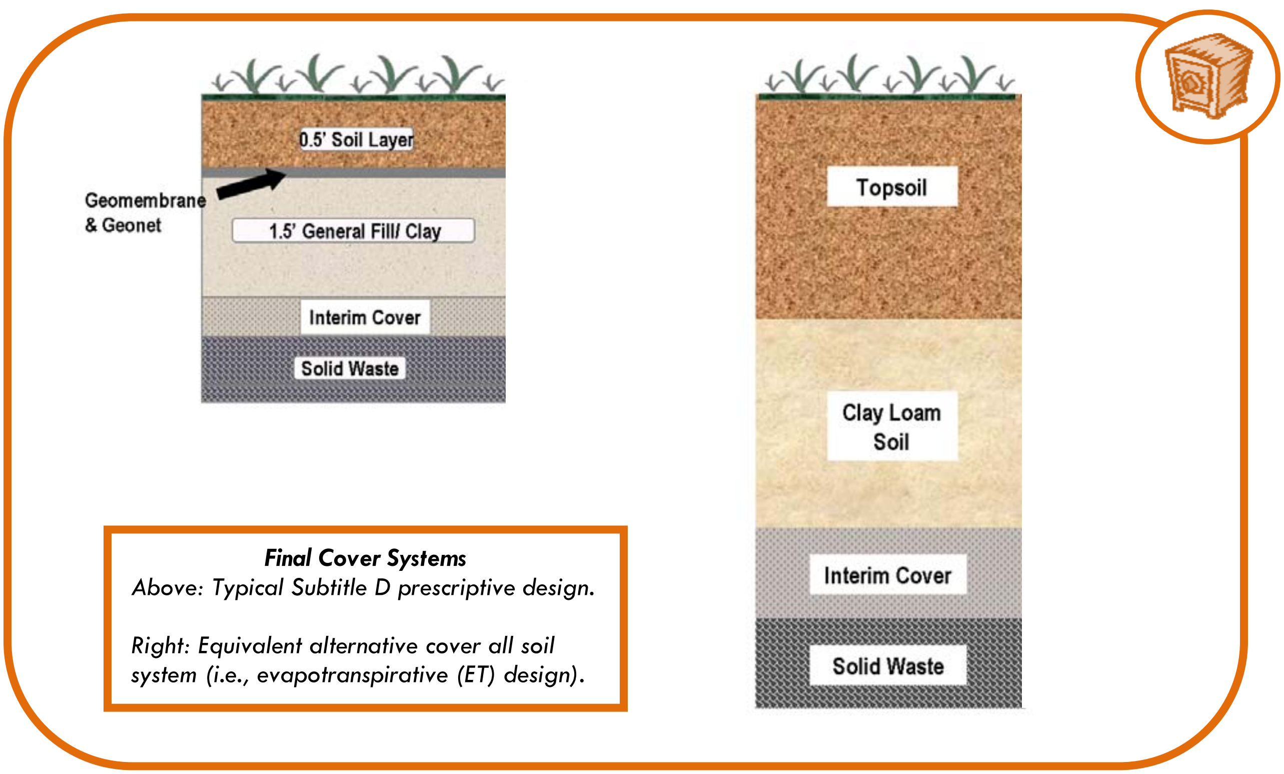
- **Infiltration Control**: Soil and/or geosynthetic layers (termed the "barrier layer" in prescriptive cover systems) are designed to control infiltration of rainwater or snow;
- **Control of Surface Water Drainage**: A soil or geosynthetic drainage layer is designed to divert surface runoff above the infiltration control layer in a controlled manner to minimize ponding and to promote flow to a constructed conveyance ditch; and
- **Vegetative Support**: An uppermost, organic-rich soil layer is designed to promote vegetative growth to resist erosion, optimize slope stability, and provide conditions consistent with the surrounding natural ecosystem if possible.

Subtitle D provides a prescriptive cover system design. However, because the regulation mandates environmental performance in final cover system design, various types of cover system designs can be used to fulfill the primary functions listed above. Some alternative cover designs not only provide protection of the environment equivalent to a Subtitle D prescriptive cover, but offer additional benefits, including:

- **Methane Destruction:** An uppermost, oxygen-rich soil layer can be very effective at reducing greenhouse gas (GHG) emissions to the atmosphere by natural oxidation (i.e., biological conversion of methane to carbon dioxide and water); and
- **Enhanced End Use Flexibility**: Some alternative final cover systems with enhanced vegetative growth can offer improved long-term slope stability and erosion resistance

along with reduced long-term maintenance requirements that increase wildlife habitat and other site reuse opportunities.

Under Subtitle D, MSW landfills must use the prescriptive low permeability cover design or an alternative cover design that meets the performance goals achieved with prescriptive covers. A typical prescriptive cover system design for a MSW landfill includes, from top to bottom, a six-inch thick soil vegetative support layer, a geomembrane (GM) upper component of a composite barrier, and an 18-inch thick compacted clay liner (CCL) lower component of a composite barrier. A sand or geosynthetic drainage layer (e.g., geocomposite or geonet) is installed above the barrier layer, or an adequate thickness of cover soil is placed to allow sufficient water storage for healthy surface vegetation in the overlying soil vegetative support layer. In northern climates, a greater thickness of soil above the barrier components is necessary to protect the cover system from freeze-thaw damage. For many final cover systems, the establishment of plant species may be aided by placing a natural or geosynthetic erosion control (GEC) layer on the surface. Many cover designs featuring low permeability barrier layers incorporate a landfill gas dissipation layer (e.g., permeable material) to prevent buildup of gas pressure under the cover system, which could negatively affect cover components.



Final Cover Systems
Above: Typical Subtitle D prescriptive design.

Right: Equivalent alternative cover all soil system (i.e., evapotranspirative (ET) design).

Figure 3-3: Final Cover System Design Alternatives

As illustrated on Figure 3-3, the function of a final cover system can also be achieved with alternative designs, including monolithic soil evapotranspirative (ET) cover systems (e.g., all-soil design), capillary-break ET cover systems, phytoremediation ET cover systems, and exposed geomembrane cover systems. These alternatives were all considered favorably in a nationwide USEPA-sponsored study.[13] These designs are often implemented as part of sustainable landfill designs, and include all-soil final covers constructed to be naturally analogous and compatible with the local ecosystem. Such "natural analog" cover designs provide protection of the environment equivalent to the Subtitle D prescriptive cover, but with the added benefits of enhanced methane oxidation, reduced GHG emissions, and ability to allow controlled infiltration for enhanced waste degradation.

3.4.2 Key Environmentally Protective Features of Final Cover Systems

Final cover systems are an important complement to liner systems as a component of waste containment at landfills, and Subtitle D regulations require that the final cover system be placed over the landfill within one year after the waste reaches its final permitted height. Beyond providing containment, the final cover system also fulfills other important functions:

- Promoting surface water runoff (which protects **surface water** from impacts due to contact with waste), and controlling infiltration of precipitation into the waste (which in turn controls leachate and landfill gas generation);
- Minimizing **erosion**, and controlling the occurrence of litter, disease vectors, and other nuisances;
- Protecting **air quality** by controlling landfill gas emissions and odors; and
- Meeting aesthetic and other **end use goals.**

The final cover system provides ongoing environmental protection in conjunction with the short- and long-term goals for reuse of the landfill property (e.g., improved gas-to-energy operations, recreational land use options, and/or increased area for natural habitat).

3.4.3 Long-Term Performance of Final Cover Systems

Long-term cover system performance is related to the ability of the barrier, drainage, and vegetative support layers to continue functioning as designed. The effectiveness of the drainage and vegetative support layers is easily observed by the absence of significant erosion damage and bare areas during cover inspections. For landfills whose final cover system is designed to limit percolation, the effectiveness of the barrier layer can be directly measured by overall reduction in leachate flow rates over time from the LCRS, and indirectly measured by the level of gas emissions from the

[13] The Alternative Cover Assessment Program (ACAP), sponsored by the USEPA, has established field demonstrations at 12 sites nationwide to evaluate the performance of various alternative cover systems, as described by Benson et al. (2005) and Dwyer (2003).

cover surface. If leachate or gas emission rates unexpectedly increase, the cause of this phenomenon is be investigated and addressed. Although some have posed concerns about final cover system failure, this is unlikely as evidenced by low to negligible leachate generation rates and continually downward trends observed at modern MSW landfills currently in PCC.[14] Further, as discussed in Section 3.2.3, the expected service life of a GM barrier layer in a composite cover system is of the order of 1,000 years, comparable to the long-term performance of GM barrier materials in liner systems. Similarly, whether in combination with an upper GM component or as a single-layer cover system, a low-permeability CCL provides an excellent long-term robust barrier to precipitation.

Performance of Landfills during Severe Natural Events

Investigations of landfill covers and environmental protection systems following a severe natural event suggest that landfills are highly resistant to damage from such events. Studies performed after the Florida hurricanes of 2004 (Roberts, et al., 2005), the Northridge and Loma Prieta earthquakes in California (Matasovic & Kavazanjian, 1998), and the San Diego wildfires of 2003 showed that the integrity of landfills had not been compromised. The only damage that occurred was to surface features such as vegetation and LFG vents that were repaired at minimal cost.

Although the final cover is far more accessible for maintenance and repair over the long term, its design and construction is managed with the same level of care and foresight as the liner system. If properly maintained, something relatively easily achieved, the CCL should meet its hydraulic conductivity criterion for several thousand years. The cover maintenance required for closed MSW landfills is primarily related to cover system vegetation (e.g., mowing, tree removal, re-vegetating), and erosion and sediment control (e.g., removal of sediment from ditches and ponds, re-grading the top deck to promote drainage). A significant portion of cover system maintenance is related to upkeep of the stormwater management system to provide proper drainage (i.e., cover drainage features, sediment trapping devices, retention/sediment control ponds, diversion channels, silt fences and other sediment control devices, and vegetation).[15]

The design and use of all-soil evapotranspirative (ET) final covers was pioneered at older landfills with pre-Subtitle D liner systems, generally at sites located in dry climates. The performance of

[14] In USEPA-sponsored studies by Bonaparte (1995) and Othman, et al (2002), the observed leachate generation rates for MSW landfills have shown continually downward trends post-closure.

[15] The expected service life and long-term maintenance requirements of cover systems is discussed in a number of seminal references, including Koerner & Hsuan (2002) and in the USPEA's "*Technical Guidance for RCRA/CERCLA Final Covers*" (Bonaparte, et al, 2002b).

ET covers at these sites has been studied for decades. ET covers have proven to be effective at alleviating potential problems with subsurface gas migration. These successes, coupled with improved availability of reliable design tools for ET final cover systems and a 2004 revision to the USEPA's Subtitle D rules which permits the wider use of alternative covers, have given rise to an increasing number of newer landfills across a variety of climatic zones closing with all-soil ET covers rather than a prescriptive RCRA Subtitle D final cover system.

Natural Analog Evapotranspirative (ET) Cover Systems

Soil covers that are compatible with the surrounding ecosystem provide a similar function to prescriptive covers and are expected to have a service life of a thousand years or more (Bonaparte, et al, 2002a).

To determine the properties that are effective in a given environment and understand how to address a possible upset, a study of the cover's compatibility with the local ecosystem can be performed. This kind of study involves evaluating a natural, and sometimes archeological, material or setting that is analogous to a proposed cover system material or setting. For example, there is ample archaeological evidence to show the very long-term integrity of certain manmade earthen structures under a wide range of climatic conditions, such as Native American burial mounds or the prehistoric earth enclosures (henges) of the British Isles. Alternatively, when ET covers are constructed with surficial site soils, their long-term performance can be inferred by observation of vegetation and precipitation recharge conditions at the site. In this context, natural analog studies have been used to demonstrate the design of ET covers for critical structures (e.g., radioactive waste depositories) to support service lives of thousands of years and to predict the effects of long-term climate change, ecological change, and soil development on these cover systems. Studies at MSW landfills have shown that ET covers can likely have service lives in excess of a thousand years with minimal maintenance and still satisfy performance criteria for infiltration control.[16]

Earthen cover systems have many potential benefits for system maintenance over time. Because these covers consist of soils that are designed to store and release water rather than provide a barrier to infiltration, they are an excellent counter-balance to increasing gas pressure within the landfill. In the event that a repair is needed, it is a relatively simple task (i.e., adding appropriate soil material) that immediately improves the performance of the system by adding storage capacity. Moreover, the properties desirable in an earthen final cover are also desirable properties to promote the oxidation of methane, since the extent of methane oxidation is influenced heavily by the availability of oxygen that diffuses vertically from the ground surface. Earthen cover systems have thus been demonstrated to effectively reduce methane emissions through oxidation (see discussion on passive gas management in Section 3.5.2), thus reducing the greenhouse gas emission potential of a MSW landfill, which is critical to future sustainable landfill management strategies.

[16] As discussed by Gee & Ward (1997), Gee, et al (1997), Waugh (1997), ITRC (2003), Scanlon, et al (2005), and Dwyer & Bull (2008).

3.5 Gas Management System

Landfill gas (LFG) is generated from the biodegradation of the waste mass. LFG management is a term that encompasses methods for controlling movement of LFG out of the landfill; such movement potentially occurs as lateral subsurface migration or emission through the cover. Direct control factors are the interception of LFG within the waste body by means of a gas management system (GMS) before it can potentially escape from the landfill. A GMS provides management of LFG within the waste mass, or at its source. A GMS can either be passive or active, and can be installed before, during, or after landfill closure. Generally, an active GMS is best installed at new large landfills during active operation or at closure. A passive GMS is best suited to small landfills, or an older site at which significant gas generating potential has already been exhausted (for this reason, large sites with active gas management will invariably transition to passive management in later years during PCC). Managed LFG can be treated (e.g., biologically oxidized), flared (i.e., burned or thermally oxidized), or used as fuel as part of a green energy strategy that can benefit the local community. Where the aim is utilizing methane in LFG for its energy value, total methane yield and production rate can be increased by liquids addition or leachate recirculation, where biodegradation rates are optimized through increasing the moisture content of the waste.

3.5.1 Active Landfill Gas Management

Active landfill gas management involves inducing a vacuum within the waste mass that can be directly measured as an indication of system performance. Active control is defined as using mechanical means (blowers) to remove LFG from the landfill under an imposed vacuum. The active GCCS consists of:

- A network of LFG extraction wells drilled deep into the waste (termed the "well field");
- Collection piping linking each well to the main gas control piping network; and
- A blower system and flare station.

The purpose of the well field is to enable collection of LFG from waste in place in the landfill. The purpose of the collection piping network is to transport LFG from the wells to the flare station, gas-to-energy plant, or other end user of the renewable energy. The wells and collection piping also feature flow control valves and monitoring ports to allow LFG extraction rates to be monitored and optimized. The blower system is used to generate vacuum pressure (suction) in the collection system, which moves the LFG through the piping network to the flare station. The flare station contains an electrical and mechanical control system for dewatering (if necessary) and compressing LFG prior to thermal destruction of LFG methane and other chemical compounds. The only significant outputs from a flare station are gas condensate from the dewatering process (which is routed back into the waste or to the leachate management system) and biogenic CO_2 from the flare stack. In some cases, additional components such as LFG treatment/purification, utilization, or energy generation facility are installed (generally in parallel with the flare station, so that the flare can be used to maintain LFG control in the event that other facilities are temporarily shut down).

Typical components of an active GMS, including (clockwise from top left): newly installed gas well, blower system, small flare station, gas-to-energy engine.

3.5.2 Passive Landfill Gas Management

The term passive LFG management covers a very wide range of operations and mechanisms aimed at protecting human health and the environment by controlling atmospheric emissions and/or subsurface migration of LFG with minimal energy consumption or maintenance. At some landfills, passive LFG management is the most protective method and can be defined as allowing the LFG to move without mechanical assistance (i.e., primarily by the pressure developed within the landfill) to a passive control system. Examples of passive control systems include:

- **Passive flaring:** This control system involves routing one or more small gas wells to passive flares with a solar sparking ignition system (pictured).

- **Passive control with physical treatment:** Alternatively, LFG may be passively captured beneath the cover and treated by routing it through granular activated carbon to physically bind and remove chemical compounds from the exit gas.
- **Passive control with biological treatment:** Examples include biowindows, biovents, permeable reactive walls, and biocovers (see further discussion below), all of which are engineered biologically active gas treatment systems through which LFG is routed and within which the methane and noxious compounds in LFG are aerobically oxidized or treated before the exit gas is safely emitted to the atmosphere.
- **Passive control (no treatment):** In many cases, LFG is of such limited volume, sufficient control can be limited to installing a cutoff trench at the toe of the landfill to intercept lateral subsurface migration.

Passive LFG management is generally used at older landfills where LFG emissions are limited, or at landfills that are too small to support installation of an active GMS. Passive LFG controls can function as a transitional management strategy before discontinuing LFG management during post-closure. Elements common to all passive LFG management strategies are that they utilize natural processes and ultimately rely on the cover system as the primary means of LFG control. Indeed, where LFG generation rates are low, whole-site oxidation of methane in LFG can be achieved using an all-soil cover or gas management (or bioactive) cover in which a layer of highly-organic aerated soil or compost is included in the uppermost layer of a composite, all-soil cover system.

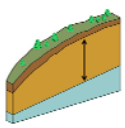
Passive flare with solar powered self-ignition system. (Photo courtesy of DSWA)

Microbial oxidation (i.e. consumption of methane by bacteria in the presence of oxygen to yield carbon dioxide and water) in biocovers represents an important natural control on methane emissions in aerated landfill cover soils. As will be described in Section 3.6.2, it has been observed that it is possible for cover soil microbes to oxidize residual methane such that surface emissions are negligible. Manipulation of landfill cover soils to maximize their oxidation potential thus comprises a large component of passive GMS design.[17] Design of biocovers is thus best included as part of the overall design of an alternative all-soil cover system.

[17] A state of the art review of methane oxidation in landfill biocovers, and the design and performance of biocovers and other biologically active gas treatment systems, is provided in Scheutz, et al (2009). Other key references include Boeckx, et al (1996), Humer & Lechner (1999), Scheutz, et al (2003), Barlaz, et al (2004b), Gebert & Gröngröft (2005), Abichou, et al (2006a and 2006b), Dever, et al (2007), Gebert, et al (2007), Kjeldsen, et al (2008), Rachor, et al (2008), and Gamperling, et al (2008).

3.5.3 Key Environmentally Protective Features of Gas Control Systems

Both active and passive gas management systems play a major role in protecting human health and environmental media at a landfill. The major environmental benefits of installing a GMS can be broadly categorized as follows:

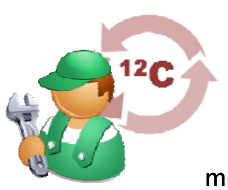


- Control of subsurface gas migration in the **vadose zone**, which leads to protection of on-site or adjacent buildings and structures, protects **groundwater** from potential impact from water-soluble pollutants contained in LFG, and reduces vegetative stress in landfill buffer areas; and

- Control of surface gas emissions and nuisance odors, protecting **air quality** and reducing vegetative stress on the cover system.

In addition, as discussed further in Section 7.3, because of its rich methane content, LFG offers numerous opportunities to provide renewable, **green energy** through landfill gas-to-energy (LFGTE) strategies. Landfill methane may also be used directly to fuel boilers, furnaces, engines, and vehicles, or as a feedstock for chemical processes.

3.5.4 Long-Term Performance of Gas Management Systems



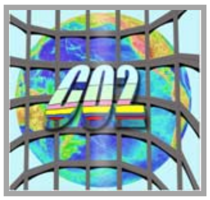
Because an active GMS is an operational system in which all components can be repaired or replaced as necessary, its long-term performance and operational efficiency is most closely related to its level of maintenance. Similarly, the long-term performance of a passive GMS is directly related to maintenance – passive systems will continue to perform as designed for as long as they are properly maintained. Because many passive LFG management strategies rely wholly on natural processes such as methane oxidation in soil covers, landfill designers can develop very low maintenance or even self-sustaining passive systems.

As first discussed in Section 1.4.1, LFG generation from MSW landfills decreases with waste age; LFG generation rates typically reach a peak about one year after cessation of waste placement (closure) before tapering off following a well-documented exponential decay curve. Peak LFG generation and the rate at which LFG generation decreases is affected by how much water infiltrates the landfill and is available for waste biodegradation processes. Therefore, the duration for which significant LFG management will be required at a site is largely driven by two factors:

- Operational conditions (most significantly, whether the landfill was operated as a “wet” landfill to enhance biodegradation rates or as a conventional “dry” landfill); and
- Cover system design and maintenance.

As the supply of LFG from an aging landfill decreases, a landfill operator may be able to phase out certain portions of an active GMS that are no longer generating sufficient LFG flow to maintain a flare, provided that the action does not trigger LFG migration or surface emissions of concern. At such a time, use of passive LFG controls as a transitional GMS is appropriate.

3.6 The Role of Managed Landfills in Controlling Greenhouse Gases



Gases in the atmosphere can contribute to the greenhouse effect (i.e., climate change) both directly and indirectly. A gas that traps heat in the atmosphere is termed a greenhouse gas (GHG). A number of atmospheric carbon and GHG sources (which emit GHGs) and sinks (which permanently capture, or "sequester," GHGs) have been identified. Landfill gas is a recognized source of methane, which if released into the atmosphere is 21 to 25 times more potent a GHG than carbon dioxide (CO_2) over a 100-year timeframe. According to the Intergovernmental Panel on Climate Change (IPCC, 2006), the waste sector (including solid waste and wastewater) account for less than five percent of global GHG emissions. In a more recent evaluation of data from 2007, the United States Environmental Protection Agency (USEPA, 2009) indicates that waste management activities in the U.S. contribute just over 2 percent of the nation's total GHG emissions. In arid western regions, or where there are more extensive landfill gas regulatory controls, the contribution of landfill methane to overall GHG emissions to may be even less; for example, the California Air Resources Board (CARB, 2009) estimates that Californian landfills contribute less than 2 percent of the state's total GHG emissions.

Although landfills are only a relatively minor potential contributor to GHG emissions in the United States, they are nevertheless capable of a very high degree of methane emission control through a combination of efficient capture of landfill gas and conversion of captured methane to CO_2 (e.g., as a result of flaring or use as green energy in active LFG control systems or due to biological oxidation in passive LFG control systems). This results in tangible reductions in the potential for landfills to contribute to GHG emissions. As discussed in the remainder of Section 3.6, landfills are therefore one of the most controllable sources of GHGs available. Further, as discussed in Sections 7.1, it is recognized that landfill gas-to-energy (LFGTE) projects are a source of renewable energy and replace energy production from fossil fuels such as coal or oil. In addition, as discussed in Section 7.2, carbon sequestration within the waste mass (which refers to the portion of biogenic carbon in waste that does not degrade completely after disposal, but rather is permanently stored in the landfill in a stable form) provides an additional GHG emission control.

Finally, as discussed in Section 7.3, artificially enhancing the availability of moisture within a landfill through "wet landfill" or bioreactor operations is a proven technique for enhancing degradation rates, resulting in a greater rate of LFG production during the landfill's operating period. This helps maximize the overlap between active operation of effective LFG control systems and significant LFG generation, and provides increased opportunity for beneficial use of LFG as an energy resource.

3.6.1 Landfill Gas Collection Efficiency

The majority of potential GHG emissions from a landfill are controlled by the LFG management system, as previously discussed in Section 3.5. The collection efficiency of a gas control system is the percentage of the total LFG generated in the landfill that is recovered by the system. Gas collection systems at modern landfills with well-engineered final cover systems have been demonstrated to have very high efficiencies and thus are proficient at reducing GHG emissions[18]. However, gas collection efficiencies are dependent on the type of cover being used during the operation of the landfill. State-of-the-practice literature regarding gas collection efficiencies under different cover conditions are summarized in the recently completed study published by SWICS (2009), which also provides collection efficiency values obtained from a comprehensive field-testing program.

Effects of Cover Conditions: The conclusions of the field tests performed for SWICS (2009) relating gas collection efficiencies to cover conditions are summarized below (it should be noted that test data on daily soil covers was limited, as stated by the experts involved with the creation and review of that document):

- **Daily Cover:** Collection efficiencies are in the range of 50-70 percent, with a mid-range default of 60 percent, for portions of a landfill that are under daily soil cover with an active LFG collection system installed;
- **Intermediate Cover:** Collection efficiencies are in the range of 54-95 percent, with a mid-range default of 75 percent, for a landfill or portions of a landfill that contain an intermediate soil cover with an active LFG collection system installed; and
- **Final Cover:** Collection efficiencies are in the range of 90-99 percent, with a mid-range default of 95 percent, for landfills that contain a final soil and/or geomembrane cover system with an active LFG collection system.

Effects of Gas System Design and Operation: The effectiveness of a gas collection system is dependent upon its intended design and mode of operation. If a gas collection system is designed for compliance with the USEPA's New Source Performance Standards (NSPS), or to meet similar air quality requirements, it will likely be capable of greater collection efficiencies than a system whose design basis was to control subsurface gas migration. Similarly, a landfill with a gas collection system installed voluntarily as part of an energy utilization project may not be capable of collection efficiencies as high as NSPS-compliant systems simply because it is often difficult to maximize gas quality (needed for optimal energy production) at maximized levels of gas collection across the entire wellfield.

In summary, the actual collection efficiency of the LFG collection system is dependent on the operational phase of landfill development and the type of cover in place. A recent white paper

[18] Appendix B provides an in-depth discussion and several references regarding the ability of landfills to control methane emissions through effective gas collection.

on the current state of the practice of LFG collection and control (SWICS, 2009) found that landfills in post-closure with active gas collection and final cover systems in place pose very limited potential to release GHGs to the atmosphere. The review of technical literature summarized in Appendix B demonstrates that active gas collection systems typically have a high collection efficiency that ranges from 90 to 99% for landfills that contain a final soil and/or geomembrane cover system. Moreover, these high gas collection efficiencies do not include the additional effects of natural methane oxidation and carbon sequestration processes.

3.6.2 Methane Oxidation in Cover Soils

LFG that is not collected by the gas management system can enter the landfill cover soil where a percentage of the methane is destroyed through oxidation to carbon dioxide. The percentage of methane oxidation can be significant depending on the type of cover material used[19]. Methane oxidation that occurs naturally in the cover system thus augments gas collection efficiencies. This increases the overall level of control of GHG emissions attained at the landfill well beyond what is achieved through gas collection systems alone.

Research shows that the percentage of methane oxidation in the cover system can be significant; for example, SWICS (2009) reviewed much of the current research regarding methane oxidation and determined that, based upon technological advancements in measurement approaches, values for the percent of methane oxidized in landfill covers range from 22 to 55 percent of the remaining LFG hypothesized to not be captured by the LFG collection system. Although active gas collection systems may not capture 100 percent of produced methane, the ability of a cover system to control residual methane provides a high degree of overall control. For example, as suggested by Chanton, et al. (2009), a cover system can be designed to essentially eliminate methane emissions by constructing a gas collection system and complementary soil barrier that limits the upward migration of methane to a range less than or equal to the oxidation capacity of the cover system. Such a cover system utilizes two distinct layers: a bottom barrier layer (typically clay) that minimizes gas migration and an upper aerated, organic-rich layer that functions as an oxidation medium. Where used in conjunction with active gas collection system, such cover designs can control up to 95% to 99% of residual methane emissions from a landfill.

3.6.3 Carbon Sequestration

When biogenic material (e.g., wood, paper, cardboard, green yard waste, and food wastes) is disposed of in landfills and does not completely decompose to biogas (methane and CO_2), the carbon that remains is effectively sequestered (used in this way, “sequestration” is a term that describes permanent storage of biogenic material in the landfill and removal of carbon from the global carbon cycle). The biokinetics of carbon sequestration in landfills are described in Section

[19] Appendix B provides specific information regarding the capability of covers to oxidize residual methane that may enter the cover.

7.2 and Appendix B. In brief, atmospheric carbon "sources" emit GHGs while "sinks" permanently capture (sequester) GHGs.

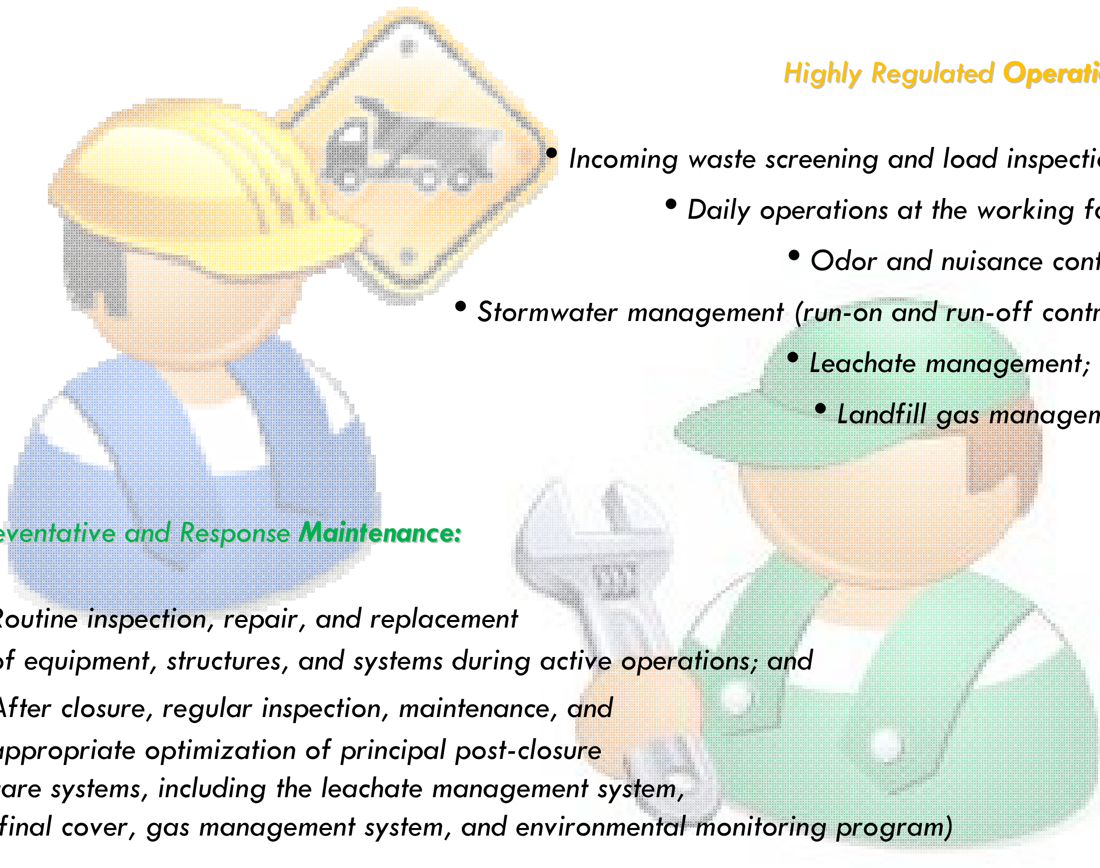
Landfills have been identified as both a source and sink for GHGs. For this reason, carbon sequestration is an important consideration with regard to estimating the actual GHG emission potential of a landfill because carbon storage in landfills can significantly offset calculated GHG emissions. For example, sequestration of biogenic material should count toward the landfill as a GHG sink while any methane generated but not captured must count toward the landfill being considered a GHG source. Note that CO_2 generated from the decomposition of organic material does not contribute to the landfill as a GHG source, because this CO_2 would have been emitted in any case.

As discussed by SWICS (2009), the decision to include and use carbon sequestration factors in estimates of GHG emissions from landfills will depend on accounting protocols, some of which do not allow carbon sequestration factors for landfills. In this regard, however, both the IPCC and USEPA, along with the Oregon Climate Trust and California Air Resources Board (CARB) recognize that carbon storage in a landfill is a reality of landfill operations and may need to be considered when calculating potential landfill GHG control measures[20]. Clearly, if carbon sequestration factors are used, the potential methane emissions from landfills will be significantly lower than current estimates. When inventorying potential GHG emissions from landfills, therefore, it is important to objectively examine the benefits offered by land disposal with special consideration given to "green" energy generation potential of the waste stream. In this regard, the argument is not *whether* carbon sequestration occurs but rather the *degree* to which this process is used to calculate net landfill GHG emissions.

In summary, considering the ability of the final cover system to oxidize methane, the relatively large percentage of biogenic carbon in the waste mass that is sequestered, and the typically high efficiency of gas management systems to collect LFG from closed landfills, the managed modern landfill effectively controls GHG emissions up to and including near-zero net emission to the atmosphere. In addition, the waste stream can be used to be beneficial use through the production of "green energy."

[20] Appendix B provides specific references to organizations such as the IPCC, USEPA, the California Energy Commission (CEC), CARB, and others that use carbon sequestration factors when calculating GHG emissions.

4. OPERATION AND MAINTENANCE OF A MANAGED SOLID WASTE LANDFILL



Highly Regulated Operations:

- *Incoming waste screening and load inspections;*
- *Daily operations at the working face;*
- *Odor and nuisance control;*
- *Stormwater management (run-on and run-off control);*
- *Leachate management; and*
- *Landfill gas management*

Preventative and Response Maintenance:

- *Routine inspection, repair, and replacement of equipment, structures, and systems during active operations; and*
- *After closure, regular inspection, maintenance, and appropriate optimization of principal post-closure care systems, including the leachate management system, final cover, gas management system, and environmental monitoring program)*

Active and responsible landfill operation is fundamental to regulatory compliance and environmental protection at the modern managed landfill. The modern landfill employs experienced personnel trained in system operation, safety, and environmental regulatory compliance programs developed to protect workers, the public, and the environment. Following site-specific operations and maintenance programs means that only acceptable wastes are disposed in the landfill, odors and stormwater are effectively managed, and leachate and landfill gas (LFG) management systems are operated as designed. Effective performance of the various landfill systems is provided through routine preventative and response maintenance programs during the active, closure, and post-closure life of the landfill. The following sections discuss these topics in greater detail.

4.1 Management of Landfill Operations

Modern landfills possess multiple inter-dependant and overlapping systems that are designed to act in combination to provide comprehensive protection of human health and the environment. Modern landfills also use many types of vehicles (e.g., compactors, bulldozers, earth-graders, etc.) and other types of mechanical, hydraulic, and electrical equipment (e.g., pumps, engines, blowers, sensors, etc.) that require skilled operators for optimal performance. Moreover, this performance must be confirmed through active environmental monitoring programs (as discussed in Section 5).

4.1.1 Landfill Infrastructure and Equipment

Fundamental to waste disposal operations, which are described in Section 4.2, modern landfills require numerous support facilities or infrastructure, including:

- Access roads;
- Gatehouse, fencing, and other access controls;
- Truck scales (to weigh the quantity of waste delivered for disposal);
- Offices and administration buildings, workshops, maintenance yards, vehicle wash facilities, and other structures;
- Utilities and communications; and
- Other support facilities (e.g., public drop-off/convenience areas and materials recovery centers).

Steel wheeled compactors are used to move and compact waste at the working face (Photo courtesy of NSWMA)

Routine maintenance and periodic repair is required for all the various mechanical, hydraulic, and electrical equipment in use daily at a landfill.

Landfill operations also require heavy vehicular equipment, including tracked dozers, steel wheeled compactors, tracked and/or rubber tired loaders, water trucks, scrapers, and road graders. This equipment is used for soil excavation, handling, and compaction (generally for liner and cover material), handling and compaction of waste at the working face, and supporting activities such as access road maintenance and dust suppression.

4.1.2 Landfill Supervision and Operator Training

Like any complex engineered system, operation and maintenance of a managed MSW landfill requires a skilled and trained workforce, directed by a supervisor who is knowledgeable of permit conditions and the proper implementation of the plans and design specifications for the landfill. Permit requirements require active management of waste screening, daily waste placement, compaction and covering at the working face, and leachate and stormwater management.

Onsite training programs are required for employees that work at the managed modern landfill. Training generally includes:

Training
Landfill Managers

Nationally recognized training programs and certifications include, for example, the Manager of Landfill Operations (MOLO) training from the Solid Waste Association of North America (SWANA) as well as first aid training from the American Red Cross.

- Screening to prevent disposal of unacceptable wastes, especially for employees who will be performing their assigned duties near the working face or at the gatehouse;
- Basic safety training related to facility operations and maintenance, procedures to be followed during an emergency, locations of emergency and first-aid equipment, and facility notification procedures;
- Understanding environmental protection features and monitoring programs used at the site; and
- Additional training, depending on an employee's actual job functions, involving familiarization with the facility design and operational plans such that the procedures described in the facility's permit are followed.

Many solid waste landfill operators have instituted structured training programs for site employees. In addition to scheduled classroom sessions, training often includes regular 'tailgate' training sessions to emphasize the need for safety for everyone on site, making sure that site personnel understand the management and operational goals for the landfill. Landfill operations discussed at tailgate meetings as well as formal classroom sessions include emergency response and shut down procedures, site safety and first aid procedures, use and maintenance of onsite operating, emergency, and support equipment, LFG and leachate management, spill and leak prevention, countermeasures, and control procedures, safe storage and handling procedures for potentially hazardous materials at the site (including understanding Material Safety Data Sheets, or MSDS), practical waste acceptance sampling and testing, and proper disposal procedures. Records documenting personnel training are maintained at each facility. A copy of facility permits is also made available to operating staff and posted at the facility.

4.2 Landfill Operation under Permit Conditions

Modern landfill operation requires four basic types of practices and requirements:

- Consolidation of incoming waste into the working face and compaction of the waste to maximize utilization of landfill capacity (termed "airspace") and to conserve land resources;
- Operation of the fill in accordance with design specifications to control settlement and optimize biochemical degradation processes in the waste (treatment);
- Covering the waste with soil or other approved cover material on a daily basis to control risk of hazards from exposed waste; and
- Prevention and control of adverse environmental impacts.

General operating considerations that apply to landfills include limiting hours of operation, sequencing waste filling, scheduling road and general maintenance, mitigating the consequences of wet and inclement weather, managing waste receipt and vehicle routing to the working face, establishing environmental controls, enhancing aesthetics, and controlling self-haul and private drop-off of waste.

4.2.1 Compliance with the Facility Operating Plan

Under federal law, the landfill permit holder is responsible for the operation, performance, maintenance, and monitoring of the landfill under state oversight. Specific procedures are provided for daily waste disposal operations (e.g., waste screening, placement and compaction, soil cover, and odor and nuisance control) and environmental impact management and monitoring (e.g., stormwater management, leachate management, gas management, and environmental monitoring). Beyond the landfill operation, permit conditions also apply specific operating and maintenance criteria to many associated facilities, including security and access controls, refuse vehicle weighing facilities, public drop-off areas, administrative offices, maintenance facilities and workshops, communications equipment, public and employee safety, and utilities.

Landfill supervisors must keep operational records and routinely report to state regulatory agencies to demonstrate compliance with permit conditions. Compliance with the operating permit is demonstrated through record-keeping, monitoring, and reporting requirements that are generally contained in the facility's operating plan. The operating plan includes:

The Landfill Operating Plan

A site-specific operating plan, which is required by rule at every managed landfill, contains standard operating procedures, best management practices, and contingency measures that must be adhered to. The plan also specifies comprehensive performance monitoring, recordkeeping, and scheduled reporting to the state agency. The landfill's compliance with all of the plan's requirements can be audited at any time.

- Standard operating procedures (SOPs) for major landfill activities such as waste compaction at the working face, application of daily cover, leachate management, and landfill gas management;
- Best management practices (BMPs) for stormwater management and erosion control, avoidance of odor problems, and control of other nuisance factors such as litter, birds, and vectors;
- Routine inspection and preventative/response maintenance requirements (see Section 4.3);
- Monitoring requirements (see Section 5); and
- Contingency measures for responding to emergencies and other potentially unsafe conditions and operational issues should they arise (e.g., leachate spills or seeps).

4.2.2 Waste Screening

Federal regulations impose strict waste acceptance criteria for all operational landfills, consistent with their class. Subtitle D MSW landfills are prohibited from accepting hazardous waste classified under Subtitle C of the solid waste regulations. Non-hazardous wastes received from industrial sources are often accompanied by a waste profile or other formal mechanism to avoid hazardous waste inclusion in the load. Site-specific permit conditions may also impose further restrictions on types of waste that are acceptable.

Waste vehicles entering a landfill site must check in with the gatehouse attendant before having their load weighed on the truck scale. Loads are visually inspected on a random basis to check on compliance. The vehicles than proceed to the working face, where landfill personnel direct their load tipping. Landfill personnel at the gatehouse and working face are specially trained in recognition of unacceptable wastes. Standard operating procedures for waste screening and follow-up actions to be taken in the event that such wastes are found are included in the landfill's operating plan. A vehicle found to contain unacceptable waste will not be allowed to tip at the working face, and will be required to exit the landfill and return its load to the point of origin.

4.2.3 Daily Operation at the Working Face

Waste inspected and cleared for disposal is subsequently transferred to the active waste placement area (working face). The working face of a landfill is the primary location where waste haulers directly interact with the daily operation of a landfill. This is one reason why a skilled workforce is needed to manage and conduct daily operations at the working face to keep this critical area of the landfill safe and in compliance with the site operations plan. In addition, as discussed above, landfill personnel at the working face are also specially trained to inspect waste vehicles and recognize unacceptable wastes; their ability to provide ongoing scrutiny of received waste provides a back-up check on the formal waste screening procedures that occur at the gatehouse.

During daily landfill operations, the working face is maintained within as small an area as possible to minimize odors and control birds and vectors. Keeping the working face small also serves to limit the area of waste that is directly exposed to precipitation, thus minimizing leachate management. Heavy steel-wheeled compactors move the waste into the working face to reduce the waste's volume and increase compaction, maximizing use of the landfill airspace and limiting short-term settlement. At the end of each day, the waste is covered with soil or an approved alternative daily cover (e.g., foam, tarps, compost, or other approved materials), to further minimize leachate management, prevent fires (which may occur if air blows into the waste), and control vectors, odors, and blowing litter.

Odor control is an important component of daily operations. Odors generated by decomposing refuse can be mitigated by covering the waste daily and checking that the cover remains intact. Additional active management solutions used to control odors include fogging or misting systems that use odor masking or neutralization agents and are generally used around the site perimeter and/or in areas where malodorous waste is managed. Although site-specific permit conditions sometimes limit the acceptance of excessively malodorous wastes (e.g., animal manure, carcasses, or septic waste) at a landfill, in many cases landfills are the safest and most practicable means for a community to dispose of such materials. Delivery of loads containing particularly malodorous materials can be scheduled such that sufficient manpower and equipment are available to immediately cover the waste. The use of lime or chemical neutralizing agents placed on the waste material can be effective at controlling odors until proper cover can be applied.

4.2.4 Stormwater Management

Rainfall that lands directly on the working face of a landfill (termed "contact water") as well as rainwater and snowmelt that infiltrates through cover material will contribute to leachate generation at a landfill. Conversely, "non-contact water" is rainfall and other precipitation that is kept from contacting exposed waste at the working face. Minimizing contact at the working face was discussed in Section 4.2.3; minimizing infiltration is generally achieved through good cover design and maintenance to prevent erosion (see Section 4.3). Non-contact water that is kept from infiltrating the cover is considered surface runoff or "stormwater" and is strictly regulated and managed via approved SOPs. Stormwater is routed away from the landfill via controlled, engineered flow paths to an appropriate natural surface water system discharge point (e.g., wetlands, streams, rivers, ponds, or lakes). This requires a well-designed and properly maintained stormwater management system (SWMS) for effective transmission of runoff water, particularly in regions experiencing periods of heavy rainfall.

Design of the SWMS considers two primary rainfall factors: intensity (how hard it rains) and duration (how long it rains). The combination of intensity and duration defines how large a rainstorm is (how much rain will fall). Clearly, the likelihood of a very large thunderstorm occurring is much lower than that of a small everyday shower; therefore, the size of a storm is defined in terms of its likelihood of occurring. In this way, a storm size that is expected to occur only once per 100 years (a "100-year storm") is very much less likely to occur on any given day than a storm that is expected to occur at least every year (a "1-year storm"). When designing a SWMS, each state typically has a "design" storm that must be considered. The typical design storm for permanent stormwater flow control structures is a 100-year storm, a very large rainfall event, which means that the ponds are large enough to contain stormwater runoff from all expected storms. The typical design storm for temporary stormwater flow control structures (e.g., channels) is generally a 25-year storm.

Depending on the maximum design flow velocity for the SWMS components, erosion protection features used to protect surfaces in contact with stormwater include grass and other vegetation, "rip-rap" (carefully placed layers of rocks, boulders, and stones), "gabions" (rock-filled wire baskets), erosion matting, and concrete. The landfill management team must understand and properly interpret rainfall run-off management requirements and regulations pertaining to compliance, proper SWMS maintenance, and protection of the environment.

The SWMS conveyance features typically include the following components:

- The landfill cover system, which is suitably vegetated, constructed, and graded to promote runoff, prevent erosion, and controls infiltration;
- Erosion protected cover drainage features such as side slope "let-down structures" or "downchutes";
- Grass waterways, diversion ditches, other erosion protected channels, and culverts (i.e., pipes running beneath roadways and other obstructions); and
- Outlet control structures such as weirs, sluice gates, or overflow pipes for controlled discharge to the natural surface water system.

Other specific stormwater controls include detention and retention ponds or basins. Detention basins hold water for a limited period from a larger drainage basin area to prevent flooding. These basins then release their water slowly, usually through an outlet pipe (or spillway in heavier flow conditions), and are often used for de-silting runoff. Retention basins are used to contain stormwater or rainfall run-off for longer periods. A retention basin provides an area to hold water from a small surrounding drainage area that would otherwise flow into other areas. The water is designed to remain in the local area with a limited outflow (e.g., a pond or lake).

Retention pond at a large landfill in a wet climate (note pond outlet control structure in foreground and rip-rap protected boundary)

During operation of the landfill, cover grades are maintained to promote good surface drainage (generally 2 – 5% slopes) and, at the same time, minimize surface flow velocities. Overly steep grading can lead to excessive erosion from fast-moving surface runoff, potentially damaging the landfill cover and side slopes, and producing runoff containing high silt levels that can block or damage the SWMS. On the other hand, overly shallow grading can lead to ponding, creating difficult and muddy working conditions and increased infiltration of rainwater into the landfill (which increases leachate generation). In addition to engineered control systems, managed landfills implement some form of operational BMP for stormwater control prior to discharge. Other common BMPs include use of wet weather decks (commonly used to minimize the working face area), run-off control berms, silt fences, straw bales, booms, and street sweeping.

4.3 <u>Maintenance of Landfill Systems</u>

Engineered structures such as a bridge, dam, or office building require ongoing preventative maintenance to function as designed, and an active landfill operation is no different. In addition to routine scheduled maintenance, response procedures must be in place for all active engineered systems should routine inspections reveal that repair is warranted ahead of scheduled maintenance. Preventative and response maintenance is a key management component during active operation of a modern landfill as well as during and following closure.

4.3.1 Preventative and Response Maintenance during Active Operations

During active operations, inspection and preventative maintenance activities are scheduled for all landfill components and are generally specified as SOPs in the facility's operation plan. Inspection and maintenance is conducted to maintain equipment, infrastructure, and related facilities in good condition and to prevent emergencies. All routine inspection and maintenance procedures follow a predetermined schedule. The frequency of inspections for equipment is based on the rate of potential deterioration or malfunction. The landfill supervisor keeps equipment inspection and service reports for each piece of equipment, noting all servicing requirements (completed or pending), unusual incidents, and faulty operational conditions.

A preventive maintenance program is implemented at the facility throughout its operating life. The purpose of the program is to reduce the possibility of damage to the facility or release of waste constituents to the environment. The preventive maintenance program includes the following:

- Inspection and repair/replacement of vehicular and heavy equipment that is used to manage waste or perform routine operational functions at the facility;
- General site maintenance, such as collection and disposal of litter, maintenance of access control systems (e.g., fences, signs, and gates), and upkeep of site infrastructure (e.g., roads and buildings);
- Inspection and maintenance of the leachate management system, including:
    - Periodic cleanout of LMS collection pipes, leachate recirculation piping (if present), and underground transmission lines and sumps;
    - Inspecting for corrosion and repairing aboveground pipes and leachate storage tanks;
    - Checking pumps, valves, and seals for proper operating characteristics; and
    - Maintaining the leachate treatment system (if present);
- Inspection and maintenance of the gas management system, including:
    - Performance inspection, maintenance, and monitoring of the well-field, transmission piping network, valves, and fittings;
    - Inspecting condensate management systems and measuring liquid levels in LFG extraction wells;
    - Checking for proper operating characteristics at the flare station (blowers, flare, flame arrestors, and control systems); and
    - Monitoring and maintaining the operation and performance of LFG treatment, utilization, or energy recovery equipment;
- Maintaining the cover system, including cover vegetation and repairing effects of erosion or subsidence;
- Maintaining the stormwater management system (i.e., cover drainage features, sediment trapping devices, stormwater retention/sediment control ponds, diversion channels, silt fences and other sediment control devices, and vegetation); and
- Inspecting environmental monitoring systems, repairing defective monitoring wells and probes as necessary, and clearing surface water sampling locations.

Ongoing construction (e.g., expansion and/or realignment) and maintenance of SWMS features, intermediate cover, and other landfill infrastructure such as roads and access ramps is essential due to the dynamic nature of landfill operations in which the size and shape of the landfill, and the location of the active working face, continually changes. Regular re-grading and grassing of the cover is necessary to minimize erosion at areas lacking vegetative cover. Similarly, during final closure, proper grading, seeding, and maintenance of cover system soils and vegetation help prevent long-term erosion and siltation problems during the post-closure care (PCC) period.

4.3.2 Post-Closure Maintenance

Subtitle D regulations require monitoring of groundwater and vadose zone gas migration, and management and maintenance of the leachate management system and cover. Performance of these systems during PCC is verified through environmental monitoring at key locations around the landfill, and PCC maintenance requires that the monitoring system (i.e., methane migration and groundwater monitoring well network) remains intact and accessible. Most post-closure maintenance is spent on the cover system since this is the main component of the landfill exposed to the elements after closure.

Cover system maintenance at a closed landfill with a Subtitle D (or approved alternative) cover typically involves:

- Inspection and maintenance of the final cover to verify that it is stable against erosion, instability, and washout;
- Inspection and repair of stormwater management system features (e.g., removal of sediment from ditches and ponds, or re-grading drainage swales or cover slopes to promote drainage);
- Mowing and fertilizing/replanting of vegetation on the surface;
- Tree removal (unless a tree cover is approved);
- Repair in the case of subsidence of the landfill cover; and
- Remediation of seeps, breakouts, or other conditions causing discharge of leachate to the ground surface.

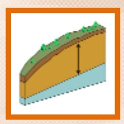
Erosion control is particularly important during PCC to prevent clogging of toe drains and exposure of the final cover system internal drainage and/or barrier components to unanticipated physical and climatic stresses. For many final cover systems, erosion control via the establishment of plant species may be aided by placing a natural or geosynthetic erosion control (GEC) matting layer on the surface before seeding. Long-term cover performance is not necessarily linked to a high level of post-closure maintenance. New performance-based designs for sustainable, low maintenance, natural analog cover systems are providing increased longevity and stability, with a performance equivalent to prescriptive Subtitle D covers. Such natural analog covers were discussed in Section 3.4 and will be re-examined in Section 6.2. For managed landfills without Subtitle D equivalent liner systems, cover maintenance, along with natural geologic barriers and environmental performance monitoring, provide overlapping levels of environmental protection. Managed care of the cover enables it to perform as designed, controlling liquid infiltration and stormwater runoff, and remaining sufficiently stable to maintain its containment function throughout the PCC period and beyond.

5. ENVIRONMENTAL MONITORING AT MANAGED SOLID WASTE LANDFILLS

__Environmental Monitoring__ is required at managed solid waste landfills by regulation and permit condition to protect human health and the environment. Active environmental monitoring is performed for:

- *Groundwater;*

- *Surface Water;*



- *The Vadose Zone (or Unsaturated Subsurface);*

- *Air; and*

- *Performance of Landfill Operational Control Systems.*

An __Environmental Monitoring Program (EMP)__ is implemented to confirm performance of the containment and treatment functions of the managed landfill. Concurrent implementation of the various EMP components is designed for early identification of any landfill component upsets and execution of preventative actions to provide continuous protection of the environment from __leachate__ and __landfill gas__.

Testing of water samples in groundwater monitoring wells is used to demonstrate that the liner and leachate collection systems are working correctly to protect groundwater.

The modern managed landfill is designed with overlapping containment systems and operated and maintained to meet strict performance objectives for protecting human health and the environment. An environmental monitoring program (EMP) is the baseline management tool used to regularly monitor environmental media at every managed landfill. It also requires that the performance of operational control systems (e.g. liner, leachate and gas management, and cover systems) be regularly monitored. The EMP is independently certified by a Professional Engineer or Professional Geologist to be fully consistent with regulatory requirements.

5.1 Why Monitor for Potential Releases from a Landfill to the Environment?

By understanding the manner in which environmental media can potentially be impacted by a landfill, the environmental performance of a landfill can be monitored and potential upsets avoided or, where environmental performance monitoring data indicate an upset may have occurred, necessary response actions can be implemented expeditiously. Monitoring data can also allow prediction of future landfill performance based on trends in past and current data.[21] The predictive element of landfill performance is particularly important in order to understand the level of active landfill management and care necessary over the long term.

5.2 Components of an Environmental Monitoring Program

Subtitle D requires an EMP be designed to detect a potential landfill upset involving leachate or LFG. The monitoring programs employed at the modern managed landfill closely network together and include monitoring systems for both operational performance and environmental media. As previously introduced in Section 1.3, the principal EMP components are summarized as follows:

Active Environmental Monitoring

Subtitle D requires specific monitoring systems and activities to provide early detection of a landfill system component upset. These systems provide environmental safeguards to provide long-term protection of HHE.

- **Groundwater** monitoring;
- **Surface water** monitoring;
- Lateral gas migration monitoring in the shallow unsaturated subsurface **vadose zone**;
- Surface emissions monitoring to detect and evaluate migration of methane through the surface of the cover system to impact ambient **air**; and
- Monitoring the **performance of operational control systems**, including:
    - o Head-on-liner monitoring (i.e., the amount of liquid build-up on the base liner system);
    - o Monitoring leachate characteristics and the leachate management system (LMS); and,
    - o Monitoring LFG characteristics and the gas management system (GMS).

Although the principal objective of the EMP is to protect human health and the environment, each individual EMP collects various types of monitoring data that together provide environmental

[21] Numerous publications describe the manner in which environmental media can potentially be impacted by landfills and methods for developing appropriate monitoring programs, including the USEPA's "*Solid Waste Disposal Facility Criteria: Technical Manual*" for Subtitle D landfills (Nov. 1993, rev. Apr. 1998). Additional seminal references include NRC (1984), USEPA (1990a+b and 1993b), Gibbons & Coleman (2001), and ASTM (2004) for **groundwater**; USEPA (2000) for **surface water**; IAEA (1992), IWM (1998), Trégourès, et al (1999), and Babilotte, et al (2008) for LFG system performance and emissions to **air**; and USEPA (1993c) and DOE (2001) for **vadose zone**.

safeguards for the managed landfill. Landfill operational performance monitoring is generally conducted by collecting real-time data through direct measurements using calibrated field monitoring meters and visual observations. Environmental media monitoring is generally conducted around the landfill using a network of monitoring wells and probes or collected from designated surface water discharge points or covered waste areas. Groundwater and surface water samples are collected and sent to certified, independent environmental laboratories and reported to regulatory-stipulated levels for data analysis and evaluation.

Leachate samples are similarly sent to certified, independent environmental laboratories after being collected directly from the leachate collection sumps or storage tanks. Finally, the potential for occurrence of LFG migration or emission from the landfill is monitored using sensitive field equipment from either subsurface unsaturated zone (vadose zone) monitoring probes located around the landfill, or from surface emission surveys conducted just above the landfill cover. Samples of LFG that are representative of conditions within the landfill waste mass are collected from the GMS (e.g., at wells within the landfill footprint or outside the footprint at the flare station).

5.2.1 Groundwater Monitoring System

The groundwater monitoring system (GWMS) is designed to provide the earliest possible detection of a potential impact from the landfill that could affect groundwater. This objective is accomplished by identifying proper sample locations (e.g., wells, streams, springs, etc.) and parameters that allow for a determination of changes in natural groundwater quality over time. The GWMS is designed based on a thorough understanding of the hydrogeologic setting and the distinct hydrogeologic characteristics of the area. The GWMS includes the rationale for both selecting appropriate monitoring parameters and identifying the most efficient monitoring well network based on the hydrogeology.

The GWMS typically comprises a network of monitoring wells screened in water-bearing units generally located at or below the base grade of the landfill. The GWMS network includes background wells designed to represent natural groundwater conditions, and downgradient (and sometimes cross-gradient) monitoring locations designed to detect a potential release from the managed landfill. The well locations and spacings are based on site-specific hydrogeologic conditions, and the monitoring programs are certified by a qualified groundwater scientist and approved by the overseeing regulatory authority. An evaluation of the rate of groundwater flow as well as flow direction is required to define the frequency of monitoring at each site.

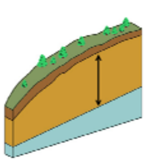
Groundwater monitoring provides additional confirmation that the liner system, LMS, and GMS are performing effectively. If a change in groundwater quality is suggested by the monitoring data, it must be investigated and reported to the regulatory authority. If further monitoring and data analysis confirm that the source of the change is the landfill, prompt and effective corrective measures must be administered to protect groundwater. The layout of the monitoring system is designed to provide ample time to conduct investigation and corrective action before there could be an impact on groundwater used by near-by property owners.

5.2.2 Surface Water Monitoring Program

The modern managed landfill is designed to provide safe conveyance of rainfall away from the landfill such that precipitation run-off and run-on is effectively isolated from the solid waste. Run-off controls convey stormwater away from contact with waste without causing excessive erosion of the cover system via constructed stormwater management system features such as drainage channels, basins, and ponds. Well-designed site layouts, slopes, and vegetation plans are important elements in controlling and managing stormwater flow. Generally, the stormwater management system is designed to safely discharge clean, sediment-free stormwater into the local stormwater sewer system or to adjacent surface water bodies such as wetlands, streams, rivers, ponds, or lakes.

The surface water monitoring program (SWMP) is designed to allow collection of sufficient representative samples of surface water to detect changes in water quality (most often suspended solids) that may require action (such as additional detention) prior to discharge from the site. Surface water monitoring may also be part of the GWMS for the site where groundwater discharges to a surface water body downgradient of the landfill. Surface water monitoring is performed in accordance with a federal or state-regulated pollution discharge elimination system permit mandated under the federal Clean Water Act (CWA). The CWA establishes maximum daily and monthly average effluent limitations attainable for the landfill site based upon application of the best practicable control technology currently available (BPT) or best conventional pollutant control technology (BCT) for MSW landfill point sources.

5.2.3 Subsurface Gas Migration Monitoring System



Modern managed landfill operators are required to monitor for potential migration of subsurface gases originating from the landfill before such gases can accumulate in an onsite structure or migrate across the property boundary. Because LFG typically contains high levels of methane (an explosive gas at certain concentrations), LFG migrating into the vadose zone has the potential to accumulate within structures, thereby posing a risk of explosion. Accumulation of LFG may also pose a risk to workers by displacing oxygen in enclosed areas. In the ambient environment, LFG can stress vegetation.

LFG migration monitoring (often termed explosive gas monitoring) at MSW landfills is required under Subtitle D such that the concentration of landfill gas in the unsaturated vadose zone does not exceed the lower explosive level (LEL) for methane at the facility property boundary and 25% of the LEL in facility structures. The vadose zone gas migration monitoring network typically consists of a number of appropriately-placed probes or wells along or near the perimeter of the landfill property. Methane monitoring probes are screened in the vadose zone above the groundwater table, and target preferential gas flow pathways (e.g., layers of higher permeable soils such as sand and gravel that may exist between layers of less permeable soils such as silts and clays). Facility structures that lie between the landfill and the vadose zone monitoring probe network are also routinely monitored for methane, and often include a combustible gas alarm device. Structures of concern include drain culverts, vaults, buildings, shops, and sheds.

Vadose zone and facility structure monitoring provides additional confirmation that the liner system, cover system, and GMS are performing effectively. If methane is detected in a facility structure or vadose zone monitoring probe, prompt corrective measures are required.

5.2.4 Surface Emissions Monitoring

Surface emissions monitoring (SEM) is common at landfills located in areas of the country with stringent air quality regulations, and is required by law at all landfills with an active gas collection and control system (GCCS) operating under a Title V Permit compliant with the USEPA's New Source Performance Standards (NSPS) for landfills. Landfills subject to these requirements are the larger modern sites that have potential for high LFG generation and, thus, are federally mandated to control atmospheric LFG emissions.

Methane is generally present at high levels in LFG (40 percent by volume or more), but is not typically present in ambient air. Therefore, the presence of methane in air directly above a landfill cover at levels above a regulatory threshold is considered an indication that LFG may be being emitted through a breach in the cover system. Such breaches could include small cracks and fissures in dry soil layers that can be effectively repaired once detected.

There are several methods used in monitoring methane emissions, including:

- Surface monitoring, the most common method approved under landfill permit conditions, which involves using an instrument to detect gases (such as an infrared gas analyzer fitted with a mechanical pump to sample air just above the cover surface) with the monitoring technician following a prescribed 'serpentine' path to provide adequate coverage;

- Direct measurement techniques, which involve gas probes or the use of sealed chambers to measure the accumulation of LFG constituents over time at set or random locations across the cover;
- Indirect measurement techniques, which use tracer gases, radar, laser, or other electronic means to infer a measure of LFG constituent accumulation in the near-earth atmosphere directly above/around a landfill; and
- Use of surrogates, such as heat flux, health of cover vegetation, or stable isotopes.

If the typical surface 'sweeping' method is not used, the technique selected depends on cover system properties, the nature of gas constituents of interest, practicality, and regulatory compliance criteria.

5.2.5 Monitoring the Performance of Landfill Operational Systems

Landfill performance monitoring is highly regulated and focused on confirming that the landfill containment systems are functioning properly and as designed. For example, a modern managed MSW landfill permitted under Subtitle D is required to include a leachate collection and recovery system (LCRS). The specific design requirements for the LCRS are that it be able to limit the hydraulic head on the liner to less than 12 inches throughout the operational, closure, and post-closure period of the landfill. Landfill performance monitoring would routinely confirm that the maximum 12 inches of leachate head-on-liner provision is maintained: deviations trigger investigation and a corrective response if necessary. Monitoring the head-on-liner requirement in this way is used to demonstrate liner performance. Although liners are designed to provide stable waste containment throughout the operating and post closure life of the landfill (and beyond), maintaining a minimal hydraulic head on the liner system reduces the reliance on the liner to contain leachate within the engineered landfill and thus provides a back up to long-term liner performance.

Other examples of landfill performance monitoring include the gas management system (GMS) and cover system monitoring. GMS monitoring combined with surface emissions monitoring is relied on to demonstrate that the cover system is controlling LFG emissions below regulatory thresholds. As discussed in the previous subsection, the performance requirements for the GMS at larger solid waste landfills are federally regulated under NSPS. Under the NSPS permit program, monthly individual monitoring of all GMS extraction wells is required for the parameters pressure, temperature, and oxygen (commonly referred to as 'PTO' monitoring). In addition, larger managed MSW landfills often recover LFG for treatment or beneficial use of methane (i.e., in gas-to-energy projects). This practice expands the monitoring and oversight of the GMS since these extraction wells will be routinely evaluated for collection efficiency and the entire wellfield "balanced" to provide effective collection of LFG from the entire landfill. This provides another important back-up safeguard for maintaining potential surface emissions below regulatory thresholds.

6. THE SAFETY OF THE MODERN LANDFILL

All modern managed landfills feature common <u>attributes</u>:

*Scientifically Engineered **Containment**;*

*Highly Regulated **Operations**;*

*Preventative and Response **Maintenance**;*

*Active Environmental **Monitoring**; and*

*Waste Biodegradation (**Treatment**).*

*Protecting our environmental media (**Groundwater**, **Surface Water**, the unsaturated subsurface **Vadose Zone**, and **Air**) is the first priority.*

*Several regulatory acceptable **Design Types** provide all the above attributes that overlap to provide protection of human health and the environment.*

- ***Type 1 Design** – Engineered Liner and Engineered Cover;*
- ***Type 2 Design** – Engineered Liner and Natural Analog Cover;*
- ***Type 3 Design** – Engineered Liner, Natural Analog Cover, and Enhanced Waste Treatment; and*
- ***Type 4 Design** – Engineered Natural Barrier and Engineered Cover.*

*Under **Active Regulatory Oversight,** each **Design Type** combined with well-managed operations, maintenance, and environmental monitoring provides protection of our natural resources.*

Previous sections have outlined the framework for environmental protection at the modern managed landfill. The combination of scientifically designed and engineered containment, preventative and response maintenance, natural or enhanced waste degradation, and active environmental monitoring produces landfills that serve community sanitary disposal needs and can ultimately be developed in concert with the surrounding environment. Managed solid waste landfills may have alternate designs and some differences in operation. Regardless of these differences, all modern landfills are designed to protect the environment. Competent design and operation is confirmed through environmental monitoring. This section is intended to highlight how landfill systems and their associated monitoring programs are integrated to provide overlapping protection that is not dependant on a single system or environmental monitoring component but instead represents a matrix of functions working in conjunction with each other.

6.1 Performance-Based Landfill Design and Management

The Subtitle D regulations establish siting, design, operation, management, maintenance, closure, post-closure care (PCC), monitoring, and financial assurance requirements for all MSW landfills. Subtitle D mandates environmental performance rather than prescriptive standards in landfill design. This approach allows flexibility to adapt to climate, hydrogeologic conditions, demographics, and other site-specific factors. Site-specific characteristics, including depth to groundwater, proximity to sensitive environments, waste treatment options, and land end use strategies, are all considered in overall landfill system design. Two examples include:

- Alternative liner designs (including a natural liner) which can be utilized when it can be demonstrated that the alternative design is "technically equivalent" to the prescriptive design in terms of performance (e.g., protective of groundwater quality, effective as a containment feature, and allow implementation of appropriate leachate management practices); and
- Alternative final covers (e.g., natural analog covers or earthen covers) which can be utilized when they are demonstrated to meet performance criteria for the cover (e.g., ability to function as designed as a barrier to infiltration, provide runoff drainage, support vegetative growth, etc.).

Often, performance-based designs offer enhanced rather than equivalent levels of environmental protection to prescriptive designs. For example, alternative covers such as earthen covers have added benefits such as optimizing slope stability. These covers counter-balance gas pressures within the landfill (since the covers consist of soils designed to naturally store and release water), which can reduce emissions of methane, a greenhouse gas, through natural oxidation processes (see discussion on passive gas management in Section 3.5.2).

6.1.1 Overlapping Systems for Landfill Operation

A performance-based design approach is used to demonstrate that a managed landfill will be constructed with back-up components and control systems to meet the performance goals of Subtitle D and protect human health and the environment. As an example, the overlapping systems, operations, maintenance, and monitoring common to different types of managed landfill design that are included for protection of ***groundwater*** resources are:

- Regulatory oversight of landfill siting and design, including thorough site characterization, identification of potential migration pathways, and identification of a groundwater monitoring system capable of detecting a potential upset of the landfill system;

- An engineered or natural liner system that is appropriately designed for known and projected climatic, hydrogeologic, and other site-specific conditions to provide containment and prevent leakage of leachate to the subsurface;

- Operation of the leachate management system to maintain minimal head-on-liner and preserve liner integrity, with standard operating procedures undertaken by a trained workforce;

- Operation of the gas management system with a workforce trained in preventative and response maintenance to prevent vertical or lateral migration of landfill gas, thus minimizing the potential for impact to the vadose zone and groundwater;

- An engineered or natural analog cover system that is appropriately designed for known and projected climatic, hydrogeologic, and other site-specific conditions, functioning to provide containment and control infiltration and leachate generation; and

- Active groundwater monitoring with independent professional sampling and laboratory analysis of water samples to promptly evaluate potential upset of the liner, leachate, or gas management systems.

As the above list illustrates, no single system is relied upon to protect groundwater. Similarly, it is the combination of multiple systems and active management (including monitoring) that is designed to provide protection of other environmental media regardless of the limitations of any given system design or site characteristic.

6.1.2 Predictability in Landfill Performance Trends

A sizable body of scientific knowledge exists to demonstrate the long-term performance of landfills under different design, operating, and closure conditions, focused on the overall predictability of LFG generation and composition and leachate quality over time based upon the stage and degree of waste decomposition (see discussion in Appendix A). In summary, the literature shows that:

- MSW landfill leachate is a non-hazardous liquid whose constituent concentrations follow downward trends that are predictable with time after capping;

- Up to half of the organic carbon within MSW is sequestered in landfills (see Section 7.2) and will not emerge in leachate;

- Mobilization of inorganic compounds in leachate over the long term is controlled by landfill system components that are strictly operated and monitored through post closure; and

- As waste material in a landfill degrades, the bottom-most layers become well decomposed and act as a biofilter, attenuating both degradable organics and non-degradable inorganics in leachate (see Section 1.4.3).

Furthermore, as discussed in Section 1.4.1, it is well documented that LFG generation from MSW landfills decreases with waste age. This behavior is also observed for long-term settlement, because such settlement is more significantly linked to waste biodegradation rather than to physical effects.

6.2 Providing Long-Term Landfill Integrity

6.2.1 Responding to Minor Upsets of Landfill Operational Systems

The operational performance of a landfill is actively monitored under the terms of RCRA Subtitle D regulations and each facility's operating permit. This monitoring is a key element in the regulatory program because:

- The processes that could result in potential impacts to human health and the environment if uncontrolled (i.e., biodegradation occurring in the waste mass, producing leachate and LFG) are well known and largely predictable, and the monitoring system alerts the operator to deviations from containment standards;
- Monitoring systems and processes are stipulated in facility permits and overseen by state regulators; and
- After landfill closure, monitoring discloses whether the systems are functioning as designed. Deviations from performance goals trigger investigation and response actions.

Monitoring systems thus function as "early warning" systems, designed to detect unexpected landfill behavior or system upsets, and triggering appropriate response before environmental media can be significantly compromised. It is important to note, moreover, that system upsets are rare at managed landfills because of the overlap that exists between integrated systems and monitoring components.

6.2.2 The Potential for Extensive Landfill Failure

A performance-based design approach includes accommodation for the potential for catastrophic failure. Seismic design standards require that landfills are constructed to be resistant to damage from earthquakes; similarly, landfill closure designs must include final cover systems that are capable of withstanding large storm events.

Examples of naturally occurring emergencies include large-scale earthquakes, hurricanes and typhoons, tornadoes, greater-than-expected storm events, and wildfires. Examination of the literature on the subject yields little to no evidence of landfill integrity being significantly compromised during such catastrophic events. First, it is important to stress that such events are very rare. Second, where modern landfills have been subject to catastrophic situations, they have been found to be highly resistant to damage with little to no resulting impact on the geotechnical stability of a landfill.

Studies performed after the Florida hurricanes of 2004 (e.g., Roberts, et al., 2005), the Northridge and Loma Prieta earthquakes in California (e.g., Matasovic & Kavazanjian, 1998), and the San Diego wildfires of 2003 show that the long-term geotechnical stability and environmental protection systems of the studied landfills had not been compromised. The only significant damage that occurred was to vegetation and other surface features such as LFG wells and vents that were readily repaired or replaced. In reviewing the literature, no evidence was found of an extensive landfill failure resulting from a naturally occurring and potentially damaging emergency situation.

Manmade emergencies, while more common than natural disasters, are similarly rare at landfills. Blight (2008) examined six of the largest failures that occurred worldwide as a result of human error in the 28-year period from 1977 to 2005. None of these major failures occurred in the United States, which can be largely attributed to the regulation of solid waste landfills at the state and federal level. Of the six landfills studied, four occurred in unmanaged dumps that had apparently not been subject to geotechnical analysis during the design stage. The remaining two occurred in engineered landfills whose causes were later investigated and well understood – inadequate design and operation in consideration of liquid waste and moisture conditions – and entirely avoidable.

The only significant modern MSW landfill failure that has occurred in the United States was a slope failure in 1996 at an operating site, the Rumpke Landfill located near Cincinnati, Ohio. This landfill failure has been subject to extensive investigation and the failure was determined to be attributable to a wide range of preventable factors related to poor standards of construction, leachate management, and operation. Other major contributing factors cited include inappropriate excavation at the downslope toe of the landfill slope and instability caused by onsite blasting[22].

Based on the literature as summarized above, it must be concluded that although the potential for a catastrophic landfill failure exists, the risk of such a failure as a result of natural events is very low. No documented catastrophic failures resulting from such events were found. The mechanisms

[22] Detailed discussion of the Rumpke Landfill failure is beyond the scope of this document but can be found in Schmucker & Hendron (1998), Eid et al. (2000), Stark et al. (2000), amongst others. Lessons learned as a result of investigation of this and other failures are well summarized by Thiel & Christie (2005). Appendix C to this document provides additional information and references regarding design and operational standards to provide long-term landfill integrity.

behind the limited number of landfill failures that have occurred due to human error have been well researched and documented. Lessons have been learned and are appropriately considered in the design and operation of modern landfills. Extensive failures and manmade emergencies at modern MSW landfills are ultimately avoidable through proper landfill design, construction, operation, and routine maintenance practiced in accordance with regulations.

An important finding from the above review of landfill failures is that none was found to have occurred at a closed landfill at which a final cover system had been installed. Ultimately, the factors influencing landfill structural stability improve over time – particularly at closed landfills that have a demonstrated trend of reduced landfill gas and leachate generation (as previously summarized in Section 6.1.2). Specifically, long-term stability of the final cover system is maintained through proper maintenance, monitoring, and gas management until all performance-based objectives are achieved. Appendix C to this document provides a more in-depth discussion of this important issue.

In consideration of the history of landfill structural stability post-closure, it is not reasonable to expect that replacement of the final cover system will be necessary. Relevant factors are evaluated for potential causes of instability before post-closure care is permitted to end.

Extensive Landfill Failures are Rare and Preventable

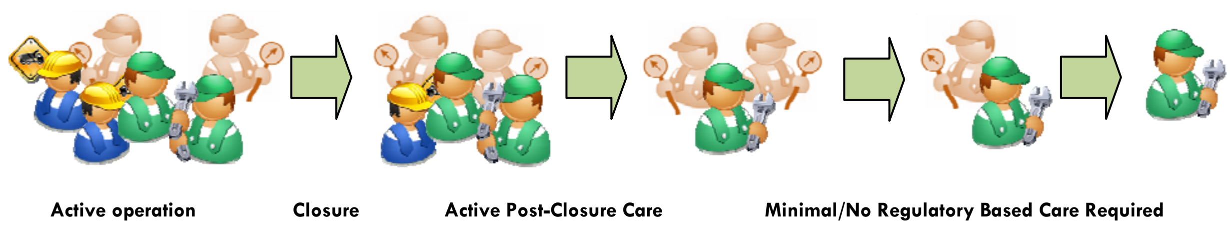
Major failures at regulated solid waste landfills are very rare. Of the handful of documented catastrophic failures, none was the result of a natural disaster and all could have been prevented with changes in design, operation, and/or maintenance practices. Natural disasters have been reported to cause only minor, easily repairable damage to vegetation and surface features.

6.2.3 Performance-Based Maintenance and Ending Care at Closed Landfills

Once a landfill is closed and a PCC program is established, monitoring data provide direct evidence that the landfill is performing as expected. Multiple studies of actual landfill data indicate that, with proper maintenance of the final cover system, landfills show decreasing leachate volumes and improvement in its quality after capping. Similarly, the landfill will begin a decreasing landfill gas generation trend within a year or so after capping (assuming active treatment of waste does not continue at time of closure, in which case the time the commencement date of the decreasing trend may be extended). With a decrease in leachate and landfill gas generation over time, the need for continuous active system management also decreases. In this way, managed care routinely performed during operations reduces the effort needed during a landfill's post-closure care period.

As designed under RCRA Subtitle D and as confirmed by the studies summarized in Section 6.1.2 (and in more detail in Appendix C), monitoring can determine the point at which active landfill management is no longer needed and regulators can be confident of protection of human health and the environment in the absence of this care. In this regard, performance-based methodologies for evaluating post-closure care, including those outlined by EREF (2006) and ITRC

(2006b) as described in Section C2 of Appendix C, provide a technically defensible approach for deciding when discontinuation of care activities can occur. Both require a demonstration that safe conditions exist before a landfill can exit permitted post-closure care.



An important component of the future of the managed landfill is use of proactive operational practices to enhance waste degradation and move quickly to reduce long-term impact potential. "Wet" or bioreactor landfills designed and operated to enhance waste degradation through active treatment promise more sustainable landfill technology. These landfills provide the additional benefit of offering a wider range of reuse options for the property. This is discussed in terms of different landfill design types in Section 6.3 and more broadly in Section 7.4.

6.3 Environmentally Protective Landfill Designs

Different types of modern performance-based landfill designs all feature integrated operational control systems to provide containment, environmental performance monitoring and data assessment, and rapid response to system upsets. Although each landfill features control systems appropriate to the particular site, most modern landfill designs can be categorized into one of the four main types, as outlined in Table 6-1. The key attributes and environmentally protective features of each of these four types of modern landfill designs listed in Table 6-1 are outlined in the remainder of this section using a series of five Tables 6-2 through 6-6.

Table 6-0 provides an at-a-glance summary of the purpose of Tables 6-1 through 6-6. It is important to note, however, that this reference tool is provided as an example only and is not exhaustive; a number of variants on these four main types of landfills exist. The links to tables listed in Table 6-0 are intended to serve as quick cross-references to highlight how each landfill type provides the key attributes of modern landfills (i.e., containment, operations, waste treatment, maintenance, and monitoring) to protect the four main environmental media (i.e., groundwater, surface water, the vadose zone, and air). As previously discussed, no single attribute is the key to protection of human health and the environment for a specific design; it is the integration of design, component systems, operation and maintenance, and environmental performance monitoring that provides overlapping levels of environmental protection.

Table 6-0: Summary of Section 6 Tables

Table No.	Purpose	Icon Key
6-1	Key Design and Operational Features of Four Main Types of Managed Landfill	
6-2	Containment Attributes Common to all Four Main Types of Managed Landfill	
6-3	Operations Attributes Common to all Four Main Types of Managed Landfill	
6-4	Waste Treatment Attributes Common to all Four Main Types of Managed Landfill	
6-5	Maintenance Attributes Common to all Four Main Types of Managed Landfill	
6-6	Monitoring Attributes Common to all Four Main Types of Managed Landfill	

Table 6-1: Outline of Four Main Types of Managed Landfill

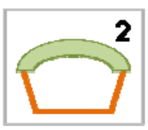
Type	Key Features of Landfill Design and Operation
Design Type 1: Engineered Liner and Cover 	• Design prescribed under Subtitle D, relies on engineered systems that feature a leachate management system (LMS) and a gas management system (GMS), which may be active or passive depending on the size and age of the landfill. • Operation, maintenance, and monitoring provide for waste containment and operational control system performance. • Waste treatment is not enhanced in this type of landfill since the objective is to minimize or control (i.e., inhibit) infiltration of moisture for the very long term. • While this type of landfill is very protective of groundwater and other environmental media, it limits end use options after closure because of the need for the final cover to remain undisturbed.
Design Type 2: Engineered Liner and Natural Analog Cover 	• Design is identical in component systems and performance to a Type 1 landfill, with the exception that it features a natural analog cover system as an alternative to the prescriptive Subtitle D cover design. • These landfill cover designs can exceed many important cover system performance criteria such as erosion control, methane oxidation, and slope stability. This landfill type controls infiltration through the cover system at a rate that can sustain active waste treatment but not result in leachate build-up and compromise of the engineered liner. • A significant advantage of this landfill design is that it affords more flexibility in end use because natural analog covers can be designed as low maintenance or even self sustaining systems. Active maintenance of the cover may not be required in the longer term for ongoing protection of human health and the environment.
Design Type 3: Engineered Liner and Natural Analog Cover + Enhanced Degradation 	• Design is identical in component systems and performance to Type 2, with the exception that it features enhanced treatment systems in the form of controlled enhanced biodegradation. • Operationally, this landfill design may require more infrastructure (such as for liquids distribution) and higher levels of operational management than other types, and is generally more costly in terms of capital expenditure. • A significant advantage of this landfill design is that it will require significantly less long-term care due to the efficient and rapid degradation of waste. This, coupled with the advantages of a natural analog cover system, affords much flexibility in end use options because long term active maintenance of containment systems should not be required in the longer term.
Design Type 4: Engineered Natural Barrier and Cover 	• Design is identical in component systems and performance to Type 1, with the exception that it features an engineered natural barrier soil liner as an alternative to the prescriptive Subtitle D liner design. • This landfill is designed to be just as protective of groundwater and other environmental media as the other types of modern landfills, but a greater focus is placed on its management elements (particularly cover maintenance and environmental monitoring). • These landfills are simpler to operate than other landfill types because they often do not require a LMS as part of their permit. However, Type 4 Landfills will typically require longer-term final cover system maintenance.

Table 6-2: Summary of Containment Attributes of Managed Landfills

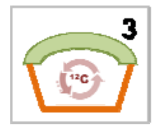
Containment Attribute 	Managed Landfill Type			
	Engineered Liner and Cover	Engineered Liner and Natural Analog Cover	Engineered Liner and Natural Analog Cover + Enhanced Degradation	Engineered Natural Barrier and Cover
				
Siting and Design	Regulatory requirements for proper siting are designed so that landfills are located at sites with natural buffer materials to retard liquid flow beneath the landfill and monitor for impacts			
Liner System	A multi-layer liner features geosynthetic and soil barriers, preventing leachate leakage			Natural engineered barrier without geosynthetics used to prevent leachate leakage
Leachate Management System	Leachate is collected and removed, reducing the pressure head on the liner			In some cases, a LMS may not exist because pressure head on the natural liner is not an issue of concern
Cover System	A multi-layer cover features geosynthetic and soil barriers, controlling infiltration	Engineered natural analog barrier without geosynthetics used to control infiltration		Same as Type1

Table 6-3: Summary of Operations Attributes of Managed Landfills

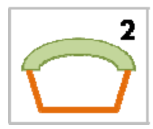
Operations Attribute	Managed Landfill Type			
	Engineered Liner and Cover	Engineered Liner and Natural Analog Cover	Engineered Liner and Natural Analog Cover + Enhanced Degradation	Engineered Natural Barrier and Cover
				
Waste Screening and Working Face Operation	Management of incoming waste streams prevents disposal of non-acceptable waste; Optimization of working face minimizes controllable leachate generation			
Stormwater Management	Management includes active controls to separate clean and contaminated surface water prevent uncontrolled off-site discharge			
Leachate Management	Leachate is collected and stored for offsite disposal, or treated prior to discharge		Leachate is recirculated back into the waste mass to enhance biodegradation	In some cases, a LMS may not exist because leachate accumulation on the natural liner is not an issue of concern
Gas Management	Gas is collected from inside the landfill; GMS is operated to meet site-specific objectives and controlling gas migration			

Table 6-4: Summary of Waste Treatment Attributes of Managed Landfills

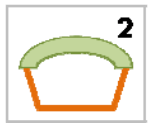
Waste Treatment Attribute	Managed Landfill Type			
	Engineered Liner and Cover	Engineered Liner and Natural Analog Cover	Engineered Liner and Natural Analog Cover + Enhanced Degradation	Engineered Natural Barrier and Cover
				
Siting and Design	Siting is key component to system design for waste treatment; also climate and local regulatory permit conditions		Landfill design is modified to reflect enhanced waste degradation (increased leachate and gas management demands)	Same as Type1
Leachate Management System	Climate and system design will affect leachate generation; local discharge limitations will affect leachate treatment options		Enhanced operation and leachate recirculation	Enhanced operation and leachate recirculation generally not allowed
Gas Management System	Climate, system design, and incoming waste stream will affect LFG generation and specific gas management system		Enhanced degradation design expected to increase gas generation; greater emphasis placed upon gas system design and operation	Same as Type 1
Cover System	Engineered cover designed to minimize infiltration and eliminate leachate head build-up on liner; Overlapping system to protect groundwater	Natural analog cover designed for long-term stability; can be designed to allow greater infiltration if ongoing waste treatment planned		Same as Type 1

Table 6-5: Summary of Maintenance Attributes of Managed Landfills

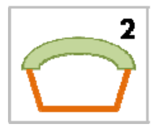
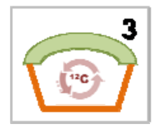
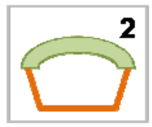
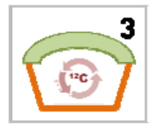
Maintenance Attribute	Managed Landfill Type			
	Engineered Liner and Cover	Engineered Liner and Natural Analog Cover	Engineered Liner and Natural Analog Cover + Enhanced Degradation	Engineered Natural Barrier and Cover
				
Leachate Management System	Management required to prevent operational failures, system clogging, and optimize leachate collection			In some cases, a LMS may not exist because pressure head on the natural liner is not an issue of concern
Gas Management System	Management required to prevent operational failures, watered-out gas wells, and optimize LFG collection			
Stormwater Management System	Management required to control run-off of contaminated surface water and prevent uncontrolled off-site sediment discharge			
Cover System	Management required to prevent erosion, repair surface cracks or ponded areas, and contain surface emissions	Once stabilized, cover maintenance is expected to be less than with prescribed engineered cover	Once stabilized, cover maintenance is expected to be less than with prescribed engineered cover	Same as Type 1

Table 6-6: Summary of Monitoring Attributes of Managed Landfills

Environmental and Performance Monitoring Attribute	Managed Landfill Type			
	Engineered Liner and Cover	Engineered Liner and Natural Analog Cover	Engineered Liner and Natural Analog Cover + Enhanced Degradation	Engineered Natural Barrier and Cover
				
Groundwater Monitoring	Indirect measure of landfill containment system effectiveness; since leachate and LFG are well characterized sources early detection allows for a prompt and effective response to system upsets			
Surface Water Monitoring	Indirect measure of landfill cover and stormwater controls; early detection allows operational solutions (such as repair or eliminate source of seeps) prior to off-site discharge			
Vadose Zone (Gas Migration) Monitoring	Indirect measure of gas collection and containment; identification of gas migration allows prompt response actions such as balancing the GMS			
Head on Liner Monitoring	Direct measure of hydraulic head; indirect measure of LMS design effectiveness; identification of condition prevents release of leachate to the surface or subsurface			LMS may not exist; in any case, head on liner monitoring omitted because pressure head on the natural liner is not an issue of concern
Leachate Quality Monitoring	Indirect measure of waste degradation processes; direct measure to meet regulatory discharge requirements			In some cases, a LMS may not exist
Gas Management System Monitoring	Direct measure of GMS system effectiveness measured at the flare station and/or well heads; data supports system working as designed to prevent uncontrolled emissions to the atmosphere			
Surface Emissions (Air Quality) Monitoring	Direct measure of cover integrity; indirect measure of gas collection efficiency; prompt identification allows modification of the cover to prevent uncontrolled emissions to the atmosphere			

7. BEYOND WASTE CONTAINMENT – LANDFILLS AS A RESOURCE

Landfills offer significant environmental and community benefits beyond just safe containment of solid waste. Four significant examples are:

Landfill Gas-to-Energy (LFGTE) *which provides green energy and optimize reduction of greenhouse gas emissions;*

Carbon Sequestration *(net removal of carbon from the atmosphere) similar to sequestering of carbon occurring in natural terrestrial ecosystems;*

Enhanced Waste Treatment *which degrades the waste faster, increasing the rate of methane production and more rapidly improving leachate quality; and*

Sustainable *landfills designed to provide flexibility in* ***Beneficial End Use*** *options after landfill closure.*

The managed, modern landfill can be designed with beneficial use as a primary driver, thereby creating a dynamic resource that can potentially produce clean, renewable energy, reduce greenhouse gas emissions, and provide flexibility in land use for the local community.

The managed modern landfill as an engineered containment structure that provides environmentally protective containment and treatment of municipal solid waste (MSW) has been described in previous sections of this document. As the final chapter of this document, Section 7 serves to briefly describe the manner in which landfills provide benefits beyond containment, including serving as a renewable energy resource and sequestering carbon produced from natural and manmade sources (which in turn helps to reduce greenhouse gas emissions). As will be illustrated in Section 7, the future of landfill technology offers several very promising and enhanced characteristics.

7.1 Landfill Gas-to-Energy and Other Proactive Green Energy Opportunities

Landfill gas is rich in methane, an important energy source, which typically comprises 50-60 percent of the gas by volume. As a result, efforts to control GHG emissions by capturing LFG serve to capture the methane as a significant energy source. Not only do such projects provide "***green energy***" from a renewable resource by offsetting traditional fossil fuel energy production plants, they help reduce the dependency on fossil fuels, particularly coal and oil. Use of renewable energy sources offsets the atmospheric emissions of CO_2 and other substances (e.g., nitrous oxides, sulfur oxides, or mercury) associated with fossil fuels.

In the U.S., many state and municipal governments and private companies are working with the USEPA in voluntary efforts to reduce emissions by implementing cost-effective LFG management methods and LFG utilization technologies. The major technology options that are presently widely employed by the industry are:

- **Establishment of landfill gas-to-energy (LFGTE)** plants where electricity is generated on or close to the landfill site using engines, turbines, or other electricity producing devices and used onsite, in the local community, or distributed to the regional power grid;
- **Direct utilization of generated energy** as an alternative fuel to displace propane, butane, or fuel oil for onsite or local commercial and domestic purposes (e.g., for heating and cooking in local homes, boilers, greenhouses, or operation of landfill control systems such as leachate evaporators);
- **Direct use as an alternative vehicular fuel**, including production of liquefied natural gas (LNG) or as a process raw material for the production of methanol;
- Sale as a **pipeline quality** (i.e., high Btu or low/medium Btu) gas product and injected into the regional natural gas distribution grid; or
- **Specialized use** such as fuel for experimental fuel cell technology.

Depending on its intended use, the raw LFG must be cleaned to some extent to remove moisture and particulates to increase the relative methane content.[23] Finally, as previously discussed in Section 7.1, increasing moisture within a landfill through "wet landfill" or bioreactor operational strategy is a proven technique for enhancing degradation rates and LFG production. Such LFG generation enhancements also provide increased opportunity for beneficial use of LFG.

A Positive Role for Landfills in the Energy Grid

"If controlled bioreactor technology were applied to 50 percent of the MSW currently being landfilled, 270 billion cubic feet of methane could be recovered each year. This volume could be used to produce one percent of the nation's electrical needs."

U.S. Department of Energy (2006)

[23] According to the USEPA's Landfill Methane Outreach Program (LMOP) website (see http://www.epa.gov/lmop/), as of December 2007, approximately 445 LFGTE projects were operational nationwide, generating approximately 11 billion kilowatt-hours of electricity per year and delivering 236 million cubic feet per day of LFG to direct-use applications. LMOP estimates that more than 500 additional landfills present attractive opportunities for LFGTE project development.

7.2 Effective Sequestration of Carbon in Landfills

Systems which emit carbon to the atmosphere are termed carbon "sources" whereas systems which capture and store carbon are termed carbon "sinks." To facilitate fair comparison between different types of carbon sources and sinks, the size of all carbon sources and sinks is measured relative to CO_2. Carbon sequestration (storage) is defined as the permanent removal of biogenic carbon (i.e., carbon of recent plant origin rather than the fossil carbon found in coal, natural gas, or oil) from the atmosphere – such sequestration therefore occurs in carbon sinks. Emissions of gases containing carbon, such as methane and CO_2, are considered greenhouse gases, or GHGs (IPCC, 2006).

Landfills as Carbon Sources: The nature of landfill gas emissions and extent of biodegradation that may be achieved in a landfill, combined with the quantity of carbon that is sequestered, are important factors in understanding the role landfills play with regard to managing GHG emissions. As previously discussed throughout this document, waste degradation in landfills generates biogas. However, with regard to landfills' role as a GHG source, the relatively small volume of methane produced at modern landfills in the U.S. is highly regulated, with engineered collection and control systems designed and monitored to minimize the uncontrolled release of methane to the atmosphere. In addition to engineered controls of GHG emissions at landfills, studies have shown that even under conditions for enhanced anaerobic (without air) degradation, only 25 to 40 percent of landfill carbon, mainly readily biodegradable organic matter, is converted to biogas carbon in the form of methane and CO_2. Therefore, although landfills are potential sources of GHGs, uncontrolled GHG emissions from managed landfills in the U.S. are limited.

Landfills as Carbon Sinks: Building on the above discussion, the term carbon sequestration as applied to landfills refers to the portion of carbon in waste that does not degrade completely after disposal, but rather is permanently stored in a stable form that cannot degrade to produce methane or carbon dioxide (CO_2). Such carbon is found in the biodegradable organic components of MSW such as wood, paper, cardboard, green yard waste, and some food wastes. These biodegradable organics are mostly composed of cellulose and hemicelluloses (C&H), complex carbohydrates that form the main structural components of cells in all green plants. Limited conversion of C&H in landfills occurs relatively rapidly, typically over the course of a few decades. However, although C&H will decompose anaerobically to methane and CO_2, the complete decomposition of C&H within a landfill is not expected. In addition, many common components of the waste mass are wood-based, which contains lignin. Lignin is highly recalcitrant to anaerobic biodegradation under landfill conditions, and will not undergo any significant decomposition.[24] This limited biodegradability, coupled with the fact that modern landfill designs isolate wastes from the environment using engineered containment systems (which further restrict anaerobic digestion from proceeding) and are required to capture and control methane, means

[24] Carbon sequestration in landfills is discussed in detail by Barlaz (1998 and 2006), Barlaz, et al (2007), and in a seminal USEPA (2006) report: "*Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks (3rd Edition)*."

that landfills are increasing the net amount of organic carbon (measured as CO_2) that is permanently sequestered as biomass. Hence, landfills can serve as a GHG sink.

In summary, although landfills are known sources of methane, an important GHG, they also sequester carbon. This sequestration is important because it removes carbon from the natural carbon cycle indefinitely, reducing net emissions of GHGs to the atmosphere. The effect of this process on overall U.S. greenhouse gas emissions is quite significant. For example, according to the U.S. Greenhouse Gas Inventory (USEPA, 2009) the annual increase in storage of carbon in landfills in 2005 offset 51 percent of landfill methane emissions. In comparison to other sources and sinks, this exceeded, in absolute magnitude, the emissions from 47 of the 54 source categories inventoried.

7.3 Enhanced Waste Treatment vs. Waste Containment

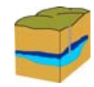
The relatively recent concept of accelerated decomposition of waste within the landfill has led to a new way to look at waste disposal. Enhanced waste degradation can be achieved both actively and passively by managing the incoming waste stream and controlling landfill moisture content. Passive approaches include recent innovations in landfill component system designs such as alternative cover systems, which allow controlled infiltration. However, active approaches for increasing the water content of wastes, either at the time of landfilling (e.g., by inclusion of sewage sludge or other high liquids content waste streams) or in conjunction with subsequent leachate recirculation or "wet landfill" (bioreactor) operations, have been demonstrated to be one of the most reliable ways of accelerating the onset of methanogenic conditions and then enhancing subsequent degradation rates. A bioreactor landfill has been defined by the Solid Waste Association of North America (SWANA) as *"any permitted Subtitle D landfill or landfill cell where liquid and/or air, in addition to leachate and landfill gas condensate, is injected in a controlled fashion into the waste mass in order to accelerate or enhance biostabilization of the waste."*

Bioreactor landfills have been the subject of significant interest by the solid waste management industry and USEPA for the past 20 years and, for this reason, are among the most studied and well-understood innovative treatment options available for MSW. Promoting in-situ MSW treatment through bioreactor operation offers the following primary benefits:

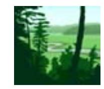
- Elimination of leachate treatment and off-site disposal, thereby reducing the load on public wastewater treatment facilities or surface water receiving systems (e.g., sustainable management of leachate); 
- Acceleration of short-term landfill gas (LFG) production, thereby increasing opportunities for economically viable green energy production; 
- More rapid exhaustion of long-term LFG generation potential (for example, significant LFG generation at bioreactor landfills is anticipated to be limited to the first ten to fifteen years after landfill closure), thereby significantly limiting 

the post closure period required for LFG control;

- More rapid reduction in leachate constituent concentrations compared to non-waste treatment operations; and



- Reduced long-term impacts from potential emissions of leachate or LFG, reduced need to rely on high levels of infiltration control and landfill management, reduction in associated scope, duration, and costs of necessary post-closure care, and enhanced opportunities for beneficial reuse of the landfill property.



Several studies have been conducted to assess the effect of waste moisture content on the stabilization and degradation of municipal solid waste.[25] These studies include laboratory experiments, mathematical modeling, and large-scale field tests. Bioreactors have higher initial design and capital costs for leachate management and installation of landfill infrastructure. Bioreactors typically require additional monitoring and maintenance during their operating life. In the long term, however, they are capable of significantly reducing the timeframe for which regulatory maintenance and monitoring are required to provide protection of human health and the environment. Many state agencies are increasingly allowing and even encouraging landfill management practices that maximize moisture availability with the goal of enhancing waste degradation. In many locations, bioreactor technology currently represents the best available technology (BAT) for meeting this goal and reducing the period during which the landfill property must be under active management.

Bioreactor Technology
Comes of Age

Quote from the Interstate Technology and Regulatory Council (ITRC) Technical Regulatory Guidance document on **Bioreactor Landfills** (February 2006):

"The team believes that available research indicates that municipal solid waste degraded in a bioreactor landfill may reduce the long term threat potential relative to a dry tomb landfill resulting from breakdown of organics and the possible sequestration of inorganics. The team believes that bioreactors can expedite beneficial reuse of landfill capacity, resources, and expedited reuse of the property…"

[25] The published body of knowledge related to bioreactors is considerable, and includes the following seminal references: Reinhart & Townsend (1998); Sullivan & Stege (2000); Haskell & Cochrane (2001); Reinhart, et al (2002); SWANA (2003); and ITRC (2006a).

7.4 Increased Beneficial End Use Options for Closed Landfill Properties

With open space shrinking and environmental awareness and stewardship expanding, more and more communities see the value of productive use of closed landfill sites. Landfills are designed from the outset with the intent for safe and potentially productive use of the site after its useful life as an active waste disposal facility has ended. Proactive "wet landfill" or bioreactor operational practices that enhance waste degradation probably provide the best means to achieve faster reductions in the level of PCC required at a landfill and enhanced flexibility in end use options.

Landfill sites can be grouped into four broad categories in terms of beneficial end use:

- Open space or wildlife habitat;
- Limited agricultural or passive recreational use;
- Use for active recreation, parking, or industrial/commercial activities; or
- Intensive uses such industrial or commercial development.

Availability of the landfill property for land-use options requiring the least maintenance of the final cover system is facilitated by:

- "Wet landfill" or bioreactor technology or other enhanced waste degradation techniques (as discussed in Section 7.1); and/or
- Design and use of passive engineering features, including:
  - Wetlands or tree farms for leachate treatment and discharge (as discussed in Section 3.3.4);
  - Earthen cover "store and release" systems, tree-covered "phytocaps", or bioactive covers and biovent systems (as discussed in Sections 3.4 and 3.5); and
  - Other passive, self-sustaining natural analogs that mimic local ecosystems as closely as possible.

In this way, an end use for the landfill property can be developed that serves as a community asset, requiring minimal or no long-term active maintenance or PCC while remaining protective of human health and the environment.[26]

[26] A technical summary of the published body of knowledge related to these topics and a bibliography of seminal references is provided in Appendix C.

Sustainable landfill designs include an end-use strategy that minimizes the long-term maintenance requirements required to preserve the functional stability of the property. Deciding on a strategy for end use is a site-specific process that considers, among other things:

- Local laws, rules, and ordinances as they relate to the facility, deed restrictions, and the likely pattern and nature of future development around the site;
- Long-term technical, geotechnical, environmental, ecological and land use issues, including storm water management and surface water quality preservation; and
- Potential liabilities, regulatory limitations, and community needs.

It is important that end use strategies be developed during the operational phase of landfill development rather than after closure as this maximizes the flexibility available to meet the dynamic needs of the local community. Covenants, deed restrictions, or other land-use control mechanisms can be used to assure that the land is used only as intended. Although deed restrictions may limit the breadth of end-use opportunities available at the site, they are an important component of community planning and supplement the facility owner's plans for beneficial end use.

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Appendix A

LONG-TERM BEHAVIOR OF MANAGED LANDFILLS

A1. OVERVIEW

A1.1 Degradation of Waste in Landfills

The contents of MSW landfills have physical, chemical, and biochemical properties that change over time as they degrade. Of these, anaerobic biochemical transformation processes are typically of most significance in landfills (Kjeldsen, et al., 2003). A number of factors affect the rate of anaerobic waste decomposition in landfills, and hence the rate and quality of landfill gas (LFG) and leachate production. These factors include waste composition and biodegradability, environmental factors (e.g., moisture content and distribution, pH and alkalinity, availability of nutrients, and the presence of inhibitors to microbial activity), and operational and process-based factors such as the physical state of the waste, addition of degradation enhancing additives, and practices of liquid addition (Christensen & Kjeldsen, 1989; Barlaz, et al., 1990; Tchobanoglous, et al., 1993).

The release of constituents from a solid into solution involves a number of interrelated transport mechanisms that are either predominantly controlled by diffusion, or by percolation and kinetics. Understanding the interrelations between waste degradation, the mechanisms by which waste constituents are released into leachate or LFG, and the factors affecting them enables identification of the various stages of waste decomposition. Based primarily on data from laboratory lysimeters and test cell studies, biodegradation of MSW in landfills has traditionally been considered to occur in five more or less sequential and predictable phases in which biochemical transformation processes occur as described by Farquhar & Rovers (1973), Rees (1980), Pohland & Harper (1986), Christensen & Kjeldsen (1989), Christensen, et al. (1992), and others. The initial phases include Phase I (aerobic), Phase II (acid), Phase III (initial methanogenic) and Phase IV (stable methanogenic). However, more recent research findings, including data from field-based studies and full-scale landfills (e.g., Calmano, et al., 1993, Bozkurt, et al., 1999 and 2000; Revans, et al., 1999; Kjeldsen, et al., 2003), propose that the fifth (i.e., long-term) phase be sub-divided into three separate phases – Phase V (methane oxidation), Phase VI (air intrusion), and Phase VII (carbon dioxide or humic) – to better describe landfill behavior over the very long-term. Figure A-1 provides a qualitative depiction of expected leachate and LFG composition over the seven phases of waste decomposition.

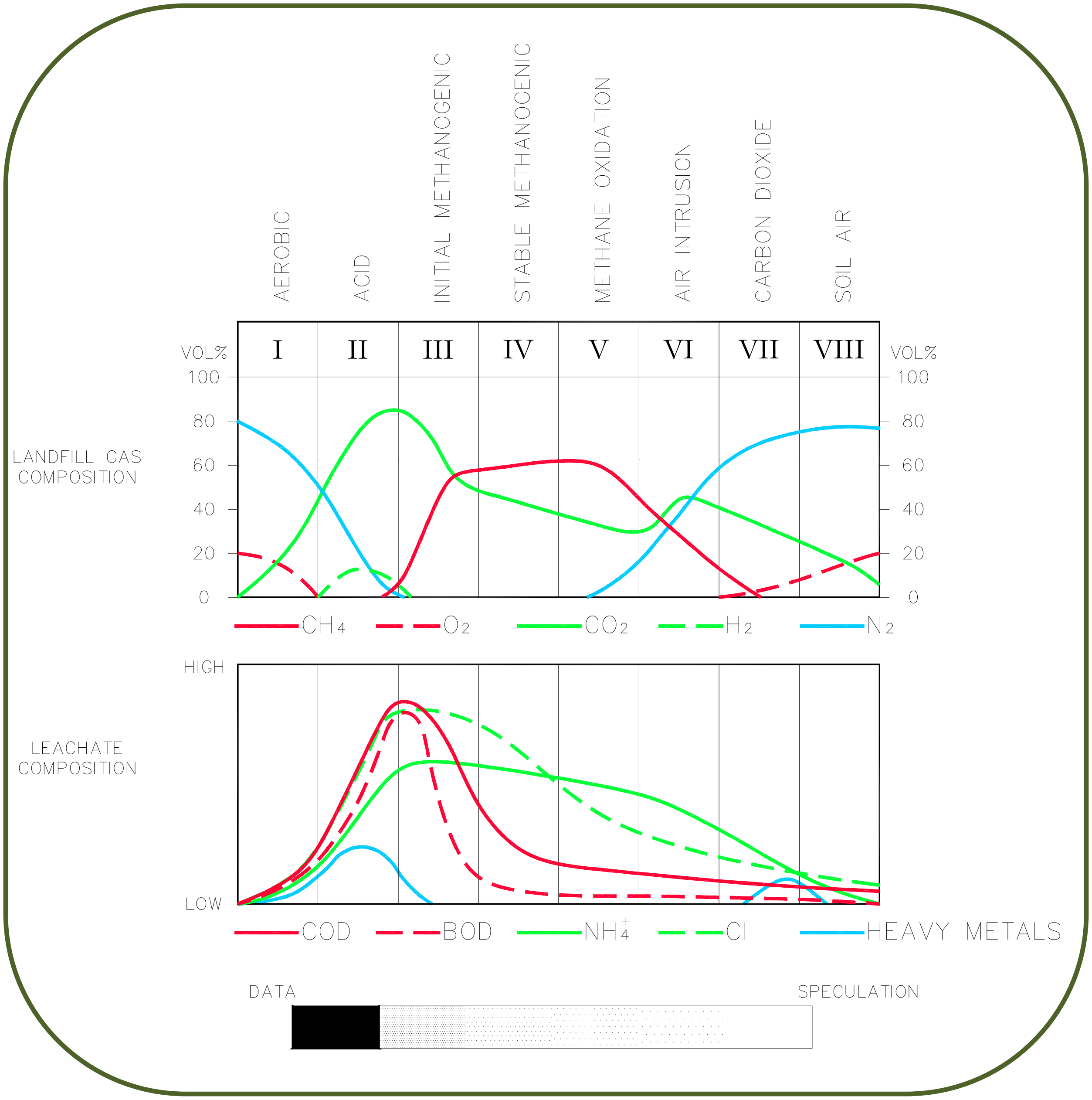

Figure A-1: Generalized Phases of Landfill Waste Degradation

(from Kjeldsen, et al., 2003)

Technical evaluations of MSW landfill characteristics such as these reveal that the chemistry of leachate from modern MSW landfills is well documented and understood. Evaluation of landfill leachate quality over time shows that leachate quality follows predictable patterns and that leachate quality improves to the extent that over time a landfill will not be expected to impact groundwater. Similarly, evaluation of LFG data over time shows predictable patterns that are a function of site characteristics, and that LFG can be managed using standard engineered collection and control systems and can be monitored for effectiveness for as long as necessary to protect human health and the environment (HHE).

A1.2 Regulatory Background

The modern regulation of municipal solid waste (MSW) landfills Subtitle D of the Resource Conservation and Recovery Act (RCRA), the Federal regulation governing land disposal of MSW, became effective in 1993 and prescribes approaches for landfill design, operation, and post-closure care, including the use of engineered liners and covers, the prohibition of hazardous and liquid wastes, installation of leachate collection systems, and environmental monitoring. Together, these approaches form the basis of the modern sanitary landfill (USEPA, 1993). Subtitle-D requires owners and operators to maintain systems at operating and closed landfills that control releases to the environment and to verify the performance of the systems through environmental monitoring. Subtitle-D was developed to minimize potential environmental impacts from operating and closed MSW landfills, for example, by requiring post-closure care (PCC) monitoring and maintenance activities at closed landfills in a manner that provides long-term protection of HHE.

A number of recent studies in the U.S. have indicated an all-round improvement in leachate quality since the enactment of Subtitle D, which supports the conclusion that the required landfill design operational controls are effective and refutes the opinion that older landfill leachate is representative of leachate quality at Subtitle D landfills. For example, a USEPA (2007) study entitled "Analysis of 40 Potential TSDs: Potential RCRA Treatment, Storage, and Disposal Facilities Proposed to the Superfund National Priority List after 1990" demonstrates that the RCRA Subtitle C regulations, which were used as the basis for development of the Subtitle D regulations, have been effective in regulating the management of hazardous waste sites and reducing the likelihood that RCRA-regulated facilities might someday need to be remediated under the Superfund program. Enactment of the landfill regulations under RCRA has also resulted in a steep decline in the number of landfill cleanups for which state taxpayers will ultimately be responsible. For example, the Minnesota Closed Landfill Program (CLP) that was established in 1994 through the Minnesota Landfill Cleanup Act (LCA) provides clear evidence to support this downward trend. At the beginning of the program in 1994, only 9 of the 112 sites in the program were identified as being of immediate concern, and in 2006 only one of the 112 sites was identified as being of immediate concern (Olson, 2007).

In conclusion, close regulation of the U.S. waste disposal industry over the last 20 years, coupled with the extensive body of knowledge that has been gained from decades of academic research on the behavior of landfills, trends in landfill emissions, and the longevity of landfill containment systems (see Appendix B) has resulted in today's disposal facilities being highly engineered structures that are designed, constructed, monitored, and maintained to prevent failure, greatly reducing the likelihood of their becoming the "unfunded liabilities" of the pre-RCRA era.

A1.3 Organization of this Appendix

In the context of leachate and LFG management at modern MSW landfills, and the potential for a modern landfill to impact groundwater and HHE, the discussion is this appendix is focused on the following three main subject areas:

- Long-terms trends in MSW leachate generation and quality;
- Potential health impacts of MSW leachate; and
- Long-term trends in LFG generation and composition.

These three subjects are addressed in the following subsections of this appendix. In each subsection, a convenient green box provides an "at a glance" synopsis of salient technical issues, summarizing pertinent landfill behavioral characteristics and representing the state-of-the-practice for modern MSW landfill design and management, along with references for seminal supporting material from peer-reviewed research, journal articles, and operational practice. Thereafter, a brief summary of the body of knowledge in support of the synopsis is provided.

A2. LONG-TERM TRENDS IN LEACHATE GENERATION AND QUALITY

A2.1 Technical Synopsis

- MSW landfill leachate is a well studied, non-hazardous liquid having properties that are distinctly different than hazardous waste landfill leachate;
- MSW leachate is composed of a variety of constituents, most significantly:
    - A large number of dissolved organic materials (collectively expressed as biochemical oxygen demand, or BOD, and chemical oxygen demand, or COD, because a higher oxygen demand indicates a higher organic loading);
    - Nutrients (mainly nitrogen in the form of ammonia/ammonium and some phosphorus); and
    - Inorganics (metals, chloride, salts, sulfate/sulfide, bicarbonate alkalinity) and other parameters including total suspended solids (TSS) and total dissolved solids (TDS).
- Leachate generation decreases by several orders of magnitude within a decade or so after capping;
- The concentrations of MSW leachate constituents follow trends that are predictable and that decrease with time after capping;
- MSW decomposition can be measured and controlled, and well-degraded lower layers of MSW in landfills can mitigate leachate quality; and
- Modern landfills are designed and operated to contain liquids, and they are monitored to demonstrate protection of HHE.

Seminal Supporting References: Pohland & Harper, 1986; Christensen, et al., 1994; Robinson, 1995; Knox, et al., 2000; Christensen, et al., 2001; Robinson & Knox, 2001 and 2003; Bonaparte, et al., 2002a; Othman, et al., 2002; Kjeldsen, et al., 2003; SWANA, 2004; Gibbons et al., 2007.

A2.1 Summary of Supporting Body of Knowledge

A2.1.1 Long-Term MSW Leachate Generation

Leachate is produced when the field moisture-holding capacity of the waste contained in the landfill is exceeded. This occurs when the waste moisture deficit (the difference between the waste moisture content at placement and field capacity) is exceeded. Leachate generation rates are most greatly affected by the type and condition of the in-place engineered cover system at the landfill. Four other factors affecting leachate production at a landfill (Rees, 1980) include: (i) the water content of the waste when placed; (ii) the volume of leachate recirculation or other liquids addition; (iii) the volume of liquids or sludges co-disposed with the waste; and (iv) waste compaction and density.

From the above, it is clear that good landfill cover design is the most important limiting factor controlling the amount of leachate generated at a site. For example, in a broad study cited by Bonaparte, et al (2002a) that included 11 MSW and 26 hazardous waste landfill cells that had a leachate collection system and cover systems including a geomembrane layer, it was found that the rate of leachate generation decreased by approximately three orders of magnitude less than ten years after closure. The above finding, coupled with the expected longevity of Subtitle D liner systems (Othman, et al, 2002) and demonstrated improvement in leachate quality over time (as liner performance gradually declines), therefore means that closed landfills relying on Subtitle D compliant cover and liner systems to limit generation and emission of leachate can expect to continue to be protective of HHE over the very long term (Pivato & Morris, 2005).

It should also be noted that new approaches to landfill operations and management have been promulgated to promote long-term threat reduction through enhanced waste degradation (i.e., enhanced organic stability) rather than reduced infiltration and leachate generation in the PCC period (see Wisconsin NR 514.07.9). This regulation uses methane and carbon dioxide generation rates as a surrogate for waste decomposition (i.e., there is an expected direct correlation between improving leachate quality and reduction in methane/carbon dioxide generation rates with time, which is clearly a function of waste decay as illustrated in Figure A-1). However, in most cases achieving the required waste degradation cannot realistically be attained without consistently adding liquid to the refuse during operations and the post-closure period. Therefore, implementing a waste degradation approach to managing the long-term impact potential will require proactive landfill operations (e.g., leachate recirculation, bioreactor operations, and/or alternative all-soil covers) to optimize the moisture content necessary for enhanced waste degradation (ITRC, 2003 and 2006a). This performance-based PCC approach will require maintaining optimum moisture contents in the waste mass while effectively managing leachate and LFG generation until the landfill becomes stable.

A2.1.2 Characterization of MSW Leachate

MSW landfill leachate contains organic compounds (typically represented by BOD and COD), inorganic ions and nutrients, and relatively low concentrations of heavy metals and volatile organic compounds (VOCs). A large number of reviews of leachate composition from multiple sites of different ages under various operating condition have been published (e.g., Farquhar, 1989; Christensen, et al, 1994; Robinson, 1995; Rowe, 1995; Reinhart & Grosh, 1998; Raininger, et al 1999; Kjeldsen & Christophersen, 1999; Knox, et al, 2000; Christensen, et al, 2001; Ehrig & Kruempelbeck, 2001; Kjeldsen et al, 2003; Robinson & Knox, 2001 and 2003; Bone et al, 2003). The body of knowledge related to this topic is very extensive.

It is important to recognize that although leachate data from older, pre-Subtitle-D landfills are often cited as being representative of long-term leachate quality from modern MSW landfills, these older landfills were constructed prior to the enactment of RCRA and thus often accepted organic solvents and other hazardous wastes that are no longer permitted in MSW landfills (except in the very limited quantities found in household waste). In support of this, a number of recent U.S. studies show an all-around improvement in leachate quality since the enactment of Subtitle-D, which refutes the opinion that older landfill leachate is representative of leachate at Subtitle-D landfills. For example, Othman, et al. (2002) found that average VOC concentrations were generally lower in leachate from post-1990 landfills than leachate from pre-1990 landfills, and almost always lower than leachate from pre-1985 landfills. A study by Gibbons, et al. (1999) concluded that MSW and hazardous waste leachate are easily distinguishable, based on the lower detection frequency and constituent concentrations of 16 key VOCs in MSW leachate.

A2.1.3 Mechanisms Affecting MSW Leachate Quality

The release of compounds from a solid to a solution (i.e., leaching) involves a number of interrelated transport mechanisms which can be grouped into those predominantly controlled by diffusion and those predominantly controlled by percolation and kinetics. The factors controlling leaching also affect the composition of the resulting leachate. These factors include: (i) the leaching mechanism; (ii) the pH and Eh (redox potential) of the leaching environment; (iii) the nature and rate of movement of percolating liquids; and (iv) properties of the waste material, particularly with regards to physical, chemical, and/or biological changes occurring (Heasman, 1997). As described in Section A1.1, the last factor depends significantly on the age of the landfill and the extent of biodegradation achieved.

A2.1.4 Long-Term Trends in MSW Leachate Quality

Numerous findings in literature on long-term leachate constituent trends (e.g., Kjeldsen, et al, 2003; Morris, et al, 2003a) demonstrate the predictability of these trends over time, broadly consistent with the stages of waste decomposition shown on Figure A-1. For example, Rowe (1995) examined the leachate concentration history for three landfills and reported that concentrations increase to a peak value and then decrease within a monitoring period of 10 to 15 years. Several researchers have investigated the characteristics of dissolved organic matter (DOM) in leachate (e.g., Ehrig, 1983 and 1988; Pohland, et al, 1986; Kjeldsen & Grundtvig, 1995; Barlaz, et al, 2002) and assign a BOD/COD value of less than 0.1 to a "stable leachate." However, ammonia typically accumulates in leachate because there is no mechanism for its biodegradation under anaerobic conditions, even in "stable leachate" (see Robinson, 1995; Burton & Watson-Craik, 1998; Kruempelbeck & Ehrig, 1999; Barlaz et al, 2002). At sites where leachate is recirculated, there are technologies available to treat ammonia and reduce its concentration prior to leachate being entered back into the landfill (Berge & Reinhart, 2003; Price, et al, 2003).

The body of knowledge devoted to the topic of metals reaction under various operating conditions is considerable (e.g., Aulin, et al, 1997; Bozkurt, et al, 1997 and 1999; Flyhammer, et al, 1998; Martensson, et al, 1999; Lagier, et al, 2001; Grischek & Bilitewski, 2001). According to Christensen, et al. (1994), potentially toxic heavy metals do not constitute a frequent groundwater contaminant problem at MSW landfill sites, partly because MSW landfill leachates usually contain only modest concentrations of heavy metals and partly because the heavy metals are strongly attenuated to waste by sorption and precipitation within the landfill. Bozkurt, et al. (2000) developed a model to predict long-term emissions of metals from landfills and concluded that heavy metals mobilization will not occur for thousands of years, if at all. Similarly, Belevi & Baccini (1989) suggested that landfills contain sufficient buffer to maintain alkaline conditions for more than 2,000 years and, therefore, did not expect significant remobilization of heavy metals due to lower pH. This is consistent with recent independent reviews of heavy metals concentrations in leachate from multiple landfills (e.g., Kjeldesen, et al. 2003; SWANA, 2004) in which concentrations were typically at or below the drinking water MCLs, even at relatively "young" landfill sites.

Characterization of xenobiotic organic compounds (XOCs) most frequently present in landfill leachate has been extensive (e.g., Christensen, et al, 2001; Kjeldsen, et al, 2003). In a study of leachate quality from over 60 landfill cells (Bonaparte, et al, 2002b), average XOC concentrations were consistently lower in leachate from post-1990 landfills than from pre-1985 landfills. To evaluate long term trends in XOC leachate concentrations, several processes must be considered, including volatilization to gas, diffusive losses, and leaching and degradation (Deipser & Stegmann, 1994; Luthy, et al, 1997). Sanin, et al (2000), Kjeldsen & Christensen (2001), and Kjeldsen & Jensen (2001), among others, describe the long term fate of XOCs, VOCs, and haloalkanes (e.g., chlorofluorocarbons) in landfills.

Two recent studies evaluating data on inorganic ions, metals, and VOC trends as a function of time have recently been completed. In the first (Gibbons, et al, 2007), a multi-year longitudinal study used an expanded database of more than 1400 sample events from 101 closed landfill cells of various MSW ages. Results indicate that a majority of constituents show a decreasing trend with time in the post-closure period generally consistent with the major indicators such as BOD. These results support findings in existing literature on long-term leachate constituent trends using a robust data set with variability in climate, waste composition, the age of waste at the time of capping and the predictability of leachate quality trends over time. A second study (Stratom, et al, 2007) was conducted using over 12 years of leachate chemical data from a single lined cell at a south Florida MSW landfill site and showed an overall declining trend in major ion chemistry. Data collected after landfill closure capping showed an overall reduction in the amplitude of short-term variations.

A2.1.5 Development of a "Biofilter" in the Bottom-Most Refuse Layer

In addition to the protection provided by proper landfill construction and operation, there are several natural processes and barriers to contaminant release that further protect HHE over time. Researchers that have operated laboratory or field-scale landfill lysimeter studies (e.g., Bookter & Ham, 1982) have noted that BOD and COD concentrations in leachate collected from upper waste layers of a landfill waste are invariably higher than those in leachate collected from lower waste layers. There is an increasing body of evidence that the observed development of stable, low BOD/COD ratios in leachate collected from the basal leachate collection systems of mature landfills is caused by liquids in a landfill percolating down through the bottom-most layers of refuse before emerging as leachate. Studies in Japan (Shimaoka, et al, 1993) and China (Youcai, et al, 2002) have demonstrated the capacity of existing lower lifts of MSW in a simulated landfill and aged-refuse-based biofilter systems, respectively, to rapidly accelerate leachate purification and waste stabilization. In the latter study where mature refuse was removed from a landfill two to ten years after closure and characterized, the waste material was found to have become organically stabilized, with most organic material degraded to inorganic substances. Over the long term, this byproduct of post-disposal degradation would continue to mitigate the potential for impacts from MSW leachate even if engineered containment structures were to degrade over time.

The above studies suggest that the bottom-most waste layers are well decomposed due to moist or saturated conditions from leachate percolation from above and these degraded layers act as a biofilter with a relatively inexhaustible attenuating capacity for consuming degradable organics in leachate. A key component of these findings is that a landfill does not have to be operated as a bioreactor to realize the benefits of developing a basal biofilter layer because, except for the most arid sites, all landfills will accumulate moisture on their bottom liner and remove it as leachate. This phenomenon is of great value in effectively evaluating long-term leachate conditions because it allows BOD to be used as a primary measure of overall leachate quality. According to the research, if an improving trend in BOD concentration in leachate can be demonstrated and leachate continues to percolate through the bottommost layers of refuse, it is reasonable to expect that the concentration of degradable leachate organics will continue to decline or remain steady in line with that of BOD.

This attenuating condition is also conducive to the continued immobilization of heavy metals that may be present (Bozkurt, et al., 1999 and 2000; Belevi & Baccini 1989). Building on this, the U.K. Environment Agency (Robinson, et al, 2004) describes an approach to design a buffer layer above the leachate collection system to neutralize and potentially remove heavy metals from the leachate. The UKEA document, which cites research work by Van Zomeren, et al (2003) who modeled the lifetime of a 3-ft thick contaminated soil buffer layer based on its density, (alkali) neutralization capacity, and rate of infiltration to remain effective for up to 450 years, concluded that "*it is clear that the inclusion of a buffer layer shows great potential in moderating the leachate quality in terms of pH and heavy metal concentration.*"

A3. POTENTIAL HEALTH IMPACTS OF MSW LANDFILL LEACHATE

A3.1 Technical Synopsis

- Modern landfills are engineered to be closed systems that incorporate liner and leachate collection systems to prevent release of contaminants to groundwater;
- Conclusions about health risks associated with modern MSW landfills cannot be extrapolated from studies of older or different types of landfills; and
- Epidemiological studies clearly indicate the absence of a link between modern MSW landfills and health impacts.

Seminal Supporting References: Redfearn & Roberts, 2002; DEFRA, et al., 2004, PhRMA (2006).

A3.2 Summary of Supporting Body of Knowledge

In response to some public misconceptions that all liners will fail and that toxic compounds will be released to groundwater and other landfill receptors, details regarding the large number of liner performance design and operational practices available to prevent a release are discussed in great detail in Appendix B. In brief, MSW landfills are engineered to be closed systems that incorporate liner and liquids collection systems to prevent release of contaminants to the environment. This concept is supported by the Interstate Technology and Regulatory Council's September 2006 Technical and Regulatory Guidance entitled "Evaluating, Optimizing, or Ending Post-Closure Care at Municipal Solid Waste Landfills Based on Site-Specific Data Evaluations" states (ITRC, 2006b): "*…a solid waste landfill is a performance-based system that is constructed and/or managed to minimize potential impacts from site-specific leachate, landfill gas, and/or groundwater. [Wastes] contained within a landfill structure may represent a potential risk; however, exposure to the wastes can be managed and evaluated on site-by-site basis to determine whether such a condition represents a threat to [HHE].*"

The potential for leachate to impact HHE is a function of the constituents it contains, the availability of a pathway to a viable receptor, and the dose a receptor may be exposed to, considering natural attenuation processes (i.e., fate) endured by the leachate during its transport (e.g., biodegradation, dilution, and/or diffusion). Because of the extremely high effectiveness of the containment systems at well-constructed modern Subtitle-D landfills and the institutional controls that prevent direct contact of receptors with waste, the potential for leachate constituents to impact a receptor via a surface water or groundwater pathway is unlikely to be significant. In any evaluation of the "toxicity" of MSW leachate, it is also critical to note that effects are dose-dependent. Even essential minerals and vitamins – generally not considered to be toxic – can impact health when taken in large enough doses, and the "doses" found in leachate from Subtitle-D landfills are very small.

Epidemiology studies performed to date for landfills have not specifically evaluated modern MSW landfill facilities. Rather, most studies have investigated hazardous waste sites that were once landfills (e.g., Superfund sites), old unregulated waste disposal sites (e.g., historically referred to as "dumps"), hazardous waste landfills, or mixtures of different types of landfills. Modern MSW landfills permitted under Subtitle-D differ substantially with respect to waste disposal history, engineering design, and daily operations from these other types of landfills. The most recent and authoritative epidemiological studies related to MSW landfills are discussed below. These studies clearly indicate the absence of a link between modern MSW landfills and health impacts.

Redfearn & Roberts (2002) reviewed the results of 13 single-site epidemiological studies related to seven landfills and four multiple-site landfill studies. They noted that most of the single-site studies focused on large, old landfills that had been operated under outdated regulatory programs or that had received hazardous or liquid chemical wastes. The multi-site studies focused on mixtures of different types of landfills, including old hazardous waste landfills that had not been capped or lined. They concluded that the study results were inconsistent with respect to specific types of health effects, citing that "*no association*" was a more common outcome than "*positive association*". They also concluded that the studies do not provide convincing, rigorous evidence for an association between landfills and adverse birth outcomes, even for the older landfills. More recent studies of congenital anomalies and cancer (Palmer et al. 2005, Dummer et al. 2003, Irvine 2003, Jarup et al. 2002, Morris et al. 2003b) have similarly shown that residential proximity to a landfill has not been demonstrated to be associated with increased risks. A comprehensive review of the health effects of MSW sites conducted by the Department of the Environment, Food, and Rural Affairs (DEFRA) in the U.K. "*did not detect an increase in the occurrence of cancer*" even in older (operating from 1983 to 1999) landfill sites (DEFRA, et al, 2004).

Finally, in 1999 the Pharmaceutical Research and Manufacturers of America (PhRMA) initiated research to evaluate the pathways and fate of active pharmaceutical ingredients from the consumer to surface waters (PhRMA, 2006). One potential pathway identified by PhRMA was the disposal of pharmaceutical-containing sources in household trash and in MSW landfills. PhRMA initiated this study to evaluate surface water exposures through the landfill disposal pathway. The landfill-to-surfacewater pathway was calculated to account for an average of 0.21 percent to 0.78 percent of the estimated aggregate annual surfacewater releases for the 23 APIs evaluated. Thus, over 99.22 percent of pharmaceutical ingredient releases to surface water are due to services other than landfill disposal.

A4. LONG-TERM TRENDS IN LANDFILL GAS GENERATION AND COMPOSITION

A4.1 Technical Synopsis

- The primary factors affecting LFG generation are similar to those affecting waste degradation;
- Methane generation from MSW landfills decreases after closure, typically peaking about one year after cessation of waste placement before tapering off in exponential form; and
- Concentrations of non-methane organic compounds (NMOC) in LFG at closed landfills decrease at rates that are similar to, or in advance of, the rate of decline in methane concentration.

Seminal Supporting References: Farquhar & Rovers (1973); Pohland & Harper, 1986; Barlaz, et al, 1990 and 2004; SWANA, 2002; Sullivan & Michels, 2000; Soltani-Ahmadi, 2002; Sullivan, et al, 2004.

A4.2 Summary of Supporting Body of Knowledge

The primary factors affecting LFG generation are similar to those affecting waste degradation as described in Section A1.1 (i.e., mass of waste, percentage of total organic material in the waste when placed, as-placed moisture content of waste, and temperature). It is well documented (e.g., Pohland & Harper, 1986; Barlaz, et al, 1990) that methane generation from MSW landfills decreases with waste age (i.e., after closure). Under normal conditions, LFG generation rates typically reach a peak about one year after cessation of waste placement before tapering off in exponential form. Although the total quantity of LFG that can be generated is fixed by the mass and nature of the MSW in place, it is well known that the rate of LFG production can be enhanced by liquid injection into a landfill (van Zanten & Sheepers, 1995; Sullivan & Stege, 2000; SWANA, 2002). In addition, a number of researchers (e.g., Hsin-Mei & Kuo, 2000; Green, et al, 2000; Sullivan, et al, 2004) have demonstrated declining concentration trends for non-methane organic compounds (NMOC) in LFG at closed landfills under a wide range of conditions, operational practices, and timeframes, and at rates that are similar to, or in advance of, the rate of decline in methane concentration. This body of knowledge forms an important technical basis for using the trends in LFG quantity and quality as an indicator that evaluation of LFG generation (and associated pressure buildup) as the principal cause of uncontrolled surface emissions or subsurface LFG migration may be based upon a first-order decay curve for LFG production after closure.

The data used by USEPA to develop default values for NMOC production were collected mainly during the 1980s (i.e., prior to RCRA's hazardous waste exclusion rules) and have not been updated despite the fact that a number of researchers (e.g., Sullivan & Michels, 2000; Barlaz, et al, 2004) have demonstrated declining trends for VOC levels in LFG since that time (similar to the case with data for XOC concentrations in leachate, as described in Section A2.1.4). Importantly, a report by the Los Angeles County Sanitation District showed an overall exponential decline in VOC emissions in LFG over a ten-year monitoring program (Huitric, 1999). A follow up study (Huitric, et al, 2001) obtained test results from 75 landfills over a two year period and found that current trace constituent levels are two to four times less than default values.

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Appendix B

LANDFILL CONTAINMENT SYSTEM PERFORMANCE AND LONGEVITY

B1. OVERVIEW

B1.1 Containment System Design and Performance

Subtitle D landfill liner systems and their overlying leachate collection systems are a reliable component of the engineered systems that provide protection of human health and the environment (HHE) for as long as that protection is needed. The expected longevity of Subtitle D liner system and final cover system components, coupled with the demonstrated ability of such systems to reduce leachate generation and improve leachate quality over time (see Appendix A), means that closed landfills relying on Subtitle D compliant liner systems and final cover systems can expect to be protective of HHE over the very long-term.

Modern engineered landfills are designed and constructed to minimize or eliminate the release of constituents into the environment. As part of this effort, MSW landfills are required by Federal, state, and/or local regulations to apply final cover over the waste materials. Final covers for Subtitle D landfills are engineered systems that isolate the waste and provide protection of HHE. The demonstrated ability of Subtitle D final cover systems to contain waste and to control, or progressively reduce, leachate generation over time means that closed landfills can rely on Subtitle-D compliant final cover systems to perform as designed for a very long time, perhaps for a period of hundreds of years or more. Historically, low-permeability barrier components have been prescribed for final cover systems in regulations without consideration of site-specific conditions. These prescriptive covers typically include a compacted clay liner or a geomembrane. However, the Subtitle D regulations include a provision for using alternative covers that meet certain performance requirements, and as many as 20 states have approved alternative covers for landfills.

B1.2 Organization of this Appendix

Many unsubstantiated and often erroneous opinions have been expressed questioning the performance and longevity of MSW landfill containment systems (i.e., liner, leachate collection, and final cover systems). This has led to the perception in some public quarters that geomembrane liners will fail, that leachate collection systems will clog, fail, and require major maintenance before the end of post-closure care (PCC), and that cover systems will not be maintained to meet their performance specifications over the long term. To address these concerns directly, the discussion is this appendix is focused on the following three main subject areas:

- Long-terms performance of liner systems;

- Long-term performance of leachate collection systems; and
- Final cover system performance and longevity.

These three subjects are addressed in the following subsections of this appendix. In each subsection, a convenient green box "at a glance" synopsis of salient technical responses is provided, representing the state-of-the-practice along with references for seminal supporting material from peer-reviewed research, journal articles, and operational practice. Thereafter, a brief summary of the body of knowledge in support of the synopsis is provided.

B2. LONG-TERM PERFORMANCE OF LINER SYSTEMS

B2.1 Technical Synopsis

- Recent studies reinforce the finding that trends in MSW leachate and LFG generation and composition are predictable and, in general, decrease over time following landfill closure;
- At landfills where low-permeability cover systems having a geomembrane barrier are installed, the time period for significant leachate and LFG production is generally anticipated to be on the order of tens of years after closure;
- While the geomembrane component of a composite liner may have a service life on the order of 1,000 years, the service life of the low-permeability soil component of a composite liner is on the order of several thousands of years and are relied upon at critical waste containment facilities that require a service life for exceptionally long time periods (e.g., tens of thousands of years); and
- The expected service life of the components of a composite liner system in an appropriately designed and constructed MSW landfill is therefore far in excess of the time period for significant leachate and LFG production.

Seminal Supporting References: Koerner, et al., 1990; Bonaparte, 1995; Rowe, 1998; Bonaparte, et al., 2002a; Koerner & Hsuan, 2002; Rowe, 2005.

B2.2 Summary of Supporting Body of Knowledge

Reports of landfill leachate quality and quantity over time show predictable patterns of improvement that support the conclusion that well-designed and operated modern landfills will not be expected to impact HHE over the long term. Leachate generation rates at a landfill are highest early in the active life of the facility, with the rates decreasing with time as the landfill is filled and progressively closed (see Figure B-1). After closure, installation of a low-permeability cover greatly reduces infiltration into a landfill, essentially eliminating the addition of moisture that causes leachate and LFG generation. Consequently, leachate and LFG generation will cease over time (Bonaparte, 1995).

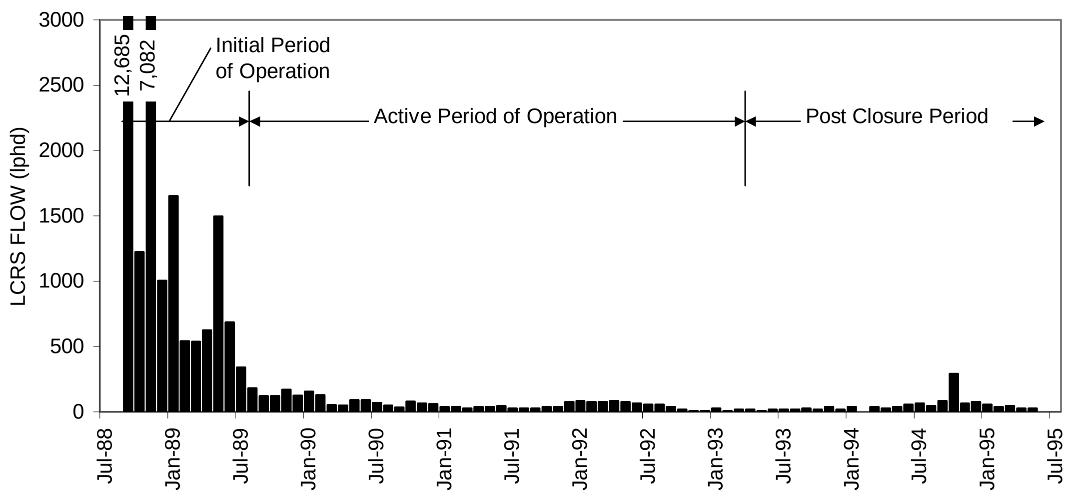

Figure B-1: Leachate Generation at an MSW landfill in Pennsylvania

(from Othman, et al., 2002)

Note: LCRS = leachate collection and removal system; lphd = liters per hectare per day

The most important limiting factors for leachate and LFG generation rates at a closed landfill are the design and the condition of the engineered final cover system. For example, in a USEPA-sponsored study of the performance of modern landfills presented by Othman et al. (2002), flow rates from the leachate collection systems of 11 MSW and 26 hazardous-waste landfill cells were found to decrease by approximately three orders of magnitude within ten years after closure with a final cover system that incorporated a geomembrane barrier component (Figure B-2). Thus, the period for significant leachate and LFG production at a closed landfill with a final cover system that includes a geomembrane barrier is generally anticipated to be on the order of tens of years after closure.

Composite liners for Subtitle D landfills consist of a geomembrane upper component and a low-permeability soil lower component. The functions of the geomembrane and underlying low-permeability soil component are complementary. Acting together, the composite materials greatly diminish the potential for liner leakage compared to the potential for leakage through a geomembrane or low-permeability soil layer alone.

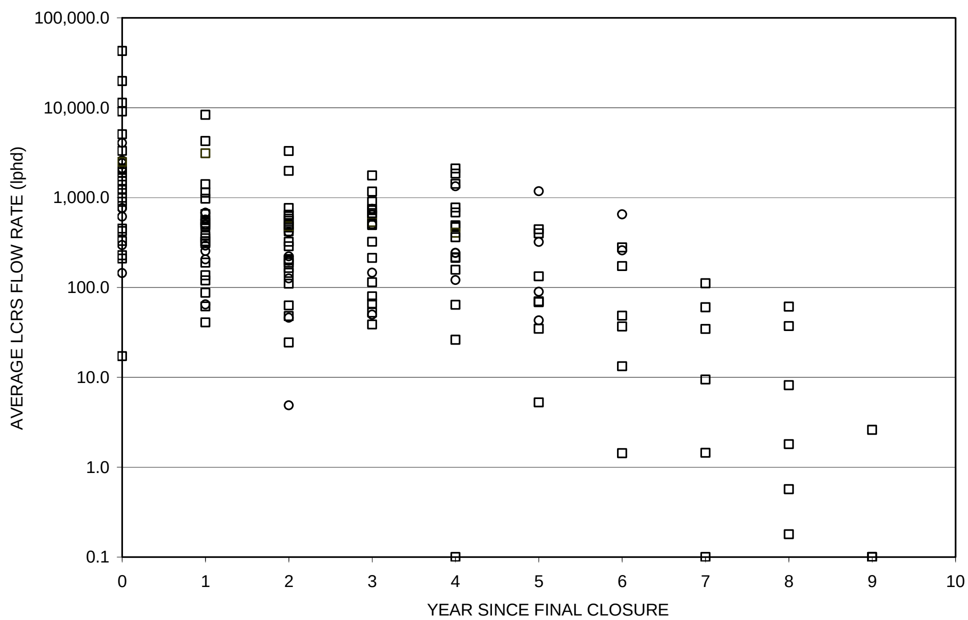

Figure B-2: Average LCRS Flow Rates after Closure for 33 Landfill Cells
(from Othman, et al., 2002)

Due to its excellent resistance to degradation by a wide range of chemicals, among other factors, high density polyethylene (HDPE) is the most common type of geomembrane barrier used in landfill liners. The service life of HDPE geomembranes is assumed to be finite due to aging of the HDPE. This topic has received significant attention in the technical literature (e.g., Koerner, et al., 1990; Hsuan & Koerner, 1998; Rowe & Sangam, 2002; Sangam & Rowe, 2002; Hsuan & Koerner, 2005; Rowe, 2005) and was the focus of a USEPA-sponsored study (Koerner & Hsuan, 2002). Aging of HDPE geomembranes is considered to result from the simultaneous processes of physical and chemical aging. In physical aging, the material attempts to establish equilibrium with its environment. Physical aging of HDPE geomembranes is manifested by an increase in material crystallinity. In chemical aging, changes occur to the geomembrane material that will eventually lead to a decrease in material properties. The most significant aging mechanism in HDPE geomembranes used in landfill liners is chemical aging, with extraction of antioxidants and then oxidation being the main degradation mechanism.

Antioxidants are added to HDPE geomembranes during processing to prevent polymer degradation and to prevent oxidation reactions from occurring during the initial stage of a geomembrane's service. As described by Hsuan & Koerner (1998) and Sangam (2001), among others, if the geomembrane is in contact with liquids for an extended time, the antioxidants in an HDPE geomembrane can be depleted due to chemical reactions with oxygen diffusing into the geomembrane and by leaching into liquids. After antioxidants are depleted, oxidation can occur as the geomembrane material begins to react with oxygen. Following an initial reaction time, referred to by Hsuan & Koerner (1998) as the "induction time", measurable material degradation begins to be observed. Oxidation reactions then proceed slowly throughout the service life of HDPE geomembranes and, eventually, the geomembrane will likely become brittle to the extent that it is considered to have reached the end of its service life (Rowe & Sangam, 2002). In their research report for the USEPA, Koerner & Hsuan (2002) select this point as the 50 percent reduction in a specific design property, such as tensile stress at break, although they note that even with this reduction in design property the geomembrane can still function, albeit at a decreased performance level. With this conservative endpoint defined, the service life of HDPE geomembranes was estimated to be on the order of a thousand years: approximately 200 years for antioxidant depletion, over 20 years for induction of geomembrane oxidation, and 750 years for 50 percent degradation of strength properties (Bonaparte, et al., 2002a).

Although a geomembrane may lose strength over time, Rowe & Sangam (2002) highlighted that the real service life of a geomembrane depends on the hydraulic and diffusive properties of the geomembrane. Thus, a geomembrane may lose strength while still performing satisfactorily as a barrier. Accordingly, the true hydraulic and diffusive service life of a geomembrane may significantly exceed the service life determined based on the degradation of the physical and mechanical properties, especially if the tensile stresses are minimal. Furthermore, burial or submersion of a geomembrane can lessen the rate of antioxidant depletion and geomembrane oxidation by decreasing the availability of oxygen. In the case of a geomembrane liner for a MSW landfill, biodegradation of waste will probably consume most of the available oxygen above the liner well before the end of PCC period (perhaps even as soon as shortly after the start of PCC).

The low-permeability soil component of a Subtitle D composite liner typically consists of a compacted clay liner (CCL), a geosynthetic clay liner (GCL), or a GCL overlying a CCL. Significant experience with the use of engineered low-permeability soil components in landfill liner system designs has been gained over the past three decades. To function adequately over its required useful life, a CCL or GCL must maintain a hydraulic conductivity no greater than its design value during this timeframe. As discussed by Rowe (1998), provided that a GCL has been properly designed, installed, and protected from desiccation, and provided that appropriate attention has been given to the chemical compatibility of the low-permeability soil layer with the anticipated leachate, the GCL should meet its hydraulic conductivity criterion for hundreds to thousands of years when used in a composite liner in a MSW landfill. For a CCL under these same design and construction constraints, the service life is even longer, on the order of thousands of years. This is the reason that CCLs are used in liner systems for containment of critical wastes (e.g., radioactive waste) and are relied upon to protect HHE over exceptionally long periods of time (i.e., tens of thousands of years).

B3. LONG-TERM PERFORMANCE OF LEACHATE COLLECTION SYSTEMS

B3.1 Technical Synopsis

- Biological and physical clogging of the leachate collection system (LCS) is considered in the design of the LCS, such that the LCS is oversized with access for monitoring and cleaning provided to allow LCS functionality to be maintained under the anticipated operating and post-closure conditions;
- The time period for significant leachate generation at a closed landfill with a final cover system that includes a geomembrane barrier is generally anticipated to be on the order of tens of years after closure (i.e., leachate generation will soon tend to be negligible as long as infiltration into the landfill continues to be controlled by a final cover system);
- The potential for development of clog material in the LCS decreases as leachate generation rates decrease and, accordingly, the likelihood of LCS clogging decreases after landfill closure; and
- Major maintenance of the LCS during the PCC period is therefore not anticipated and is needed only on extremely rare occasions at landfills currently in a PCC period because quantities of leachate generated during this period are small.

Seminal Supporting References: Bass, et al., 1983; Koerner & Koerner, 1989, 1990, 1991, and 1995; Rohde & Gribb, 1990; Rowe, 2005.

B3.2 Summary of Supporting Body of Knowledge

A LCS for a modern MSW landfill typically contains, at a minimum, a granular or geocomposite drainage layer and a piping system bedded in gravel. A well-designed LCS may also include a sand or geotextile filter between the drainage layer and the overlying soil or waste layer. Leachate collected in the drainage layer is conveyed to collection pipes and then out of the landfill by pumping it from a sump or via a gravity flow pipe. The geonets and the pipes used in a modern LCS are designed to function under the maximum anticipated loads of the overlying waste and to be structurally stable during landfill operation and through the post-closure period. LCS design and selection of suitable LCS components are relatively straightforward. There is extensive information in the technical literature on LCS design and performance (e.g., Rowe, 1998; Othman, et al., 2002; Bonaparte, et al., 2002a) as well as the design and selection of sand and geotextile filter components (e.g., Giroud, 1982 and 1996; Lafleur, et al., 1989; Luettich, et al., 1992; Koerner, 1998).

Although leachate generation rates are anticipated to be very low after landfill closure, LCSs are conservatively designed to rapidly convey large leachate flows to sumps (Rowe, 1998) throughout the operating and PCC periods. Flow rates in LCSs are typically high enough to function even after accumulation of leachate particles in the drainage layer and pipes. Cleanout pipes that connect to the main LCS pipes in the landfill are incorporated into the design to flush debris from the main LCS pipes, if necessary. In addition, the high design flow rates reduce the potential for the LCS to have sustained periods of saturation, decreasing the potential for development of biological and chemical clog material in the LCS.

The potential for LCS clogging in MSW landfills has been considered by a large number of researchers (e.g., Bass, et al., 1983; Koerner & Koerner, 1989, 1990, 1991, and 1995; Rohde & Gribb, 1990; Brune, et al., 1991; Craven, et al., 1999; Fleming, et al., 1999; Fleming & Rowe, 2004; Van Gulck & Rowe, 2004; Rowe and Van Gulck, 2004; Cooke et al., 2005; Rowe, 2005). These studies indicate that clog material forms "*by biologically induced processes that involve the removal of some of the organic leachate constituents (as implied by the reduction in COD) and precipitation of some inorganic leachate constituents (as implied by the reduction in calcium concentration)*" followed by "*an accumulation of inorganic particles originally suspended in the leachate*" (Rowe, 2005). They also suggest that the potential for clogging depends on the amount and composition of leachate and on the details of the design of the LCS.

Based on the above studies, for clogging to occur, the following two conditions generally need to exist: (i) inadequate design of a sand or geotextile filter; and/or (ii) unexpectedly high rate of relatively high strength leachate produced in the landfill that keeps the LCS near saturation. The first condition is mitigated by properly designing the filter to resist physical clogging. A LCS generally includes a geotextile filter that is wrapped around LCS pipe bedding gravel; it may also include a sand or geotextile filter between the drainage layer and the overlying soil or waste layer. Methods for design of filters are well established, and there is extensive information in the technical literature on sand and geotextile filter design (e.g., Giroud, 1982 and 1996; Lafleur, et al., 1989; Luettich, et al., 1992; Koerner, 1998). The second condition for clogging of LCSs in landfills is primarily related to the rate of leachate generation. The lower the leachate generation rate, the lower the potential for clogging (other factors being equal). Given the significant decrease in leachate generation rates after landfill closure, the potential for biological clogging of the LCS decreases after the landfill is closed with a final cover system. The second condition can therefore be avoided through good landfill operation (to limit unnecessary leachate generation) and prompt application (as required under Subtitle D) of a suitably designed cover system after site closure, supplemented with knowledge of leachate compositional trends (as described in detail in Appendix A).

B4. FINAL COVER SYSTEM PERFORMANCE AND LONGEVITY

B4.1 Technical Synopsis

- The service life of the barrier layer of a final cover system of an appropriately designed and constructed MSW landfill is designed to greatly exceed the length of the PCC period (i.e. hundreds to thousands of years);
- Recent USEPA-endorsed guidance includes several cover performance goals in addition to prevention of infiltration, including functioning with minimum maintenance; preserving habitat; supporting ecological diversity and density; and supporting future land use;
- The ability of well-maintained final cover systems to provide suitable levels of performance during the PCC period is evidenced by decreasing trends in leachate generation rates observed for modern MSW landfills in their PCC periods;
- Evapotranspiration (ET) final covers systems can be designed and constructed to maintain their function for a very long time (e.g., 10,000 years) with minimal maintenance; and
- Soil cover systems have been documented to reduce greenhouse gas emissions from landfills through oxidation of methane with factors ranging from 22-55 percent depending on cover material.
- Typical gas collection efficiencies relative to landfill cover types show that landfills containing a final soil and/or geomembrane cover systems with an active LFG collection system have efficiencies in the range of 90-99 percent.

Seminal Supporting References: Bonaparte, 1995; Kavazanjian, et al, 2001; Bonaparte, et al, 2002a and 2002b; Koerner & Hsuan, 2002; Othman, et al, 2002; ITRC, 2003; IPCC 2006; USEPA, 2006; Chanton, et al, 2009; SWICS, 2009; Scheutz, et al, 2009.

B4.2 Summary of Supporting Body of Knowledge

B4.2.1 Final Cover System Components and Specifications

Covers at Subtitle D landfills consist of a low-permeability barrier layer (e.g., a geomembrane or a compacted clay layer, CCL) overlain by a vegetative soil cover layer. Due to its excellent durability, linear low-density polyethylene (LLDPE) geomembrane is the most common type of geomembrane barrier used in final cover systems. The durability properties of LLDPE are similar to those described for HDPE in Section B2. Laboratory results suggest that it will take approximately 200 years for the antioxidants in LLDPE geomembrane to be “depleted” and another 800 years for the geomembrane strength properties to be reduced by 50 percent. Even with this loss in strength properties, the LLDPE geomembrane is expected to function adequately as a barrier. From a practical standpoint, geomembrane manufacturers, like the producers of many consumer products, warranty geomembranes for far less than their service life. For example, a typical warranty for an exposed LLDPE geomembrane that is not protected from the environment by an overlying soil layer may be on the order of one year. This is intended to provide the warrantee sufficient time to install the liner and perceive manufacturing defects; it is not intended to correspond to service life. Therefore, the warranty period is clearly not relevant to the in-service performance of a geomembrane barrier used in a Subtitle D final cover system.

The prescriptive low-permeability soil component of a cover system for a Subtitle-D landfill is a CCL which, when properly installed, provides an excellent barrier to infiltration. If maintained, the CCL should meet its hydraulic conductivity criterion for hundreds to thousands of years when used as a barrier in a MSW landfill. The high performance of final cover systems during the PCC period is evidenced by the low to negligible leachate generation rates observed for modern MSW landfills currently in PCC (see, for example, previous Figure B-1).

The goals of final covers are changing to address new regulations and to optimize environmental stewardship. In December 2003, the Interstate Technical and Regulatory Council (ITRC), which represents a consensus of over 40 state regulatory agencies, Federal regulatory agencies, and many other stakeholders and is supported by the USPEA, published a "Technical and Regulatory Guidance for Design, Installation, and Monitoring of Alternative Final Landfill Covers". The document evaluates the range of landfill covers and the features of each that provide benefits in terms of long-term stewardship and performance. The document concludes that alternative covers can provide protection equivalent to prescriptive Subtitle D covers with the added benefit of increased longevity and stability.

B4.2.2 Maintenance of Final Cover Systems

During the PCC period, the performance of the final cover system can be evaluated by monitoring leachate generation rates over time. If rates were to unexpectedly increase, the cause would be investigated. Although it has been speculated that final cover system failure is inevitable during the PCC period, such findings are not being observed at modern MSW landfills that are currently in PCC periods with properly maintained covers. The cover maintenance that is required for closed MSW landfills has primarily been related to cover system vegetation (e.g., mowing, tree removal, re-vegetating) and erosion and sediment control (e.g., removal of sediment from ditches and ponds, regrading the top deck to promote drainage). The effectiveness of the barrier layer in conventional cover systems is evidenced by measured overall reduction in leachate flow rates over time from the LCS (see Figures B-1 and B-2 and, secondarily, measurement of LFG emissions (Bonaparte, 1995; Othman, et al, 2002).

An increasing number of landfills are being closed with an evapotranspirative (ET) final cover system (i.e., all-soil covers) rather than a prescriptive final cover system with a CCL/geomembrane barrier. The concern is that a CCL barrier will desiccate in arid and semi-arid climates if not protected by an overlying geomembrane and a sufficiently thick soil erosion layer. An ET final cover typically consists of more loosely compacted soils of sufficient thickness to optimally store and release water through ET processes. For this reason, ET covers tend to be thicker than conventional covers, and the soils are not compacted but, rather, are installed less dense and dry of optimum moisture contact. An ET cover system emphasizes the water storage capacity of the cover soil profile and its ability to retain infiltrated water during precipitation events and later releases it via ET processes.

Since ET covers are constructed using only soils, they represent an extension of the surrounding environment, and their long-term performance can be predicted based on comparisons to natural soil slopes having similar characteristics (i.e., natural analogs). Natural analog studies have been used to demonstrate the design of ET covers for critical structures (e.g., radioactive waste landfills) that are required to have service lives of thousands of years and to predict the effects of long-term climate change, ecological change, and soil development on these cover systems (e.g., Gee & Ward, 1997; Gee, et al., 1997; Waugh, 1997; Scanlon, et al., 2005). A natural analog study involves evaluating a natural, and sometimes archeological, material or setting that is analogous in some aspect to a proposed cover system material or setting to determine the properties that are effective in a given environment or the processes may lead to possible modes of failure. For example, when ET covers are constructed with surficial site soils, their long-term performance can be inferred by observation of vegetation and precipitation recharge conditions at the site. The studies referenced above demonstrate that such cover systems can have service lives that exceed 1,000 years with minimal maintenance and still satisfy the performance criteria of infiltration control (Bonaparte, et al., 2002b).

B4.2.3 Estimating Air Emissions from Landfills

Landfills produce landfill gas (LFG), which is typically rich in methane (CH_4) generated through the biodegradation of cellulose and semi-cellulose products (Barlaz, et al, 2004a). Methane is an important contributor to global climate change with a 100-year global warming potential of 21 to 25 times that of carbon dioxide (CO_2). For this reason, concern for landfills as a potential contributor to atmospheric greenhouse gas (GHG) emissions is prevalent in the public eye. However, a number of direct and indirect control factors exist to limit the level of LFG emissions from a landfill (i.e., the residual, or net, proportion of LFG that is uncontrolled and migrates vertically up through the landfill cover to emerge as a fugitive emission).

Indirect Control Factors: Indirect factors generally affect the rate of biodegradation within a landfill and hence the level of gas emissions from it. Examples include waste type, density, particle size, moisture content, pH and alkalinity, temperature, presence of inhibitors or nutrients, oxidation/reduction potential (ORP) and pressure affect LFG production in landfills (IWM, 1998). The mechanisms involved were previously discussed in Sections A1 and A4 describing landfill processes and long-term LFG generation in Appendix A. Where LFG extraction systems exist with the aim of utilizing the gas (e.g., as part of an LFGTE scheme), a number of indirect control factors are used to increase the total gas yield and production rate. This is the case with bioreactor and "wet" operated landfills where biodegradation rates are optimized, especially with regard to moisture provision (Green, et al, 2000).

Direct Control Factors: Direct control factors affect the actual level of LFG emissions from a landfill. The most important examples of direct control factors are the type of cover system installed and interception of LFG by means of a gas collection system before it escapes from the landfill. Gas extraction wells can be installed before, during or after landfill operations and laid out in either horizontal or vertical patterns. Where direct measures to control LFG emissions exist at a landfill, it is normally assumed that it is the control of methane that is of concern, although the USEPA's New Source Performance Standards (NSPS) and Emission Guidelines (EG) for landfills (USEPA, 1996) are specifically targeted at control of non-methane organic compounds (NMOC) and hazardous air pollutants (HAPs). Collected LFG can be vented, flared, oxidized, or used as part of an LFGTE scheme. Collection of LFG for flaring results in the conversion (thermal oxidation) of potential CH_4 emissions to biogenic carbon dioxide (CO_2) emissions, and is the most important example of an engineered control on the level of greenhouse gas (GHG) emissions from a landfill. Important natural controls of methane emissions include microbial oxidation (i.e. consumption of methane by methanotrophic microorganisms in aerated landfill cover soils) and carbon sequestration (i.e., permanent removal of biogenic carbon from the atmosphere).

Landfill Gas Emission Estimates and Assumptions: Section 2.4 (i.e., Municipal Solid Waste Landfills) of the USEPA document "*AP-42, Fifth Edition, Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources*" (USEPA, January 1995, most recently updated under Supplement E in November 1998, draft update in review October 2008) deals with gas emissions from landfills. The current AP-42 version states: "*…the USEPA method of estimating emissions could result in conservative (i.e. high) estimates of emissions, since it provides estimates of LFG generation and not LFG release to the atmosphere. Some capture and subsequent microbial degradation of organic LFG constituents within the landfill surface layer is likely to occur. However, no data was identified to adequately quantify this process.*" This quote illustrates that the only way to rigorously quantify the extent of methane control achieved is to have a measure of collected methane and fugitive methane emissions from the same area at the same time. While measures of collected methane are readily available, measures of fugitive emissions are considerably more difficult to obtain and have only been reported for a few landfills; a comprehensive summary is provided in SWICS (2009). In one study reviewed (Spokas, et al, 2006) the following equation was used to estimate net emissions:

$$CH_4 \text{ generated} = CH_4 \text{ emitted} + CH_4 \text{ oxidized} + CH_4 \text{ recovered} + CH_4 \text{ migrated} + \Delta\, CH_4 \text{ storage}$$

Ignoring subsurface gas migration, calculation of net air emissions from landfills is a therefore a function of three main factors – methane recovered through gas controls, cover system design (in terms of control of gas flux emissions and optimization of methane oxidation potentials), and carbon sequestration. In brief, LFG collection efficiency is the amount of LFG that is collected relative to the amount generated by the landfill. Methane oxidation is consumption of methane by methanotrophic microorganisms in aerated landfill cover soils. Carbon sequestration (as applied to landfills) refers to the portion of biogenic carbon in waste that does not degrade completely after disposal, but rather is permanently stored in the landfill in a stable form.

The USEPA, along with state and local regulators, often use assumed gas collection efficiencies to calculate landfill emissions for regulatory purposes. A default value of 75 percent (as a representative mean of a reported range of 60 to 85 percent) is frequently assumed as set forth in the most current (i.e., 1998) version of the AP-42 document. However, the collection efficiency presented therein was based on engineering judgment and professional opinion, compiled by various practitioners in the LFG industry in the 1980s and 1990s, as opposed to extensive field test data. Similarly, the current AP-42 document also states that: "…*average oxidation of methane (on a volumetric basis) in some laboratory and case studies on landfill covers have indicated ranges from 10 percent to over 25 percent with the lower portion of the range being found in clay soils and higher in topsoils*." The USEPA thus recommended a conservative default factor of ten percent methane oxidation for uncollected landfill gas that escapes through the cover. The current AP-42 document makes no allowance for carbon sequestration in landfills.

The implications of the USEPA's AP-42 default assumptions for gas collection efficiency, methane oxidation, and carbon sequestration are profound because, in many cases, landfill owner/operators and regulatory agencies calculate the collection system efficiency from the actual volume of gas collected relative to the volume projected by LFG models for generation, for example using the USEPA's Landfill Gas Emissions Model, or LandGEM (USEPA, 2005). However, LandGEM and other first-order decay models predict LFG generation using a variety of conservative default inputs to the model, mainly because of difficulties in determining site-specific values. As a result, LandGEM commonly overestimates LFG generation rates and, therefore, net GHG emissions. This is examined in more detail in the remainder of Section B4.

B4.2.4 Gas Collection Efficiency

In more recent studies (cit. in SWICS, 2009), the collection efficiency of a gas collection system has been demonstrated to be more proficient at reducing GHG emissions, where efficiencies are dependent on the type of cover being used during the operation of the landfill. In evaluating collection efficiency, it is important to recognize that the efficiency of a gas extraction system will vary continuously while a landfill is in operation. While waste is received daily, gas extraction systems can only be extended into newly filled sections of a landfill on a much less frequently basis. Although an increasing number of landfills use horizontal trenches and other means of gas extraction from active areas that allow for a reduced period between refuse placement and gas recovery, the most practicable schedule expansion of a gas system is generally annually or even biannually. Thus, at any time during the life of a landfill, there may be sections with only daily cover and no gas extraction system, sections with intermediate soil cover and only limited gas extraction, and areas with final cover and optimal placement of gas extraction wells. To address this, SWICS (2009) provides collection efficiency values obtained from a comprehensive field-testing program under different cover system types. Collection efficiencies are reported in the range of 90-99 percent, with a mid-range default of 95 percent, for landfills that contain a final soil and/or geomembrane cover system with an active LFG collection system. In other words, a default collection efficiency of 95 percent should be assumed for landfills in the post-closure phase with Subtitle D-compliant final cover systems.

In summary of the above, the USEPA's default landfill gas collection system efficiency of only 75 percent in their AP-42 document is not supported by recent studies and field tests results provided by SWICS (2009) which demonstrate that active gas collection systems at modern managed landfill typically have a much higher collection efficiency that ranges from 90 to 99% for landfills that contain a final soil and/or geomembrane cover system. These high gas collection efficiencies do not include the additional effects of natural methane oxidation and carbon sequestration processes that also occur within the landfill system as described below.

B4.2.5 Methane Oxidation in Landfill Covers

Microbial oxidation (i.e. consumption) of methane by methanotrophic microorganisms in aerated landfill cover soils is an important natural control of methane emissions. It has been observed that it is possible for cover soil methanotrophic microbial populations to oxidize all of the methane generated from within a landfill and, in addition, to oxidize methane diffusing into the soil from atmospheric sources (Bogner, et al, 1997). Manipulation of landfill cover soils to maximize their oxidation potential and development of "bioactive" covers could thus comprise an essential component of any strategy aimed at controlling landfill methane emissions, especially at old sites lacking active gas extraction systems or where gas production rates are low and do not warrant installation of an active system.

The stoichiometry of methane oxidation under differing landfill cover soil conditions, and the design and performance of biocovers and other biologically active gas treatment systems, is exhaustively discussed by Boeckx, et al (1996), Börjesson & Svensson (1997), Humer & Lechner (1999), Hilger, et al (1999), de Visscher (2001), Scheutz, et al (2003), Barlaz, et al (2004b), Gebert & Gröngröft (2005), Abichou, et al (2006a and 2006b), Dever, et al (2007), Gebert, et al (2007), Kjeldsen, et al (2008), Rachor, et al (2008), and Gamperling, et al (2008), among others. A state of the art review is provided by Scheutz, et al (2009). In brief, the methane oxidation capacity of a cover soil is dependent on the depth of oxygen penetration into the soil, soil moisture and nutrient status, soil organic content, temperature, the microbial populations present and their level of stress and competition with other soil organisms, in-situ methane concentrations, and pH. The transport of oxygen, moisture and nutrients into a landfill cover soil is in turn dependent on climatic factors and a number of physical properties of the soil such as soil compaction, density, porosity, tortuosity, and composition. All of the above help explain the observed seasonal and diurnal variations in landfill methane emissions. The extent of oxygen penetration into a cover soil also depends on whether or not active LFG extraction is taking place, as this will tend to draw oxygen into upper layers of the soil.

Recent studies on landfill methane oxidation show much higher rates of cap and cover material oxidation than the AP-42 default assumption of ten percent of uncontrolled methane. For example, based on review of 47 field studies conducted in a variety of soil types and landfill covers, SWICS (2009) reported mean oxidation rates ranged from 22 percent in clay soils to 55 percent in sandy soils. Oxidation rates in organic covers and other mixtures were reported at 38 and 30 percent, respectively. The overall mean fraction across all 47 studies was 35 percent with a standard error of 4 percent. Importantly, of all the determinations of methane oxidation reported, only four report values of 10 percent or less. These findings are consistent with previously reported field measured rates that ranged from 7 to 50 percent (Czepiel, et al, 1996) and 10 to 30 percent (Lubina, et al, 1997) and oxidation levels of up to 60 percent reported in laboratory studies (Hilger, et al, 1999).

In summary, although active gas collection systems may not capture 100 percent of produced methane, a well-designed cover has the ability to mitigate a significant proportion of the uncontrolled (i.e., residual) methane. The finding that more permeable and organic cover materials exhibit higher rates of oxidation as compared to low permeable clay covers is important, and is one reason that alternative (i.e., all-soil) final covers are becoming a favorable design alternative around the country. Careful design and operation of a landfill, especially in semi-arid and arid regions, is necessary for optimal oxidation rates to occur in cover soils. For example, as suggested by Chanton, et al (2009), a cover system can be designed to eliminate methane emissions by constructing a gas collection system and complementary soil barrier that limits the upward migration of methane to a range less than or equal to the oxidation capacity of the cover system. Such a cover system utilizes two distinct layers; a bottom barrier layer (typically clay) minimizes gas migration and an upper aerated, organic-rich layer functions as an oxidation medium. Where used in conjunction with active gas collection system, such cover designs can control up to 95% to 99% of residual methane emissions from a landfill. Soil earthen covers can be designed to meet or exceed cover performance equivalency requirements (including infiltration) as well as be effective at significantly reducing GHG emissions well beyond that achieved through gas collection alone.

B4.2.6 Carbon Sequestration in Landfills

Carbon sequestration is defined as the permanent removal of biogenic carbon (i.e., carbon of recent plant origin rather than the fossil carbon found in coal, natural gas, or oil) from the atmosphere – such sequestration therefore occurs in carbon sinks (IPCC, 2006). The nature of landfill gas emissions and extent of biodegradation that may be achieved in a landfill, combined with the quantity of carbon that is sequestered, are important factors in understanding the role landfills play with regard to managing GHG emissions.

Landfills as Carbon Sources: With regard to landfills' role as a GHG source, the relatively small volume of methane produced at modern landfills in the United States is highly regulated, with engineered collection and control systems designed and monitored to minimize the uncontrolled release of methane to the atmosphere. In addition to engineered controls of GHG emissions at landfills, studies have shown that even under conditions for enhanced anaerobic (without air) degradation, only 25 to 40 percent of landfill carbon, mainly readily biodegradable organic matter, is converted to biogas carbon in the form of methane and CO_2. Therefore, although landfills are potential sources of GHGs, uncontrolled GHG emissions from managed landfills are limited.

Landfills as Carbon Sinks: Building on the above discussion, the term carbon sequestration as applied to landfills refers to the portion of carbon in waste that does not degrade completely after disposal, but rather is permanently stored in a stable form that cannot degrade to produce methane or CO_2. Such carbon is found in the readily biodegradable organic components of MSW such as wood, paper, cardboard, green yard waste, and some food wastes. These readily biodegradable organics are mostly composed of cellulose and hemicelluloses (C&H), complex carbohydrates that form the main structural components of cells in all green plants. Limited conversion of C&H in landfills occurs relatively rapidly, typically over the course of a few decades. However, although C&H will decompose anaerobically to methane and CO_2, the complete decomposition of C&H within a landfill is not expected. In addition, many common components of the waste mass are wood-based, which contains lignin. Lignin is highly recalcitrant to anaerobic biodegradation under landfill conditions, and will not undergo any significant decomposition (Barlaz, 2006). This limited biodegradability, coupled with the fact that modern landfill designs isolate wastes from the environment using engineered containment systems (which further restrict anaerobic digestion from proceeding) and are required to capture and control methane, means that landfills are significantly increasing the net amount of organic carbon (measured as CO_2) that is permanently sequestered as biomass (Barlaz, et al, 2007).

Clearly, accounting for carbon storage in landfills can significantly offset GHG emissions from landfills. The Intergovernmental Panel on Climate Change (IPCC), USEPA, Oregon Climate Trust, and California Air Resources Board (CARB) all recognize that carbon storage in a landfill should be considered a sink when calculating potential carbon emissions. These organizations recognize that when biogenic waste is disposed in landfills and does not completely decompose, the carbon that remains is effectively removed from the global carbon cycle. For example, SWICS (2009) states:

"…the USEPA has published reports that evaluate carbon flows through landfills to estimate their net GHG emissions. The methodology the USEPA employed recognizes carbon storage in landfills. In these studies of MSW landfilling, the USEPA summed the GHG emissions from methane generation and transportation-related carbon dioxide emissions, and then subtracted carbon sequestration (treated as negative emissions).

Furthermore, the 2006 GHG emissions inventory published by the California Energy Commission (CEC) indicated that landfill disposal of urban wood waste and yard trimmings is a GHG sink. The report included only the categories of yard trimming and wood waste, and neglected sequestration from paper, boxes, yard waste, lumber, textiles, diapers, demolition, medical waste, sludge, and manure. In California, urban wood waste and yard trimmings represent only 16.4% of the total California waste stream and only 46% of sequestered carbon within landfills; therefore, restricting estimates of carbon storage to only these waste types produces an extremely low value of overall carbon storage for the total amount of waste disposed. Landfill sequestration estimate includes sequestration from paper, boxes, yard waste, lumber, textiles, diapers, demolition, medical waste, sludge, and manure.

CARB estimates the total carbon sequestration in landfill to be 4.94 million MTCE in 2005, which is 17.2 million metric tonnes carbon dioxide equivalent ($MMTCO_2E$). CARB estimates that GHG emissions from landfills were 5.62 $MMTCO_2E$ in 2004, much less than the value of the carbon stored in the landfill."

In summary of the above, carbon sequestration should be a part of the inventory of potential GHG emissions from landfills. Since carbon sequestration factors are typically not considered for landfills, the potential methane emissions from landfills are likely overestimated.

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Appendix C

POST-CLOSURE CARE AND LONG-TERM LANDFILL INTEGRITY

C1. OVERVIEW

C1.1 Factors Affecting Landfill Performance during Post-Closure Care

The performance of a landfill during and after post-closure care (PCC) is a function of many factors, including:

- Waste properties and degradation;
- Trends in leachate quality and quantity;
- Trends in landfill gas (LFG) generation rates and the potential for LFG migration;
- The landfill's containment system design and maintenance; and
- Site-specific geology, hydrogeology, and potential receptors.

Appendix A previously provided a summary of the substantial body of knowledge on leachate quality and quantity as it relates to predictability and long-term performance evaluation of closed municipal solid waste (MSW) landfills. Numerous studies were cited demonstrating that the degree of degradation of MSW in a closed landfill can be accurately characterized in terms of the quality and quantity of leachate and LFG produced by the landfill, and that degradation follows well-established trends.

The regulatory framework, coupled with the predictability of landfill processes and known longevity of Subtitle D containment systems (as discussed in Appendix B), require that PCC not be ended without demonstrating that HHE is protected. Appendix C describes how the discussion in Appendix A supports use of a performance-based approach to evaluate PCC. This appendix presents the technical and regulatory basis for using a performance-based approach to verify that landfills are unlikely to cause impacts to HHE over the long-term.

C1.2 <u>Organization of this Appendix</u>

The discussion is this appendix is focused on the following three main subject areas:

- Landfill performance during PCC;
- PCC monitoring systems; and
- Long-term integrity of landfills.

These three subjects are addressed in the following subsections of this appendix. In each subsection, a convenient green box provides an "at a glance" synopsis of salient technical issues, summarizing pertinent landfill behavioral characteristics and representing the state-of-the-practice for modern MSW landfill design and management, along with references for seminal supporting material from peer-reviewed research, journal articles, and operational practice. Thereafter, a brief summary of the body of knowledge in support of the synopsis is provided.

C2. LANDFILL PERFORMANCE DURING POST-CLOSURE CARE

C2.1 Technical Synopsis

- Modern landfills are designed and operated to contain liquids and LFG and are monitored and maintained during active operation and PCC to provide protection of HHE;
- A performance-based approach for evaluating the need for PCC has both a regulatory and technical basis and can be incorporated into a management approach that is protective of HHE for as long as required;
- Future concentrations of landfill gas and leachate constituents can be estimated and the potential for a landfill to impact HHE can be measured and quantified; and
- Monitoring can be used to demonstrate that making changes to PCC systems or activities results in acceptable outcomes, and thus confirm the decision to modify or end PCC.

Seminal Supporting References: USEPA, 1993; ITRC, 2003, 2006a and 2006b; EREF, 2006; Gibbons & Bull, 2006; Gibbons, et al., 2007.

C2.2 Summary of Supporting Body of Knowledge

It is a commonly held misconception that after the prescribed 30-year PCC period under Subtitle D has expired, an owner/operator would simply be allowed to stop providing any further care for the landfill. Another position commonly advocated is that an owner/operator be required to provide perpetual PCC at MSW landfills. Further, it has been suggested that this care would involve providing PCC for all elements of the landfill (i.e., the landfill cap, the leachate and LFG management systems, and groundwater monitoring system). This assumes that a prescriptive level of PCC will always be required, without evaluating actions taken to biodegrade the organic waste components (e.g., through bioreactor operations), efforts to evaluate landfill system data (e.g., LFG quality and production, leachate quality and production, waste settlement, etc.), and/or verification that these media have not caused impacts to HHE (Houlihan, et al., 2002).

It should be understood from the outset of any discussion on PCC that the Subtitle D solid waste regulations do not stipulate a fixed period for providing care; rather, the regulations require that monitoring and care activities continue until a demonstration can be made that it is technically appropriate to end PCC. Subtitle D regulations allow the state Director to reduce or terminate PCC at MSW landfills once it is demonstrated that the landfill does not present a threat to HHE at the point of exposure or, conversely, to extend PCC if needed (USEPA, 1993). In addition to the Subtitle D solid waste regulations, other state and local regulations (e.g. security, general liability management, property, custodial and property ownership ordinances, and/or deed restrictions) often preclude an owner/operator from changing or ending site care provisions unless it is demonstrably appropriate to do so. The main issue faced by the regulatory and regulated community therefore is how to make a technically defensible demonstration that PCC may be extended, reduced, or terminated.

Some States have begun implementing regulatory approaches to evaluate ending PCC in terms of waste stabilization (e.g., Florida Administrative Code, Chapter 62-701.620.1, Rule Workshop Draft August 2007; Wisconsin Administrative Code, Chapter NR 514.07(9), WDNR March 2007). These approaches have focused on development of landfill operations and management techniques to promote long-term threat reduction through enhanced waste degradation (i.e., enhanced organic stability) rather than reduced infiltration and leachate generation (i.e., containment and isolation). A number of such proactive landfill operations approaches (e.g., leachate recirculation, alternative covers) are available to optimize the moisture content necessary for enhanced waste degradation while effectively managing leachate and LFG generation until the landfill no longer represents a threat at the point of exposure (ITRC, 2003 and 2006a).

Building on the above but going a step further to include all landfill operational conditions, a performance-based approach focuses PCC obligations on actual landfill conditions and defines when the end of regulatory PCC is appropriate for site-specific conditions, potential threats to HHE, and future use of the property. Performance-based approaches to evaluating PCC focus on identifying and quantifying the potential for a landfill to pose a threat to HHE at the point of exposure and evaluating the duration for which care is necessary. This type of evaluation generally involves examining statistical trends in leachate, LFG generation, and/or groundwater quality, as well as other relevant biological, chemical, and/or physical data, to predict future performance based on current or past trends. A number of key reference tools for making statistically valid, site-specific, performance-based assessments of PCC at MSW landfills have recently been developed through multi-year studies of PCC, including Gibbons & Bull (2006), ITRC (2006b), and EREF (2006). The fundamental approach, termed the *Evaluation of Post-Closure Care (EPCC) Methodology*, involves a series of evaluations that help an owner/operator assess the potential for impacts after PCC is modified or terminated. If an evaluation shows that no impacts are expected, then monitoring is recommended to confirm the conclusion. If, on the other hand, impacts are expected, then the owner/operator continues PCC until such time that impacts are not expected after PCC is ended. In this way, rather than relying on a determination that PCC is either complete or must be continued at the same level of intensity, the methodology evaluates each potential exposure mechanism and allows for the possibility that certain aspects of PCC could be discontinued while others are maintained. For example, it may be appropriate to discontinue or significantly lessen the frequency of leachate management or groundwater monitoring although, at the same time, it may be appropriate to continue cover inspections and maintenance.

C3. POST-CLOSURE CARE MONITORING SYSTEMS

C3.1 Technical Synopsis

- The processes that may result in impacts to HHE are well known and can be monitored for;
- PCC monitoring systems are established and continually appraised in accordance with strict technical and regulatory guidelines; and
- PCC monitoring can be performed as long as needed to verify that impacts to HHE have not occurred and will not likely occur.

Seminal Supporting References: USEPA, 1993 and 1996; Barlaz, et al., 2002; Bonaparte, et al., 2002.

C3.2 Summary of Supporting Body of Knowledge

As previously described, the duration of PCC can be evaluated using a performance-based evaluation such as the EPCC Methodology developed by EREF (2006) and advocated by ITRC (2006b). Under this methodology, for example, the technical basis for evaluating the duration of groundwater monitoring is that groundwater must be monitored for a sufficient period of time to detect an impacting release of leachate, if such a release has indeed occurred. The evaluation must demonstrate that there is no potential for leachate to impact groundwater at the point of compliance (POC) even under a 'worst-case' leachate release (i.e., assuming maximum/default concentrations). The approach also requires a site-specific time-of-travel calculation based on a conservative dilution factor (DF) or dilution/attenuation factor (DAF) calculation to estimate the time required to detect an impacting release. Based on this approach, PCC will continue as long as needed to detect an impacting release.

Groundwater monitoring systems at landfills are developed for the purpose of detecting a release and for protection of aquifers. The well locations and spacings are based on site-specific hydrogeologic investigations, and the monitoring programs are certified by a qualified groundwater scientist and approved by competent State regulators. Current regulations also require that the effectiveness of the groundwater monitoring systems be routinely evaluated. Further, an evaluation of the groundwater flow rates and direction must be performed to define the frequency of monitoring at each site. Therefore, the fundamental nature (e.g. design and operation) of groundwater monitoring systems at all landfills is focused solely on the early detection of a release from the permitted unit.

During the landfill design process, the fate of leachate in groundwater is evaluated based on advection, dispersion, sorption to the aquifer matrix, and biodegradation. The processes are evaluated using commonly available contaminant fate and transport models. Default DF and DAF values and methods for calculating site-specific values for use on sites with a variety of source contaminants are provided in the May 1996 USEPA guidance document EPA/540/R-95/128. A number of widely used and accepted computer models are available to assess groundwater fate and transport pathways. These include the USEPA's MULTIMED, which was specifically developed for evaluating the potential for groundwater impacts at Subtitle-D landfills and is recommended in Subtitle-D when developing a performance-based design (see USEPA document EPA530-R-93-017, "*Solid Waste Disposal Facility Criteria: Technical Manual*", Subpart D, Design Criteria). This approach allows landfill operators and regulators to consider the environmental performance of different landfill designs by assessing leakage from a landfill, attenuation in the unsaturated zone, and dilution and contaminant transport in the saturated zone.

Field data indicate leachate production rates of 0.5 to 20 gal/acre/day for landfills with a final cover, as well as an observation that leachate generation rates decreased to close to zero within ten years after final cover installation (as discussed in Section C4). Field data from operating landfills indicate LCRS efficiencies of 99 percent for liners built with good quality control, which suggests leachate release rates on the order of 0.1 gal/acre/day (Bonaparte, et al., 2002). Estimates based on the frequency of liner defects also suggest leachate release rates of less than 1 gal/acre/day. These data suggest that long-term leachate release rates are likely to be very low (Barlaz, et al., 2002).

C4. LONG-TERM INTEGRITY OF LANDFILLS

C4.1 Technical Synopsis

- Factors that can affect the integrity of a landfill during or after PCC are well understood and accounted for during the design of modern Subtitle-D landfills;
- Extremely few landfill failures have occurred, and those have occurred at operating landfills during construction or operation, not during or after PCC;
- There are no major failures at closed, modern landfills cited in the literature;
- Catastrophic events have not caused significant impacts to landfills; and
- Performance-based approaches for evaluation of PCC require that long-term integrity of the landfill be demonstrated before PCC can be ended.

Seminal Supporting References: Sowers, 1973; Landva & Clark, 1990; Singh & Murphy, 1990; Mitchell & Mitchell, 1993; Augello, et al, 1998; Kavazanjian, 2001; Bonaparte, et al, 2002; Bachus, et al, 2004; Hendron, 2006; Zekkos, et al, 2006; Blight, 2008.

C4.2 Summary of Supporting Body of Knowledge

Landfill integrity is a key focus for engineers during the design process. When evaluating the integrity of a landfill during or after PCC, it is important to consider the factors that could cause instability and the changes in those factors during and after PCC. The data from large-scale direct-shear tests conducted on waste recovered from bioreactor landfills (Kavazanjian, 2001), as well as laboratory testing and back-calculated shear strengths from landfills having highly degraded waste and zones of high liquid content (Isenberg, 2003), indicate that there is little to no difference between the strength for "dry" waste from conventional landfills and "wet" degraded waste from bioreactor landfills. When viewed in terms of effective stress, the drained shear strength of degraded waste (based on tests of waste from bioreactor landfills) is similar to values used in engineering practice today to characterize the strength of MSW. The high degree of saturation of the waste in some portions of closed landfills suggests that the undrained strength of the degraded waste in a landfill nearing the end of PCC is of greater engineering significance than in a conventional MSW landfill. Undrained strength is particularly important in seismic design and other cases of rapid loading (e.g. rapid waste placement or waste excavation). Studies by Kavazanjian, et al. (2000) and USEPA (1995) show that well-designed landfills are resistant to damage resulting from seismic events. Further, post-closure stability is improved by the fact that, after steady-state leachate and landfill gas conditions are achieved in the landfill (as demonstrated through PCC monitoring), driving forces decrease and resisting forces increase as a result of waste and foundation settlement.

A review of the literature shows that the number of landfill failures that have occurred have been extremely small compared to the number of landfills, and no significant failures are known to have been reported at landfills that have been closed or that have exited PCC. Several publications describe landfill failures and the causes of the failures, including Kavazanjian, et. al. (2001), Merry, et al. (2000), Mitchell & Mitchell (1993), Bonaparte, et al. (2002), and Hendron (2006). These references describe conditions in landfills that experienced liner or cover system instability. The few significant landfill stability problems reported resulted from severely inadequate operations or from poor construction practices. In contrast, the vast majority of the referenced issues involved minor stability problems that were addressed in the normal course of operations without resulting in any adverse environmental impact, demonstrating the fact that most stability issues occur during construction or operations and are mitigated. None of the referenced failures occurred at closed landfills or landfills that had been released from PCC.

Recently, Blight (2008) performed a global study of six large-scale failures of municipal solid waste dumps and landfills that have been recorded in the technical literature between 1977 and 2005. Of the six failures studied, four – Sarajevo in the former Yugoslavia (1977), Istanbul, Turkey (1993), Quezon City, Phillippines (2000), and Bandung, Indonesia (2005) – occurred in largely unregulated dumps that, as far as is known, had not been subjected to any prior technical investigation of their geotechnical stability. The remaining two failures occurred in engineer-designed landfills. In the first case (Doña Juana Landfill in Bogota, Colombia, 1997), leachate recirculation was practiced at an aggressive rate, but the effects of elevated moisture conditions and high injection pressures on landfill stability had not been the subject of rigourous engineering analysis. The leachate management system was also inadequately designed and the landfill was not operated in accordance with safe procedures for reinjection of leachate. In the second case (Bulbul Landfill in Durban, South Africa, 1997), co-disposal of liquid waste along with solid waste was permitted, but the engineer-designed drainage provisions had been omitted and the landfill constructed without professional oversight involving the design engineer. This record supports the conclusion that failures are the rare exception, not the rule, in landfill performance, and are essentially unknown at modern managed MSW landfill facilities that are designed, constructed, and operated in adherence with regulatory and professional oversight.

Studies on the performance of landfills during catastrophic events suggest that landfills are highly resistant to damage from such events. Studies performed after recent disasters including hurricanes (such as the Florida hurricanes of 2004; see for example Roberts, et al., 2005), earthquakes (such as the Northridge and Loma Prieta earthquakes in California; see Matasovic & Kavazanjian, 1998), and fires (such as the San Diego wildfires of 2003) show that the long-term environmental protection systems of the landfills had not been compromised and that the only damage that occurred was to surface features (e.g., vegetation and LFG vents) that were repaired at reasonably small cost and level of effort. This documented information shows that landfill contaminated systems have a high degree of resistance to damage from severe natural events.

In conclusion, contention that major landfill failures will occur after PCC ends is unwarranted, because the causes of failure are understood and the landfill is evaluated for those causes before PCC is permitted to end. The literature cited above shows that the potential causes of failures are well known, that the factors influencing failure can be monitored, that remedies can be implemented to improve stability if needed, and that the factors determining stability improve over time at closed landfills that have a demonstrated trend of reduced LFG and leachate generation. The methodologies outlined by EREF (2006) and ITRC (2006b), for example, both require that such conditions be shown to exist before a landfill can exit permitted PCC.

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