United States Environmental Protection Agency

EPA/600/R-14/335| September 2014 | www.epa.gov/ord

Permitting of Landfill Bioreactor Operations: Ten Years after the RD&D Rule

Office of Research and Development

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Permitting of Landfill Bioreactor Operations: Ten Years after the RD&D Rule

U.S. Environmental Protection Agency
Office of Research and Development
Waste Management Branch, National Risk Management Research Laboratory
Cincinnati Ohio

Notice

This research was funded by the National Risk Management Research Laboratory (NRMRL) of the U.S. Environmental Protection Agency (EPA), Office of Research and Development (ORD) under the Sustainable and Healthy Communities Research Program. This report was prepared by Geosyntec Consultants of Columbia, Maryland under subcontract to RTI International of Research Triangle, North Carolina. Work was performed in accordance with the Performance Work Statement issued by ORD under Task Order #11 of EPA Contract EP-C-11-036.

Foreword

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

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

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

Cynthia Sonich-Mullin, Director
National Risk Management Research Laboratory

Table of Contents

List of Figures

List of Tables

List of Appendices

Abbreviations and Acronyms

ANPR	Advance Notice of Proposed Rulemaking (U.S. EPA)
ASTSWMO	Association of State and Territorial Solid Waste Management Officials
CRADA	Cooperative Research and Development Agreement (U.S. EPA)
EGC	exposed geomembrane cap
EPA	U.S. Environmental Protection Agency
FBDP	Florida Bioreactor Demonstration Project
Florida DEP	Florida Department of Environmental Protection
GHG	greenhouse gas
HFCs	hydrofluorocarbons
ITRC	Interstate Technology and Regulatory Council
Kentucky DEP	Kentucky Department for Environmental Protection
LandGEM	Landfill Gas Emissions Model
L	liter
LCS	leachate collection system
LFG	landfill gas
MACT	Maximum Achievable Control Technology
Mg	megagram (10^6 g)
MSW	municipal solid waste
NESHAP	National Emission Standards for Hazardous Air Pollutants
NRMRL	National Risk Management Research Laboratory (U.S. EPA)
NSPS	New Source Performance Standards
NSWMA	National Solid Waste Management Association
OLL	Outer Loop Landfill, Kentucky
ORD	Office of Research and Development (U.S. EPA)
PCC	post-closure care
Project XL	Project eXcellence in Leadership Pilot Program (U.S. EPA)
QAPP	Quality Assurance Project Plan
RCRA	Resource Conservation and Recovery Act
RD&D	Research, development, and demonstration
Rule	U.S. EPA RD&D Rule
SWANA	Solid Waste Association of North America
TCEQ	Texas Commission on Environmental Quality
Virginia DEQ	Virginia Department of Environmental Quality
Wisconsin DNR	Wisconsin Department of Natural Resources
WM	Waste Management, Inc.

Executive Summary

Municipal solid waste (MSW) landfills in the United States have conventionally been designed and operated under the containment principles described in Subtitle D of the Resource Conservation and Recovery Act (RCRA). Disposal of bulk free liquids is thus not permitted and low permeability final cover systems are required. This minimizes leachate and landfill gas (LFG) production and reduces the risk of groundwater and atmospheric pollution. Although it was known at the time that enhanced waste degradation can be effectively achieved by stimulating microbial activity through the controlled addition of moisture to the waste, the U.S. Environmental Protection Agency (EPA) considered that insufficient information was available to allow full-scale addition of outside liquids to MSW landfills to be permitted under the regulations. Concerns about the 'bathtub' effect (i.e., buildup of hydrostatic head on the liner due to the rates of infiltration and liquids addition outpacing leachate removal) also contributed to Subtitle D being focused on containment.

Since promulgation of Subtitle D in 1991, a growing number of landfill sites have practiced leachate recirculation as well as addition of bulk free liquids, generally under *ad hoc* state-level research and development programs (e.g., the Florida Bioreactor Demonstration Project) or site-specific permitting mechanisms administered in association with EPA (e.g., Project XL). The main premise behind bioreactor landfills is the controlled introduction of moisture into the solid waste mass to increase the waste degradation rate. This has a number of associated benefits, notably acceleration of short-term LFG generation, which increases opportunities for economically viable and beneficial utilization of methane in renewable energy options. Promotion of renewable energy options and control of greenhouse gases such as methane are keystones of EPA's Climate Action Plan. Bioreactor operations require increased levels of engineering design, operational control, and monitoring to safely achieve the benefits of accelerated LFG generation and meet EPA's goals for responsible waste management and climate change mitigation.

To formally promote innovative landfill technologies, including adoption of alternative cover systems and bioreactor technology, the EPA published the Research, Development, and Demonstration (RD&D) Permit Rule (the Rule) on 22 March 2004. The Rule allows Subtitle D landfills a variance option for adding bulk free liquids if a demonstration can be made that such a variance will not increase risk to human health and the environment relative to standard permit conditions for the landfill. RD&D permits can only be issued by the jurisdictional solid waste authority in approved states or on tribal lands as a site-specific federal rulemaking by the EPA (i.e., the Rule is not self-implementing and states are required to adopt the Rule and obtain EPA approval for their RD&D program in order to issue a RD&D permit). Although it is not required that states take this step (i.e., states may waive the option to issue RD&D permits), any state that does choose to adopt the Rule and issue RD&D permits must seek formal approval from EPA to do so. Additionally, states that had their own RD&D-like provisions in place at the time that EPA published the Rule are required to revise their regulations to address and be consistent with the Rule.

Ten years after promulgation of the Rule, this report describes the current status of Rule adoption and investigates issuance of RD&D permits at the state level. Major challenges and hurdles for adoption of the Rule are also identified, both in adoptive and non-adoptive states. For this report, the status of Rule adoption by a given state was established based on whether an announcement of such appeared in the Federal Register. Based on this criterion, by March 2009 (i.e., five years after Rule promulgation) only nine states had adopted the Rule and been approved by EPA or had applied for EPA approval. An RD&D permit was also approved for the Salt River Landfill on Salt River Pima-Maricopa Indian Community land within Arizona. Five years later in March 2014, a total of 16 states had adopted the Rule and had received approval from EPA to issue RD&D permits. The most recent adoptees of the Rule are Massachusetts and Oregon in January and April 2013, respectively.

One state (New Mexico) reported being approved, but formal confirmation of this was not found in the Federal Register. An explanation given by a state employee was that their adoption of the Rule was included in a package of new regulations submitted for approval by EPA and thus may not have appeared in a stand-alone announcement. In any case, no RD&D permitted projects currently exist in New Mexico. Six further states reported having adopted the Rule and applying for EPA approval, or being in the application process as of March 2014. However, this was independently confirmed by announcement in the Federal Register for only one state (Arizona).

As of March 2014, 27 states had not adopted the Rule, including 11 states with their own provisions for issuing exceptional permits that do not specifically match the EPA's RD&D requirements or reference the Rule. In this regard, it is noted that some states have interpreted the Subtitle D regulations to prohibit only the addition of bulk liquid wastes and not all liquid amendments to landfills. Therefore, some states permit landfills to operate as *de facto* bioreactors under state-specific beneficial use legislation. For example, Washington reportedly allows landfills to augment leachate recirculation with addition of clean water such as stormwater or groundwater. Further, three states (Maryland, South Carolina, and Texas) believe that they are legally entitled to issue RD&D permits without the need to specifically adopt or reference the Rule.

Prior to promulgation of the Rule, there were approximately 20 full-scale bioreactor projects in North America, including one in Canada. Of these, six were permitted by EPA (four Project XL sites and two projects listed separately under a cooperative research agreement at the Outer Loop Landfill in Kentucky). In March 2014, there were about 40 bioreactor projects reported, including 30 active RD&D projects in 11 approved states and one project on tribal lands. Wisconsin features the largest number of projects at 13, due primarily to the fact that landfill owners in the state must either eliminate landfill disposal of biodegradable materials or achieve the complete stabilization of deposited organic waste at MSW landfills within 40 years after closure. Most landfill operators have selected a bioreactor approach to attempt to achieve the latter goal.

In summary, only 16 of 50 states (32%) have currently adopted the Rule, with a further seven (14%) reportedly in the process of Rule adoption, meaning that development of RD&D permitting procedures that are consistent with EPA's requirements has not occurred in the majority of states. The predominant single reason cited for not adopting the Rule was lack of interest amongst landfill facilities in the state. Subtitle D and its state derivatives already allow leachate recirculation over prescriptive (i.e., minimum technology) liner systems, which is often the primary goal of site operators seeking to control leachate treatment costs. From a site owner/operator's perspective, therefore, the extra RD&D permitting needs, costs for operation, and data collection and annual reporting are a deterrent given insignificant market pressure or other economic incentives for accepting bulk commercial liquids.

Few technical concerns over site stability, environmental protection, or public safety were raised as issues against Rule adoption, which is a positive finding. Some frustration was expressed over the long lag time in the approval process following Rule adoption by states, but this generally appears misplaced. Although three states did wait over a year for approval, the average waiting time was only seven months, with four states waiting three months or less. In this regard, it is also noted that delays are common in almost all new permitting processes: applications based on familiar designs are easily approved while those based on innovative, complex designs are slowed by the unfamiliarity of permit reviewers. This works against innovation, as recognized by the Interstate Technology and Regulatory Council (ITRC), which is why ITRC, with the support of EPA, prepares guidance documents to assist permit reviewers deal with new technologies. Other reasons cited related to concerns over increased costs and the complexity of the permitting procedure for both state personnel and individual applicant sites. This again seems unwarranted as EPA has developed guidance to aid development of RD&D procedures. However, many states seemed unaware that this guidance and support was available.

1. Introduction

1.1 Overview and Terms of Reference

There are a growing number of landfill sites in the United States that are operating as bioreactors. The main premise behind bioreactor landfills is the introduction of moisture into the solid waste mass to increase the solid waste degradation rate. This has a number of associated benefits (Section 2.1.1), albeit at increased levels of operational monitoring and control (Section 2.1.2).

Municipal solid waste (MSW) landfills in the United States have conventionally been operated with the objective of minimizing the amount of moisture entering and retained in the waste. This landfill management approach hinders biological activity and leachate and landfill gas (LFG) production, which reduces the risk of groundwater and atmospheric pollution following the containment principles described in Subtitle D of the Resource Conservation and Recovery Act (RCRA) (Federal Register, 1991). The Subtitle D regulations codified under 40CFR Part 258 thus restrict disposal of bulk free liquids in MSW landfills and require low permeability final cover systems. To promote innovative landfill technologies, including adoption of alternative cover systems and bioreactor technology, on 22 March 2004 the U.S. Environmental Protection Agency (EPA) published the Research, Development, and Demonstration (RD&D) Permit Rule (the Rule) (Federal Register, 2004). The intent of the Rule is to further encourage innovative approaches within RCRA. Of interest to this report, the Rule allows Subtitle D landfills a variance option for adding bulk free liquids at a MSW landfill if a demonstration can be made that such a variance will not increase risk to human health and the environment relative to standard permit conditions for the landfill. RD&D permits can only be issued by the jurisdictional solid waste authority in approved states or on tribal lands as a site-specific federal rulemaking by the EPA (i.e., the Rule is not self-implementing and states are required to adopt the Rule and obtain EPA approval for their RD&D program in order to issue a RD&D permit).

1.2 Definitions

Research and practice have resulted in several different definitions of bioreactors. A broad inclusive definition encompassing this philosophy has been proposed by the Solid Waste Association of North America as (SWANA, 2003):

> *"Any permitted Subtitle D landfill or landfill cell where liquid or air is injected in a controlled fashion into the waste mass in order to accelerate or enhance biostabilization of waste".*

Building on such definitions, the general terms "wet," "leachate recirculation," or "bioreactor" are often used rather interchangeably in technical and popular literature to describe any landfill operated under conditions of elevated in-situ moisture content. Certainly, recirculating the leachate generated from a landfill is a primary and fundamental attribute of all bioreactor operations. However, not all leachate recirculation facilities can be described as bioreactors, particularly as this practice is often employed for cost-effective onsite leachate management rather than with the intention of enhanced biodegradation. Similarly, wet landfills include several pre-Subtitle D units with soil covers in humid regions. A notable example is the Delaware Solid Waste Authority's Area A/B at the Central Solid Waste Management Center in Sandtown, Delaware, which was operated from 1980-1988. Very high rates of waste stabilization that meet many bioreactor objectives have occurred at this unit, although the most significant source of water for in-situ biodegradation was infiltration through the soil cover rather than leachate recirculation (Morris et al., 2003).

Given the focus of this report, which is the extent of bioreactor permitting under the Rule, leachate recirculation sites operated fully within Subtitle D and other wet landfills are excluded as these would not require an RD&D permit. In this report, the term bioreactor is thus used to refer only to MSW landfills at which the addition of bulk free liquids is permitted in addition to recirculation of leachate and LFG condensate with the primary goal of enhancing anaerobic waste degradation. Bulk free liquids may be from offsite sources as well as onsite sources such as stormwater. This definition is in keeping with EPA's original definition of bioreactors (cit. in ITRC, 2006) as:

> *"Landfills where controlled addition of non-hazardous liquid wastes or water accelerates the decomposition of waste and landfill gas generation"*

However, it should be noted this definition is deliberately more inclusive than EPA's stricter definition of a bioreactor in 40CFR Part 63 Subpart AAAA in the context of the National Emission Standards for Hazardous Air Pollutants (NESHAP) for MSW landfills (Federal Register, 2003), which specifies that a bioreactor is "a MSW landfill or portion of a MSW landfill where any liquid other than leachate [and LFG condensate] is added in a controlled fashion into the waste mass…to reach a minimum average moisture content of at least 40 percent by weight…"

1.3 Objectives

RD&D permits can only be issued by the jurisdictional solid waste authority in each state or on tribal lands as a site-specific rulemaking by the EPA. States are required to adopt the Rule before being approved by EPA to issue RD&D permits, including states that had their own RD&D-like provisions in place at the time that EPA published the Rule.

The primary purpose of this report is to describe the current status of Rule adoption and issuance of RD&D permits at the state level. Specifically, the following objectives are addressed:

- Ascertain which states have and have not adopted the Rule;
- Identify major challenges and hurdles for adoption of the Rule, both in adoptive and non-adoptive states;
- Estimate the number of permitted bioreactor projects in states that have adopted the Rule; and
- Outline the structure and contents of permit application documentation and operation and monitoring plans developed for projects successfully permitted in states that have adopted the Rule.

It is anticipated that by understanding the main challenges experienced by states in adopting of the Rule, EPA may incorporate lessons learned in future plans to modify or extend the Rule.

1.4 Data Collection and Analysis

1.4.1 Sources of Secondary Data

Published articles in peer-review journals as well as white papers and reports issued by federal and state agencies were considered of paramount value as secondary data sources for this report. Project summary reports by university faculty research teams and theses or dissertations prepared by graduate students were also highly valued. To provide the broadest possible coverage of secondary data sources (e.g., databases, conference papers and presentations, manuals, white papers, position statements, surveys, and reports) within the scope and timeframe available, web searches of the following were also conducted:

- Selected federal and state government agencies;
- Industry organizations and professional societies such as the Solid Waste Association of North America (SWANA) and National Solid Waste Management Association (NSWMA);
- Regulatory associations such as the Association of State and Territorial Solid Waste Management Officials (ASTSWMO) and Interstate Technology and Regulatory Council (ITRC);
- Industry and trade magazines such as MSW Management, Waste Management World, Waste 360, and Waste Business Journal;
- State and local popular press; and
- Private and public solid waste management operators.

Discussions with regulators, landfill operators, consultants, and industry associations were conducted where possible to obtain more details regarding information from secondary sources. This involved communication with personnel at state environmental agencies with regulatory oversight responsibilities for solid waste permitting.

1.4.2 Data Validation and Analysis

Collection and review of secondary data from published sources and interviews was performed in accordance with the quality assurance project plan (QAPP) for development of this report. The QAPP was developed by RTI International according to guidance provided in the EPA's National Risk Management Research Laboratory (NRMRL) adhering to quality assurance requirements for secondary data projects (U.S. EPA, 2008). The QAPP was approved by EPA prior to the initiation of data gathering. Given that a secondary data project involves the examination of existing environmental data for purposes other than those for which they were originally collected, the primary focus of the QAPP was to ensure that the environmental and related data compiled for reference or use on this project are complete, accurate, and of the type, quantity, and quality required for their intended use.

2. Technical and Regulatory Background

2.1 Overview of Bioreactor Technology

Experience has shown that enhanced waste degradation can be effectively achieved by stimulating microbial activity through the controlled addition of moisture to the waste via leachate recirculation and addition of supplemental liquids (Reinhart et al., 2002). Although this was known at the time of promulgation of Subtitle D based on the results of laboratory and pilot-scale simulations (e.g., Pohland, 1975a; Ham & Barlaz, 1987), EPA considered that insufficient information was available to allow full-scale addition of outside liquids to MSW landfills to be permitted under the regulations (Federal Register, 1991). Concerns about the 'bathtub' effect (i.e., buildup of hydrostatic head on the liner due to the rates of infiltration and liquids addition outpacing leachate removal) also contributed to Subtitle D being focused on design and operation of landfills with the explicit objective of minimizing the amount of moisture entering and retained in the waste (U.S. EPA, 1993). As a result, conventional Subtitle D landfills are commonly termed "dry tomb" landfills. However, Since the 1990s, a growing number of landfill sites in the United States have practiced leachate recirculation as well as addition of bulk free liquids (SWANA, 2009).

Detailed description of bioreactor design and operation is beyond the scope of this report. In brief, there are generally three types of bioreactor landfill operations (ITRC, 2006; SWANA, 2009):

- Anaerobic bioreactor: Only moisture is added to the waste mass, which maintains an oxygen depleted environment. Elevated moisture conditions encourage microbial decomposition of waste, leading to enhanced methane generation.
- Aerobic bioreactor: Air and liquids are simultaneously injected into the waste mass to promote rapid aerobic microbial activity and accelerate waste decomposition. In a process similar to composting, this generates significant heat as well as carbon dioxide and water vapor.
- Hybrid bioreactor: Both anaerobic and aerobic methods are employed sequentially, aerating waste in the upper portion of the landfill to enhance degradation while collecting LFG from the lower portion. Hybrid bioreactor landfills generate methane earlier than strictly anaerobic bioreactor landfills, and thus require earlier installation and operation of gas collection systems.

Anaerobic bioreactors are predominant and thus of most interest to this report. In all cases, leachate is removed from the bottom of the waste and re-injected into the landfill at a higher elevation in a controlled manner, often supplemented by the addition of uncontaminated water, wastewater sludge, or other non-hazardous liquids to enhance microbial decomposition.

Bioreactor designs can be implemented "as-built" (i.e., designed from the initial landfill planning process to be bioreactors, giving the advantage of construction and operation while waste is actively deposited) or "retrofit" (i.e., built as traditional MSW landfills, with bioreactor technology implemented once the landfill nears or reaches capacity). As-built designs allow for airspace recovery while the landfill is still active and afford more options for liquid application methods and infrastructure.

In the U.S., Waste Management, Inc. (WM) and Veolia have the most operational experience with full-scale bioreactors. Hater (2007) lists 15 active or former bioreactor sites operated by WM, while a survey by SWANA (2009) reported that Veolia operated seven active bioreactors, although sale of the company in 2012 may have affected these operations. WM has used several different methods and has experimented with full-scale leachate, liquid sludge, and outside commercial liquids addition using various techniques for application to the working face or surface of landfills, in horizontal and vertical trenches, to infiltration blankets or galleries, and bermed surface infiltration galleries (Hater, 2005). Horizontal and vertical wells performed least favorably in WM's experience, with primary issues being related to their short service lives and high failure rate. For example, Hater (2007) reported that 30 percent of horizontal wells become watered out and unusable each year. Spraying leachate at the working face has generally been found to be the most effective method of evenly distributing leachate into the waste mass (Mandeville, 2006). This method now serves as the "method of choice" for many bioreactor operators, including WM.

2.1.1 Bioreactor Benefits

Pioneering work on the benefits of anaerobic bioreactor technology and leachate recirculation was initiated in the U.S. in the 1970s and 1980s by research teams at the University of Wisconsin, Madison (e.g., Ham & Bookter, 1982; Barlaz et al., 1987) and Georgia Institute of Technology, Atlanta (e.g., Pohland, 1975b; Pohland & Harper, 1986). Since then, several studies have been conducted to assess the effect of waste moisture content on the rate of waste degradation and stabilization, LFG generation, and leachate quality (e.g., Barlaz et al., 1992; Miller and Emge 1997; Norstrom et al., 2001; Mehta et al., 2002; Sponza and Agdag, 2004; Bareither et al., 2012). Promoting in-situ degradation through liquid addition to landfills offers the following primary benefits (Reinhart and Townsend, 1998; Sullivan and Stege, 2000; Haskell and Cochrane, 2001; Barlaz et al., 2002; Reinhart et al., 2005a; Berge et al., 2009):

- Acceleration of LFG generation, thereby increasing opportunities for economically viable and beneficial energy utilization options, increasing the period over which capture of LFG (i.e., control of greenhouse gas and other air emissions) is technically and economically feasible, and more rapid exhaustion of long-term LFG generation potential, potentially limiting the post-closure period required for LFG control;
- Elimination/minimization of leachate treatment and offsite disposal, thereby reducing the load on public wastewater treatment facilities;
- More rapid reduction in concentrations of many leachate constituents of concern, potentially limiting the post-closure period required for leachate control; and
- An increase in the rate of landfill settlement and airspace reclamation, thereby promoting efficient utilization of permitted landfill capacity.

Reducing the impact potential of leachate and LFG emissions after closure of the landfill is likely to offer many long-term benefits, including reductions in the scope, duration, and costs of post-closure care (PCC) and enhanced opportunities for beneficial reuse of the landfill property (Morris and Barlaz, 2011).

2.1.2 Potential Challenges of Bioreactor Operation

Key to the ability to implement bioreactor operations are availability of liquids, a significant limiting factor where insufficient onsite sources are available. Thereafter, beyond the administrative complexities, uncertainties, and potential confusion over regulations to permit bioreactors investigated for this report, a number of potential challenges are associated with use of the technology. These include (ITRC, 2006; SWANA, 2009):

- Increased engineering design requirements and more complex construction;
- Higher capital costs and increased operating and monitoring obligations and costs;

- Higher levels of oversight and operator skill due to increased complexity of conducting day-to-day operations;
- Issues with temperature control, particularly in aerobic bioreactors;
- Geotechnical stability issues and lateral leachate seeps; and
- Increased LFG collection and control obligation and challenges, particularly with regard to control of odors and fugitive methane emissions from accelerated onset of gas production.

Of primary technical concern is that buildup of saturated conditions and rapid waste settlement as a consequence of accelerated waste decomposition could compromise the structural stability of the waste mass if not accounted for and managed properly (Bachus et al., 2004). In addition, moisture addition may contribute to the physical instability of the waste, which could result in localized side slope failures and damage to LFG collection wells and pipes or the liquid delivery system.

2.2 Summary of Current Bioreactor Regulations

2.2.1 The Rule in the Context of RCRA Subtitle D (40CFR Part 258)

As introduced previously, the EPA published the Rule in 2004 to promote innovative landfill technologies in the U.S. In proposing the Rule in 2002, the preamble in the Federal Register notes EPA's desire "to allow permits for alternative design and operating requirements because EPA has become aware of new or improved technologies for landfill operations and design since promulgation of the criteria for Subtitle D in 1991. These include: (1) improvements in liner system design and materials; (2) improvements in the design of, and materials used in leachate drainage and recirculation systems; (3) new processes for more rapid degradation of waste which require the addition of water; (4) new liquid distribution techniques…; and (5) improvements in various monitoring devices... As a result, the approved States would have flexibility in allowing the operation of new and innovative technologies in permitting the landfilling of municipal solid waste. The State and the owner/operator must assure there is no increased risk to human health and the environment when instituting any of the new techniques or processes which would be allowed. . ."

The liquids addition provision of the Rule, which is codified under 40CFR § 258.4, is the basis of allowing bioreactor landfills. Without this provision, 40CFR § 258.28 limits liquids placed in MSW landfills to LFG condensate and leachate derived from the same landfill unit. The Rule thus allows landfills to apply for a variance under a RD&D permit; however, the landfill owner/operator must, at a minimum:

- Demonstrate compliance with groundwater protection requirements;
- Implement LFG collection and control sooner than currently required under EPA's New Source Performance Standards (NSPS) (Federal Register, 1996);
- Have a LCS capable of limiting head on liner to less than 30 cm, even under conditions of elevated moisture content encouraged by liquids addition; and
- Address the risk of geotechnical instability that liquids addition may encourage.

RD&D permits can only be issued by the jurisdictional solid waste authority in each state or on tribal lands as a site-specific rulemaking by the EPA. States are required to adopt the Rule before being approved by EPA to issue RD&D permits. RD&D permits are issued for three years, each with the option for three renewals allowing a total of 12 permitted years of operation. Further details regarding final provisions of the Rule, major issues raised in comments and responses, and supplementary information regarding the process of Rule implementation at the state and tribal level can be found at http://www.epa.gov/osw/nonhaz/municipal/landfill/mswlficr/rdd-pre.pdf.

2.2.2 NESHAP for MSW Landfills (40CFR Part 63 Subpart AAAA)

In 2003, EPA issued its final rule on National Emissions Standards for Hazardous Air Pollutants (NESHAP) for MSW landfills, which define bioreactors as MSW landfills that utilize liquids other than leachate and gas condensate to achieve an average moisture content of more than 40 percent on a wet weight basis. Under the Maximum Achievable Control Technology (MACT) regulations, landfills defined as bioreactors under NESHAP with a total disposal capacity equal to or greater than 2.5×10^6 Mg are required to include a system to actively collect and control LFG that will commence operation within 180 days after liquids addition or after the average landfill moisture content reaches 40 percent, whichever occurs later (Federal Register, 2003).

It is noted that as part of the President's Climate Action Plan (see Section 2.6) and strategy to reduce GHG emissions, EPA is updating air standards for landfills. On 30 June 2014, EPA issued an Advance Notice of Proposed Rulemaking (ANPR) seeking broad public input on whether and how to update current emissions guidelines for existing MSW landfills to further reduce their emissions, including methane. Alternative thresholds and timelines will be considered for conventional and wet landfills, including for bioreactor landfills applying outside liquids. Further details on the scope of the ANPR are available at http://www.epa.gov/ttn/atw/landfill/landflpg.html.

2.3 Precursors to the Rule

In publishing the Rule in 2004, the EPA was able to draw on experience gained from permitting approaches employed at a number of bioreactor demonstration projects. The most important of these, which allowed as-built and retroactive implementation of leachate recirculation and bioreactor technology at full-scale operating landfill sites in the U.S., are outlined in this section.

2.3.1 Project XL

EPA's Project XL (eXcellence in Leadership) was established in 1995 as a national-level pilot program allowing limited regulatory flexibility for businesses, state and local governments, and federal facilities for research and development initiatives contributing to superior environmental performance and public health protection. The information and lessons learned from Project XL were intended to assist EPA in redesigning its regulatory and policy-setting approaches. For the case of MSW landfills, Project XL allowed for leachate, as well as other industrial liquids, to be added to Subtitle D landfills that do not meet the composite liner criterion. In turn, the designers of the Project XL landfill bioreactors hoped that the leachate recirculation/LFG recovery requirements would enhance groundwater protection and provide for additional capacity to accommodate more waste at individual landfills, thus extending the life of existing landfill cells.

Unfortunately, because of difficulty in obtaining a Project XL landfill bioreactor permit, only four landfill pilot projects were approved to operate as pilot bioreactor projects before EPA ceased accepting Project XL proposals in 2003. The four landfills permitted under this effort were:

- Buncombe County Landfill, North Carolina: In this permit, Buncombe County General Services Department primarily sought regulatory flexibility to recirculate leachate over MSW landfill units constructed with an alternative liner system to the prescriptive Subtitle D liner.

- Maplewood Landfill, Virginia: Similar to Buncombe County, the landfill operator WM primarily sought regulatory flexibility in this permit to recirculate leachate over MSW landfill units constructed with an alternative liner system.

- King George County Landfill, Virginia: Under this permit, WM requested flexibility from the requirement under 40CFR §258.28 prohibiting application of outside bulk liquids in MSW landfills. An important research goal was to compare the performance of the King George County and Maplewood Landfills in order to examine the costs and benefits associated with operating a leachate recirculation system versus a bioreactor system.

- Yolo County Bioreactor Landfill, California: Yolo County requested to operate a controlled bioreactor landfill over part of their landfill and sought regulatory flexibility from the requirement under 40CFR §258.28 prohibiting application of outside bulk liquids and flexibility on other restrictions regarding landfill cover and containment. Yolo County also requested flexibility in state regulatory requirements for bottom linings based on project performance.

Further details on the specific goals and technical approach employed for each program can be found at http://www.epa.gov/osw/nonhaz/municipal/landfill/bioreactors.htm#xl. It should be noted here for completeness that, as reported in the second interim report for the Outer Loop Landfill (U.S. EPA, 2006), a fifth Project XL agreement was signed in December 2000 for a bioreactor demonstration project at the Millersville Landfill operated by Anne Arundel County, Maryland. However, this agreement was not fully executed and a bioreactor project was never initiated at the site.

Permitting under the Project XL program was reported to be complex and time-consuming. For example, the two Virginia landfills required a state-specific RD&D permit under the Virginia Department of Environmental Quality's (DEQ's) solid waste regulations in parallel with the federal Project XL permit issued in 2002, with permit renewal required every three years (Mandeville et al., 2005).

To date, all Project XL programs have been terminated. Bioreactor operations at King George Landfill have been fully suspended. Since 2011 leachate recirculation at Maplewood has been permitted solely under a RD&D permit issued by Virginia DEQ. Similarly, the Yolo County Landfill remains an active bioreactor under a California RD&D permit. Leachate recirculation continues at the Buncombe County Landfill under a state permit, although North Carolina has not adopted the Rule.

2.3.2 Outer Loop Landfill, Kentucky

EPA's Office of Research and Development collaborated in research to evaluate innovative bioreactor technologies at the Outer Loop Landfill (OLL) in Louisville, Kentucky under a Cooperative Research and Development Agreement (CRADA) Number 0189-00 with WM between 2001 and 2010. The primary purpose of this multi-year joint research effort was to collect sufficient information to ascertain the best operating practices to promote the safe operation of bioreactor landfills. Six full-scale bioreactor cells (both as-built and retrofit) were monitored in the study, each with varying design and operating features including semi-aerobic (hybrid) bioreactors and facultative bioreactors, which use a technology that involves converting ammonia present in the leachate to nitrate ex-situ and adding the nitrated leachate back into the landfill where it is used by facultative microorganisms.

A seminal reference document was developed at the mid-stage of this project:

- Landfill Bioreactor Performance – Second Interim Report – Outer Loop Recycling and Disposal Facility, Louisville, Kentucky, EPA/600/R-07/060 (http://www.epa.gov/nrmrl/pubs/600r07060.html)

Since conclusion of the project, two peer-review journal papers have been published.

- Abichou, T., Barlaz, B.A., Green, R., Hater, G., 2013. The Outer Loop bioreactor: A case study of settlement monitoring and solids decomposition. *Waste Management, 33, 2035-47.*

  Synopsis: This paper reported on landfill settlement data from the OLL and compares settlement rates, strain, and modified compression indexes based on measurements from a conventional landfill control cell, as-built semi-aerobic bioreactor cell, and retrofit leachate recirculation cell. The objective was to summarize the results of settlement data and assess how these data relate to solids decomposition monitoring. The retrofit cell started to settle as soon as liquids were introduced. The cumulative settlement during the eight years of monitoring varied from 60 to 100 cm. These results suggest that liquid recirculation caused a 5–8% reduction in the thickness of the waste column. The average long-term settlement in the as-built and control cells was about 37% and 19%, respectively. The modified compression index was 0.17 for the control cell and 0.2–0.48 for the as-built cell. While the as-built cell exhibited greater settlement than the control, the data did not support biodegradation as the only explanation. The increased settlement in the as-built cell appeared to be associated with liquid movement and not with biodegradation because both chemical (biochemical methane potential) and physical (moisture content) indicators of decomposition were similar to the control. The solids data were consistent with the concept that bioreactor operations accelerate the rate of decomposition, but not necessarily the cumulative loss of anaerobically degradable solids.

- Abichou, T., Barlaz, B.A., Green, R., Hater, G., 2013. Liquid balance monitoring inside conventional, retrofit, and bioreactor landfill cells. *Waste Management, 33, 2006-14.*

  Synopsis: This paper reported on liquids balance monitoring at OLL based on measurements of initial and interim moisture content of waste samples, leachate and liquids addition and leachate removal, and estimated infiltration using the HELP model. This companion paper to the one above reported data from the same conventional landfill control cell, as-built semi-aerobic bioreactor cell, and retrofit leachate recirculation cell. During the monitoring period, the retrofit, control, and as-built cells received 48, 14, and 213 liters of liquids per metric ton of waste (L/Mg), respectively. The leachate collection system yielded 60, 57, and 198 L/Mg from each respective cell. The head on liner in all cells was below regulatory limits. In the control and as-built cells, leachate head on liner decreased once waste placement stopped. The measured moisture content of the waste samples was consistent with that calculated from the estimate of accumulated liquid by the liquid balance. Additionally, measurements on excavated solid waste samples revealed large spatial variability in waste moisture content. The degree of saturation in the control cell decreased from 85% to 75%. The degree of saturation increased from 82% to 83% due to liquids addition in the retrofit cell and decreased back to 80% once liquid addition ceased. In the as-built cell, the degree of saturation increased from 87% to 97% during filling activities and then started to decrease soon after filling activities ceased, rescinding to 92% by the end of the monitoring period. The measured leachate generation rates were used to estimate the saturated hydraulic conductivity of in-place waste in the range of 10-8 to 10-7 m/s, which is lower than reported in previous bioreactor studies. In the control and retrofit cells, the net loss in liquids, 43 and 12 L/Mg, respectively, was similar to the measured settlement of 15% and 5–8% strain, respectively, as reported in the paper above. The increase in net liquid volume in the as-built cell indicates that the 37% (average) measured settlement strain in these cells cannot be due to consolidation as the waste mass did not lose any moisture but rather suggests that settlement was attributable to lubrication of waste particle contacts, softening of flexible porous materials, and additional biological degradation.

2.3.3 Florida Bioreactor Demonstration Project

The Florida Bioreactor Demonstration Project (FBDP) at the New River Regional Landfill was supported under a grant from Florida Department of Environmental Protection (DEP) and operated between 1998 and 2008. The project featured vertical injection wells for both liquids and air injection, an exposed geomembrane cap (EGC), gas collection from below the EGC and the LCS, moisture and temperature instrumentation, and a segregated leachate collection system (Jain et al., 2005). The leachate recirculation system was installed after the landfill was filled. The wells were installed as clusters of three to assist in moisture distribution. Instrumentation allows the collection of in-situ measurements of parameters such as leachate head on the liner, waste moisture content, waste load, gas composition, and temperature of the waste. A full copy of the final report by the Hinkley Center for Solid and Hazardous Waste Management, dated December 2008, as well as the following two seminal references emanating from this project, can be downloaded at http://www.bioreactorlandfill.org/publications.html.

- Bioreactor landfill operation: A guide for development, implementation and monitoring, version 1.0, prepared by T. Townsend, D. Kumar and J. Ko for the Hinkley Center for Solid and Hazardous Waste Management, Gainesville, FL, dated July 2008.

  Synopsis: One of the specific project objectives for the FBDP was to develop standardized design and operation procedures for bioreactor technology. This document was produced to help meet this objective by providing information useful for landfill operators considering implementing bioreactor technology as well as those operating bioreactor landfills. However, this document was not specifically intended as a design resource. While regulations are mentioned, users are advised to consult appropriately regulatory agencies.

- Bioreactor landfill moisture management, prepared by D.R. Reinhart, T. Townsend, N. Gawande, P. Jain, P. Thomas and C. Ziess for the Urban Waste Management and Research Center, University of New Orleans, LA, dated July 2004.

  Synopsis: The presence and movement of moisture in landfilled solid waste play a major role in the rate of landfill stabilization. Instruments that can monitor the in situ moisture content of landfilled waste would be of great benefit to landfill operators, especially those at bioreactors. Two potential technologies were examined in this research: resistance based and time domain reflectometry (TDR) sensors. 135 resistance-based sensors and 12 TDR sensors were installed in a leachate recirculation well field at the FBDP. The resistance-based sensors were found to respond to an increase in moisture resulting from leachate recirculation. The initial spatial average moisture content determined by the sensor readings (using a laboratory-derived calibration) was 42% compared to 23% from gravimetric readings. This was attributed to the greater leachate conductivity values encountered in the landfill compared to that used in the calibration, inability of the MTG sensor to detect moisture contents below ~35%, and the potential for the sensors to intercept leachate flow from preferential paths. The TDR sensors were also found to respond to leachate recirculation. The moisture contents from the TDR sensors (obtained using laboratory-derived calibration) were compared to the moisture contents from the resistance-based sensors. The results showed that both technologies predicted transient moisture changes in the landfill. The heterogeneous nature of landfilled waste and its variable leachate electrical conductivity were observed to affect the calibration equations for both moisture measurement technologies. Moisture measurement devices have advantages over gravimetric moisture measurement techniques because of their less expensive manufacturing costs, ease in automation and ability to predict the transient moisture changes with time.

2.4 Seminal Publications

2.4.1 State of the Practice Reviews

Long-term studies have been conducted for EPA to evaluate the state-of-the-practice of bioreactor landfill technology in the U.S. The objectives were to provide EPA and the community of regulators, designers, owners, and operators with a thorough, unbiased evaluation of data from operating bioreactor landfills. Factors such as regional (climatic) distribution, design history (new vs. retrofit), public vs. private operation, and operational strategy (recirculation vs. liquid addition, anaerobic vs. aerobic, etc.) were considered when selecting the sites to maximize the diversity of the selected landfills and data sets.

The first study (Benson et al., 2007) was conducted in 2002 and included six landfills (five in the U.S. and one in Canada). The second, more comprehensive study was conducted in 2005-2008 and included five bioreactor landfills in the U.S. (Bareither et al., 2010; Barlaz et al., 2010). In summary, this study showed that:

- Bioreactor landfills operate and function in much the same manner as conventional landfills, with designs similar to established standards for waste containment facilities;
- Leachate generation rates, leachate depths, leachate temperatures, and liner temperatures, are essentially the same in bioreactor and conventional landfills; and
- The integrity and performance of landfill containment systems have not been observed to be affected by liquids addition such that leakage rates though liners beneath bioreactor landfills are comparable to those for conventional landfills.

However, analysis of leachate quality data showed that bioreactors generally produce more concentrated leachate than conventional landfills during the first two to three years of recirculation. Comparison of rates of recirculation to a previous study conducted in 2002 showed that higher rates are effective at degrading waste, enhancing methane production, and accelerating waste settlement. Based on findings, recommendations were made for rate coefficients used for predicting gas generation from bioreactor landfills and compression parameters for settlement of waste for various levels of leachate recirculation.

2.4.2 Textbooks and Guidance Documents

A number of textbooks and guidance documents have been developed to provide recommendations for design, permitting, operation, performance, and monitoring of bioreactors and leachate recirculation systems.

- Pohland F.G., 1975. Sanitary landfill stabilization with leachate recycle and residual treatment, EPA-600/2-75-043. Prepared for U.S. EPA Office of Research and Development, Cincinnati, OH.

- Reinhart D.R. and Townsend T.G., 1998. Landfill bioreactor design and operation. Lewis Publishers, New York, NY.
- Reinhart D.R., 1998. Prediction and measurement of leachate head on landfill liners. Florida Center for Solid and Hazardous Waste Management, Report #98–3, Gainesville, FL.
- United States Environmental Protection Agency, 2004. Monitoring approaches for landfill bioreactors, EPA/600/R-04/301. Prepared by Tolaymat T., Kremer F., Carson D. and Davis-Hoover W. for Office of Research and Development, Cincinnati, OH.
- United States Environmental Protection Agency, 2005. Example moisture mass balance calculations for bioreactor landfills, EPA-456/R-05-004. Office of Air Quality Planning and Standards, Information Transfer and Program Integration Division. Research Triangle Park, NC.
- United States Environmental Protection Agency, 2005. First-order kinetic gas generation model parameters for wet landfills, EPA-600/R-05/072. Prepared by Reinhart D.R., Faour A.A. and You H. for Office of Research and Development, Cincinnati, OH.
- Interstate Technology and Regulatory Council, 2006. Technical and regulatory guidance for characterization, design, construction, and monitoring of bioreactor landfills, ALT-3. ITRC Alternative Landfill Technologies Team, Washington, DC.
- Townsend T.G., Jain P. and Tolaymat T.M., 2006. Liquids introduction design criteria for bioreactor landfills. Prepared for U.S. EPA Office of Research and Development, Cincinnati, OH (Draft).
- Vazquez R.V., 2008. Enhanced stabilization of municipal solid waste in bioreactor landfills. CRC Press/Balkema, Leiden, the Netherlands.
- Solid Waste Association of North America, 2009. The solid waste manager's guide to the bioreactor landfill – 2009 update. SWANA Applied Research Foundation, Silver Spring, MD.

2.5 Fundamentals of Bioreactor Design and Operation

2.5.1 Slope Stability Analysis

Liquids injection into bioreactor landfills can negatively affect landfill stability due to generation and distribution of excessive pore fluid pressures near side slopes (Bachus et al, 2004; Blight, 2008). When performing a slope stability analysis to address the flow of the introduced liquid through the waste, three issues must be considered:

- Increased weight of the waste compared to the weight of "dry" waste;
- The possibility of perched liquids, which would cause a localized build-up of pore-water pressure; and
- Liquid migration along a soil/MSW interface layer, which could break out on the face of the slope and induce a veneer stability failure.

A related stability issue involves the accelerated rate of LFG generation; if this gas is not collected, then gas pressure could build up within the waste mass and increase pore pressures, contributing to instability and increasing the potential for side slope seepage. The heterogeneous and anisotropic nature of MSW and the increased pore gas pressures caused by leachate recirculation must also be considered in stability analysis. Numerical two-phase flow models can be used to investigate the effects of heterogeneity and anisotropy on moisture distribution and pore water and capillary pressures and their resulting impacts on stability during liquids injection events (Giri & Reddy, 2014).

As noted by Bachus et al. (2004), the primary defense against instability is the use of sound design and operational practices. The primary design practice is to promote efficient and uniform distribution of the liquid and, concurrently, good LFG collection. Sufficient hydraulic connection between the liquids distribution system and the waste should be provided by constructing the system using high-permeability materials and by preventing continuous, low-permeability layers within the waste that could restrict downward flow of liquid through the landfill. The primary operational practice is monitoring of the landfill to confirm that liquids are not accumulating at levels that could lead to excessive pore pressures.

2.5.2 Design of Liquids Application Systems

Methods employed for leachate recirculation and liquids addition vary widely, as do their effectiveness, operational complexity, and requirements for dedicated infrastructure such as pipes, tanks, manifolds, and pumps. Methods commonly employed include:

- Direct application at the landfill working face, generally using a water truck fitted with a rear sprayer (Mandeville, 2006);
- Surface infiltration from open trenches, ponds, or shallow depressions (Hater, 2005);
- Subsurface infiltration from horizontal injection trenches (Jain et al., 2010a) or blankets (Khire and Haydar, 2005); and
- Subsurface infiltration from vertical wells or conduits (Jain et al., 2010b).

Surface application methods are limited more by operational and space constraints than design attributes. The key parameters for designing a horizontal source (e.g., horizontal trenches, infiltration ponds, infiltration galleries, or blankets) for steady state are the rate liquids can be added, the lateral and vertical extents of the zone of impact, and the volume of liquid needed to wet the waste within the zone of impact (Bachus et al., 2003). These parameters are functions of source dimensions, injection pressure, and MSW properties (e.g., porosity, hydraulic conductivity, and anisotropy). Site-specific or published data can be used to derive these parameters. Using principles of fluid flow in porous media, models such as SEEP/W can be used simulate liquids flow under steady state conditions from a horizontal source (Haydar & Khire, 2005), or design charts such as those presented by Jain et al. (2010a) can be used to design a liquid introduction system within the range of expected conditions. Similarly, the rate at which liquids can be added to a vertical well, the lateral zone of impact of the well, and the liquids volume needed to wet the waste within the zone of impact of the well are the key inputs needed to design a vertical well system. Again, models such as SEEP/W or design charts (Jain et al., 2010b) can be used to estimate these inputs as a function of MSW properties, well dimensions (radius and screen length), and injection pressure.

Design methodologies for combined systems of liquid application and gas extraction have been developed (e.g., Eden, 1994) but have largely been abandoned due to high levels of clogging encountered in such systems.

2.5.3 Landfill Gas Collection System Design

The most widely used model for design of LFG collection systems is the EPA's Landfill Gas Emission Model (LandGEM), in which methane generation is modeled using a first-order decay equation (U.S.

EPA, 2005). Input factors include the methane generation potential, L_0 (generally expressed as m^3/Mg on a wet waste basis) and a first-order waste decay rate, *k* (per year). EPA presents default values for *k* (0.04/year or 0.02/year, depending on precipitation) and L_0 (100 m^3/Mg) in its AP-42 air emissions database (U.S. EPA, 1995). These values were derived from historical gas collection data and are used extensively in practice by regulators and engineers. Landfill owners also have the option to present a site-specific estimate for these values. However, only limited data have been published on *k* for bioreactor landfills.

Use of LandGEM for design of LFG collection systems at bioreactor landfills requires modified operation and input criteria to account for accelerated methane generation (Reinhart et al., 2005b). Recently, decay rates (*k* values) of 0.3/year and 0.11-0.21/year were estimated for landfills that were wet throughout and landfills that experienced some leachate recirculation, respectively (Faour et al., 2007). Based on data from the Outer Loop Landfill CRADA project, Tolaymat et al. (2010) utilized site-specific L_0 and methane production rate data collected over a four-year period to estimate *k* for conventional and bioreactor landfill cells. L_0 (volume of methane produced on a wet weight basis) was estimated at 48.4 m^3/Mg based on the biochemical methane potential of freshly buried refuse. The value of *k* for the conventional cells was estimated at 0.06/year from measured methane collection, which is comparable to the AP-42 default value of 0.04/year, whereas estimates for the two bioreactor cells were substantially higher at 0.11/year.

2.5.4 Performance Monitoring

To assess bioreactor performance, the characteristics and properties of LFG, leachate, and the waste mass can be monitored and evaluated (U.S. EPA, 2004). A brief description of useful monitoring parameters is presented below.

- Physical Parameters: This includes monitoring of the waste quantity and composition (type) disposed at the landfill, liquid added at the landfill, precipitation, and leachate generated. These parameters are necessary to perform a moisture balance evaluation of waste disposal units at the landfill.
- Leachate Monitoring: Leachate parameters can be used to help assess the extent of waste decomposition and stabilization. This includes leachate temperature, pH, volatile organic acids (VOA), chemical oxygen demand (COD), biological oxygen demand (BOD), ammonia, heavy metals, semi-volatile and volatile organic compounds (SVOCs and VOCs), cations and anions (e.g., chloride), and phosphate.
- Landfill Gas Monitoring: The LFG generation rate and methane composition can be monitored in order to provide an estimate of the rate of waste decomposition in the landfill. The rate of LFG generation, and the methane content of the LFG, can then be compared to either typical representative values for landfills in similar environments or, if available, site specific data based on spatial or temporal differences in liquid addition.
- Solid Waste Sampling: Sampling of either incoming waste or in-place waste can provide a direct measure of the waste properties and decomposition phase, in contrast to leachate and LFG monitoring. Waste samples can be analyzed for moisture content, biochemical methane potential (BMP), volatile solids, and cellulose/lignin content. However, in practice these measures have significant practical limitations in that the large spatial and temporal variability of the waste stream makes it difficult to determine how representative the samples are of the waste mass.

- Settlement Monitoring: Enhanced settlement is expected at a landfill operated with liquid addition, which can be assessed by whole-site surveys or measuring the vertical movement of settlement plates installed at different locations of the landfill.
- Geotechnical Stability Monitoring: Increased amounts of liquid in the waste and the resulting waste decomposition process may result in changes to the pore pressure and the waste properties such as density and shear strength. These parameters may affect the stability of waste slopes. Geotechnical stability monitoring may include visual inspections as well as physical monitoring such as settlement plates, piezometers, or inclinometers.

The fate of the liquid added to the waste mass is generally best analyzed by means of a simple water balance (Yuen et al., 2001). In this way, the amount of liquid added as part of an RD&D project can be compared to the amount of liquid from other sources (i.e., infiltration through the cover and incoming water held in the waste). The mechanisms of water removal (i.e., leachate collected and discharged in the LCS, water converted to methane or carbon dioxide and removed through the GCS, or discharge as water vapor or condensate removed through the GCS) can also be assessed and quantified, and the amount of added liquid can be compared to the remaining absorptive capacity of the waste mass.

A useful approach to quantifying the amount of water that should be added to the waste is to obtain a representative measure of the typical moisture content of incoming waste at the facility. Samples of in-place waste can be analyzed for moisture content to estimate the extent of wetting that is taking place in specific areas of the waste mass. The most efficient approach is to collect waste samples when new infrastructure (e.g., LFG extraction wells, horizontal collection trenches, etc.) is installed at the landfill. However, it is important to note that this approach has significant practical limitations in that the large spatial and temporal variability of the waste mass makes it difficult to determine how representative the samples are. More sophisticated approaches to monitoring moisture distribution in landfills have been developed, with varying degrees of success and wide distribution in costs. These include pressure transducers and electrical resistivity/impedance moisture sensors (Imhoff et al., 2007; Kumar et al., 2009), neutron probes and time domain reflectometry (Li & Zeiss, 2001; Staub et al., 2010), electrical resistivity tomography (Grellier et al., 2008; Clément et al., 2011), and partitioning gas tracer tests (Jung et al., 2012).

2.6 Bioreactors and Climate Change

President Obama's Climate Action Plan, which was released in a June 2013 Presidential Memorandum, outlines several broad-based measures to cut the carbon pollution that causes climate change and affects public health (Executive Office of the President, 2013). The plan provides a schedule for meeting the President's commitment to reduce U.S. greenhouse gas (GHG) emissions in the range of 17 percent below 2005 levels by 2020 by supporting renewable energy (which includes landfill gas to energy), establishing stricter fuel economy standards and limits on carbon emissions from power plants, promoting energy efficiency in homes and buildings, and reducing emissions of short-lived climate pollutants such as hydrofluorocarbons (HFCs), black carbon, and methane. Such pollutants are relatively short-lived in the atmosphere but have more potent greenhouse effects than carbon dioxide. With particular relevance to landfills, methane currently accounts for about 9% of U.S. GHG emissions; however, the U.S. has achieved notable reductions in methane emissions since 1990. Contributing to this reduction has been the enforcement of LFG collection standards for landfills under the NSPS regulations (Federal Register, 1996), and stricter standards under NESHAP (Federal Register, 2003) for bioreactors in which waste degradation and methane generation is accelerated. As previously discussed in Section 2.2.2, an ANPR was issued by EPA on 30 June 2014 to seek input on whether and how to update current emissions guidelines for landfills, including bioreactors.

The 2013 Presidential Memorandum serves as the basis for the U.S. EPA's climate action plan, which includes initiatives aimed at landfills such as the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollution, which has grown to include more than 30 partner countries and other key partners such as the World Bank and the U.N. Environment Program, and the Global Methane Initiative, which works with 42 partner countries and an extensive network of over 1,100 private sector participants to reduce methane emissions. These initiatives facilitate technology transfer and allow lessons learned from control and utilization of methane from landfills and bioreactor sites in the U.S. to be applied worldwide.

3. Status of Rule Adoption by States

3.1 Historical Context

The early uptake rate of Rule adoption and status of other state RD&D statutes that predate the Rule are best summarized in a comprehensive survey by Gardner (2006), which reported that only eight states had adopted the Rule and had applied for EPA approval or had already been approved (Figure 3-1). A further six states were reported to be in the process of adopting the Rule. Three states indicated that their programs were already consistent with the Rule and that they did not plan on seeking separate EPA approval as they were not legally compelled to do so in order to issue an RD&D permit, while a further seven states indicated they had no intention of adopting the Rule. Of the remaining 26 states, 13 had not initiated the process of Rule adoption, including six states (e.g., Colorado, New Jersey, and New York) that were reported to have RD&D programs within their current solid waste regulations. In most cases, however, these programs were not entirely consistent with the Rule. The exact status of Rule adoption was reported as uncertain for the remaining 13 states (shown white in Figure 3-1).

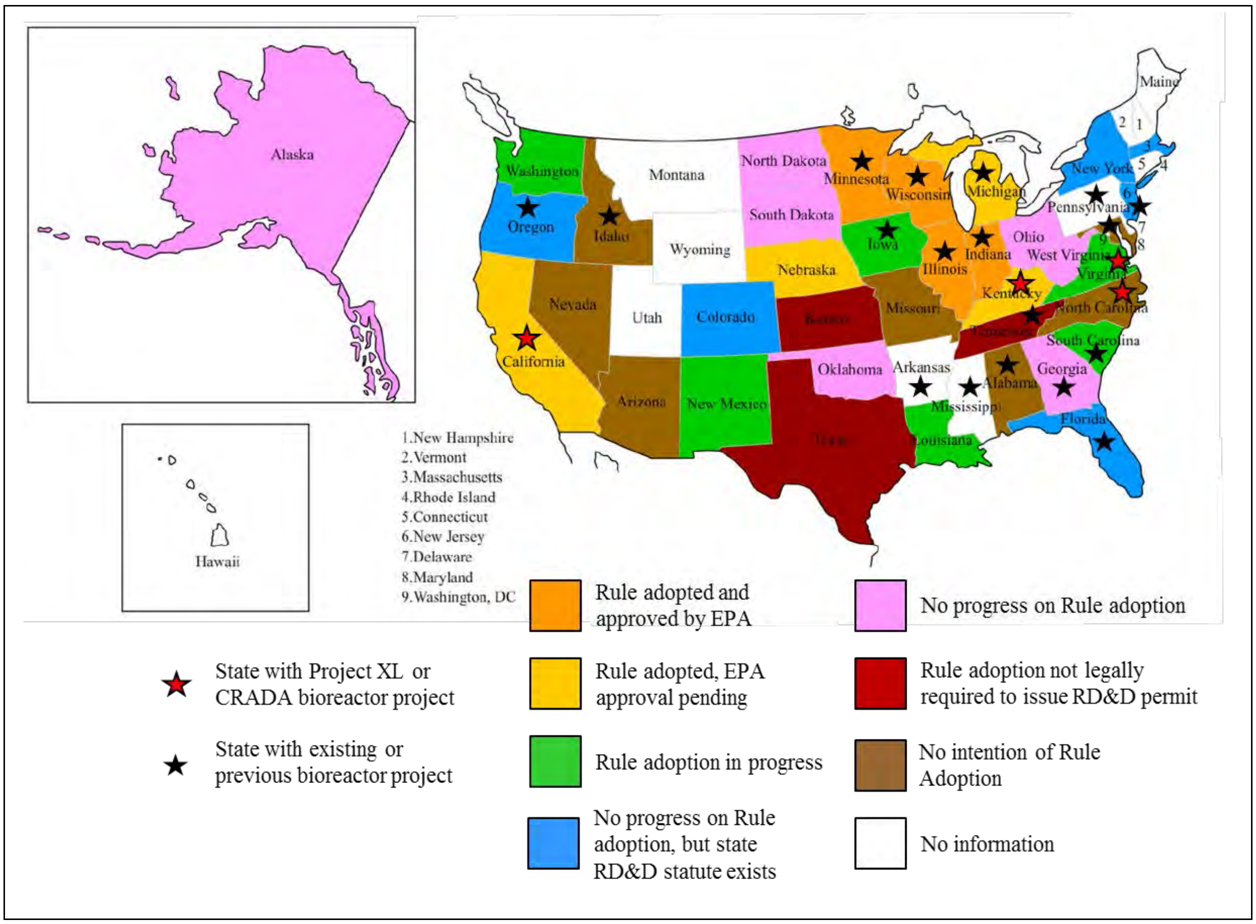

Figure 3-1. Historical bioreactor permitting mechanisms and status reported by Gardner (2006) and states with active or previous bioreactor projects (as of 2009)

In an informal survey reported by SWANA (2003), there were approximately 20 full-scale bioreactor projects in North America in 2002, including one in Canada. These included the four Project XL sites (Section 2.3.1), two projects listed separately under the CRADA at the Outer Loop Landfill in Kentucky (Section 2.3.2), the Florida Bioreactor Demonstration Project (Section 2.3.3), and an additional 13 projects, of which eight were at WM facilities. Seven years later, a more comprehensive survey by SWANA (2009) lists 30 active bioreactor projects in 17 states as well as Canada and the Bahamas. A graphical depiction of states reported to have at least one existing or previous bioreactor project from the mid-1990s through 2009 is also provided on Figure 3-1, based on information compiled from Reinhart et al. (2002), SWANA (2003), Gardner (2006), Hater (2007), SWANA (2009), and SAIC (2011).

For completeness, it is noted here that SAIC (2011) indicates that a bioreactor CRADA project previously existed in Florida. Although a CRADA was signed in 2003 between U.S. EPA and Polk County for a bioreactor project at the North Central Landfill in Winter Haven, Florida, this agreement did not generate a final report. As such, the Polk County project is probably best associated with the bioreactor research program administered by the Hinkley Center for Solid and Hazardous Waste Management (http://www.bioreactorlandfill.org/florida.html). Therefore, Florida is depicted on Figure 3-1 as having had existing bioreactor projects prior to 2009 but not a CRADA project.

3.2 Current Situation

3.2.1 States that Have Adopted the Rule

Due to some of the uncertainty surrounding bioreactor permitting mechanisms and reported rate of Rule adoption by states, for this report the current status of EPA approval for states to issue RD&D Permits under the Rule was established based on whether an announcement appeared in the Federal Register. Based on this, 16 states were confirmed to have adopted the Rule and had received approval from EPA to issue RD&D permits as of 28 February 2014 (Figure 3-2). Of these, nine had adopted the Rule by March 2009 (i.e., within five years of Rule promulgation). The most recent adoptees of the Rule are Massachusetts and Oregon in January and April 2013, respectively. In March 2009, EPA Region 9 also approved an RD&D permit for the Salt River Landfill on Salt River Pima-Maricopa Indian Community land within Arizona.

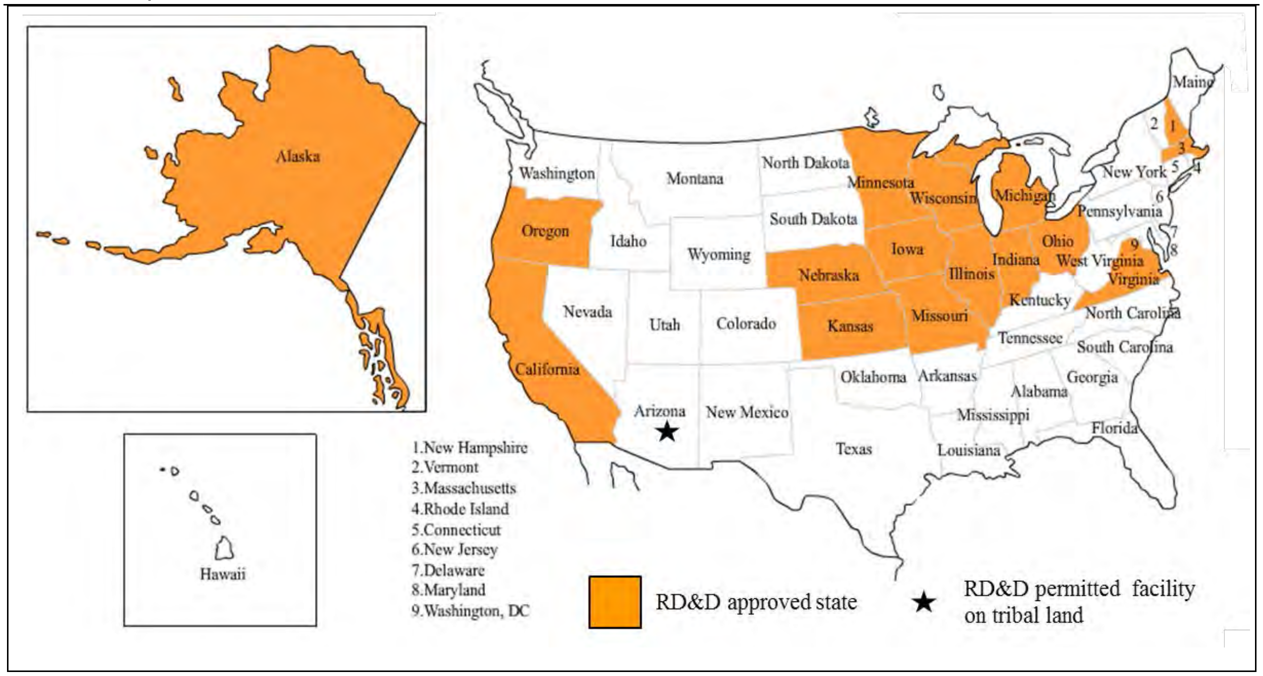

Figure 3-2. States approved by EPA to issue RD&D permits

Intuitively, it was expected that the rate of Rule adoption would be fastest in states that had already issued RD&D-type permits or hosted bioreactor projects prior to enactment of the Rule in 2004. This can generally be confirmed by comparing Figures 3-1 and 3-2, with some notable exceptions such as Alaska and Ohio, neither of which had hosted a bioreactor prior to 2004 or reported any progress on Rule adoption by 2006. It is, however, interesting that the list of approved states includes only three of the four states reported in 2006 as having adopted the Rule pending EPA approval. It is not known exactly why Kentucky did not follow through with Rule adoption; discussions with a Kentucky Department for Environmental Protection (DEP) employee (see Section 4.2) indicated only that there was insufficient operator interest within the state to move forward with an application. It is possible that Gardner (2006) considered the Outer Loop CRADA project as evidence of Rule adoption. Perhaps most interestingly, the list also includes Kansas and Missouri, which indicated in 2006 that they had no need or intention, respectively, of adopting the Rule. This may be illustrative of a change of heart or again an error in the 2006 data collection effort.

3.2.2 States in the Process of Rule Adoption

Seven states have adopted the Rule and applied for EPA approval to issue RD&D permits, or were in various stage of application as of 21 March 2014 (Figure 3-3).

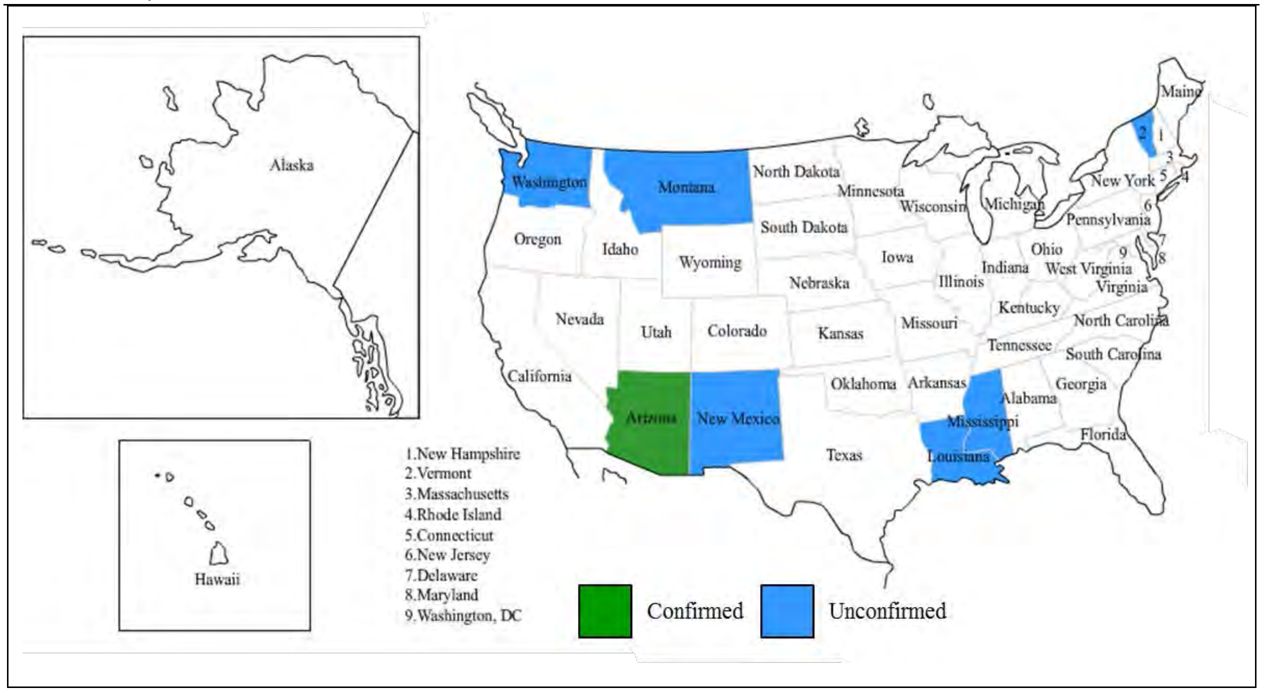

Figure 3-3. States in the process of Rule adoption

Reasons for the current status of Rule adoption in these states based on discussions with state solid waste program employees are listed below. As such, it should be recognized that the information provided is limited.

- Arizona: Although Gardner (2006) reported that Arizona had definitively stated it would not pursue RD&D permitting ability, Arizona had adopted the Rule and sought EPA approval in June 2010 (as confirmed by the Federal Register). However, approval of the RD&D program was stalled first due to the state's concerns with budgetary and staffing resources and second due to strong public opposition to perceived RD&D approval for industrial liquids disposal in a MSW landfill.
- Louisiana: The state is in the process of seeking EPA approval for adoption of the Rule, but was unclear as the exact status of the application. The state's action seems mostly motivated by interest on the part of specific facilities to obtain a RD&D permit.
- Mississippi: Presently, the state is working on several revisions to their waste law, and an RD&D permit provision is included. When asked why it has taken nearly 10 years to make this addition, two reasons were given. First, there has only been one facility to request this option, and that facility had been instructed to address other issues before the state would consider issuing a permit. The overall lack of interest in the state is believed to be due to a perception that bioreactor permitting and operation is complex and costly, along with increasingly muted reports on the benefits of doing so. Second, the state may not be fully convinced of the net benefits of bioreactor technology, and thus lacks urgency in adopting the Rule.

- Montana: The state has an RD&D permit provision citing language that very clearly matches the Rule. Although there is no sign in the Federal Register that an application for approval has been submitted, Montana is reportedly in the process of applying.
- New Mexico: The state reported being EPA-approved for RD&D permitting, although formal confirmation of this was not found in the Federal Register. An explanation given by a state employee was that their adoption of the Rule was included in a package of new regulations submitted for approval by EPA and thus may not have appeared in a stand-alone announcement.
- Vermont: In March 2012, the state finalized changes to their solid waste statues to match the Rule, and they are presently in the midst of the EPA approval process. Vermont decided to adopt the Rule because a few facilities had shown muted interest in obtaining RD&D permits, although it is not clear if they were actually seeking approval for leachate recirculation rather than bulk liquids addition. The state's urgency in seeking EPA approval is low, because no facilities are actively seeking a permit.
- Washington: The state is well advanced in the process of Rule adoption and expects EPA approval later in 2014. One facility in the state is already permitted under state law to add liquids for bioreactor operations and another will soon be permitted. Delays in seeking EPA approval reportedly occurred due to the Director placing restrictions on adoption of new regulations.

3.2.3 States that Have Not Adopted the Rule

As of 21 March 2014 there were still 27 states that have not adopted the Rule. Of these, 11 states have their own provisions that allow RD&D-type permits, but have not revised their regulations to specifically match or reference the Rule (Figure 3-4). The need to formally adopt the Rule and seek EPA approval may seem less urgent under these circumstances. In this regard, it is noted that some states have interpreted the Subtitle D regulations to prohibit only the addition of bulk liquid wastes and not liquid amendments to landfills. Therefore, even prior to implementation of the Rule, some states permitted landfills to operate as a bioreactor under state-specific beneficial use legislation, such as allowing landfills to augment leachate recirculation with addition of "clean" water such as stormwater or groundwater. For example:

- Although Washington is currently in the process of Rule adoption, SWANA (2009) cites an EPA-approved change to Washington State's solid waste regulations that allowed controlled water addition into an MSW landfill.
- The City of Denton Landfill was approved by the Texas Commission on Environmental Quality (TCEQ) to add stormwater to leachate for recirculation under a 2009 permit (City of Denton Solid Waste and Recycling, 2014).

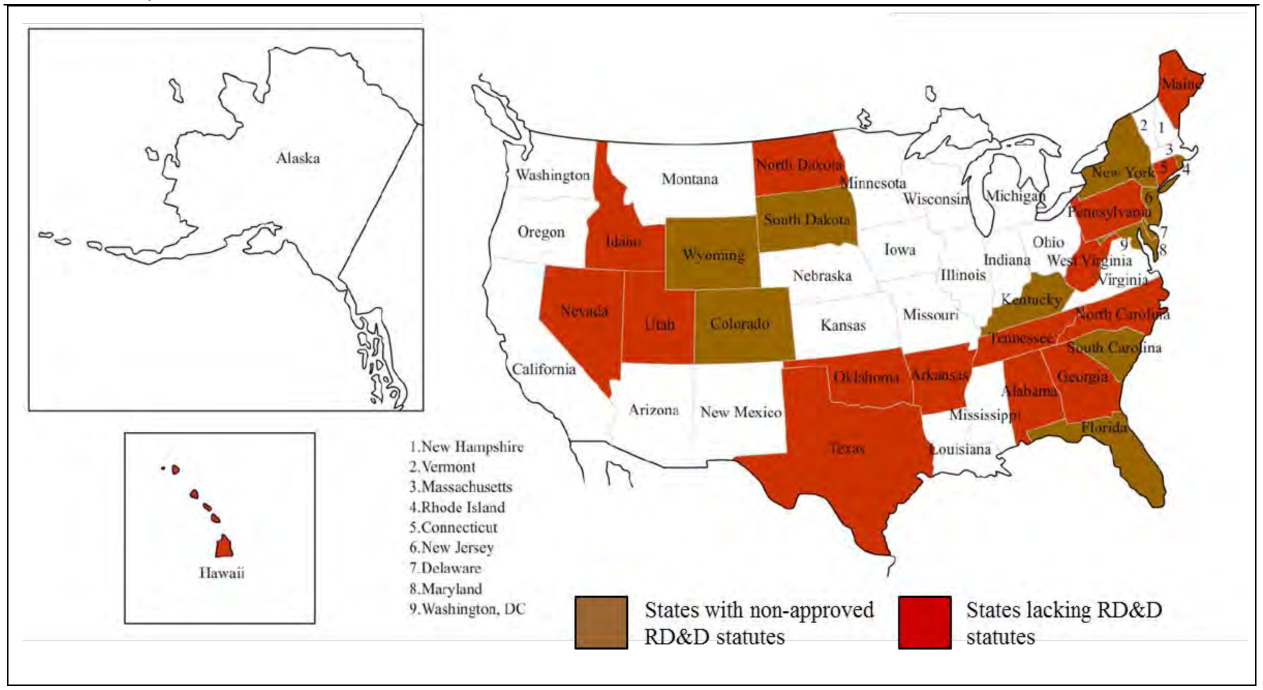

Figure 3-4. States that have not adopted the Rule

4. Challenges faced by States in Adopting the Rule

From Section 3, it is clear that adoption of the Rule has been slow across the states and development of RD&D permitting procedures that are consistent with EPA's requirements has generally not occurred. There are a variety of reasons for this, but feedback from approved states often related to long lag times in the EPA's review process for Rule adoption. For example, California, Nebraska, and Iowa waited an average of 16 months for final approval. However, the period between announcements of application and approval in the Federal Register indicated that the average wait time for all 16 approved states was only seven months, with Massachusetts, New Hampshire, Ohio, and Michigan all waiting three months or less. Overall, these review periods are not unreasonable. For comparison, similar inspection of the Federal Register reveals that the average lag time for adoption of the Subtitle D regulations after 1993 was about two years (based on data for 30 states), with the review period ranging from 5 to 72 months.

Acknowledging potential uncertainties faced by states in adoption of the Rule, in 2005 EPA developed a guidance briefing entitled "Procedures for State Modifications to Incorporate RD&D Final Rule," a copy of which is provided as Appendix I to this report. This provides a simple overview of adoption and notification procedures, as well as examples of a formal state request for approval to modify their solid waste program for Rule inclusion, a listing of items that should be reviewed to ensure that the modification is consistent with federal provisions, and an example of a Federal Register notice approving a modified state program. In accordance with this guidance, EPA's Regional Administrator worked closely with Alaskan state officials in modification of their program for Rule adoption in 2011. Similarly, New York, which currently remains a non-adoptive state, has also worked through the guidance in consultation with EPA Region 2. However, it is not certain to what extent most other states are aware of the level of support that can be available.

Of particular significance to this report are the hurdles cited by the 27 states that have not adopted the Rule (Section 3.2.3). A number of drawbacks have been voiced by landfill operators (Hater, 2007):

- States requiring additional experimental testing instead of results and experience from other states;
- RD&D permits requiring major modifications, instead of easier permitting mechanisms;
- High costs of obtaining RD&D permits;
- Uncertainties in the outcome of the RD&D permit process (for example, after making major investments, WM eventually abandoned plans for permitting bioreactor operations at sites in Ohio, Mississippi, and Texas);
- Delays resulting in the areas demarcated for bioreactor demonstration at a facility being filled before approval can be obtained; and
- Lack of funds for state agencies to conduct adequate workshops to educate state and industry stakeholders on the anticipated RD&D permit process requirements.

Overall, it seems clear that operators are generally more interested in obtaining permanent provisions for bulk liquids addition under 40CFR Part 258 than participating in RD&D-type activities with specific permitting and reporting requirements.

Discussions with state employees from all 27 non-adoptive states were conducted in an attempt to ascertain their current reasons for delaying or opposing Rule adoption. A summary of primary reasons given is presented below, although it should be recognized that the data are limited to personal communications and that formal surveys or interviews were not conducted.

- The predominant reason for not adopting the Rule was lack of interest amongst landfill facilities in the state. The lack of motivation by facilities to be inclined to apply for an RD&D permit was likely related to the reasons cited by Hater (2007) above.
- In addition to lack of interest from permitted facilities, about 10% of states cited other non-technical issues (e.g., perceived high cost or administrative burden) as reasons against Rule adoption.
- A minority of 10-15% of states indicated general technical concerns over bioreactor operations (e.g., threats posed to groundwater or geotechnical stability) or practical constraints (e.g., arid conditions) as reasons limiting their interest in Rule adoption. The perceived constraint posed by arid conditions is somewhat counter-intuitive, as drier sites would seem more suitable for addition of outside liquids. However, declining aquifer storage and restrictions or priority on water uses in some arid areas could preclude use of groundwater for bioreactor projects. Some state regulations are also restrictive of the use or diversion of stormwater. Even wastewater may be required to be recycled and reused at the point of origin or redistributed as gray water for agricultural irrigation or domestic use.
- Several state employees noted that Subtitle D and its state derivatives already allow leachate recirculation over prescriptive (i.e., minimum technology) liner systems, which is often the primary goal of site operators seeking to offset leachate treatment costs. From a site's perspective, therefore, the extra RD&D permitting needs are a significant deterrent to considering addition of supplemental bulk liquids. Applications for RD&D permits requiring major modifications to existing operating permits or collection of additional site data impose extra effort on landfill employees, often at substantial cost. Overall, the benefits of bioreactor landfills seem less significant when the cost in time and money to properly permit them is taken into account. As a result, restricting wet landfill operation to leachate recirculation is thus a more attractive and simpler alternative.
- Other simpler reasons given for the lack of interest on the part of states and facilities are state-specific and include low numbers of suitable landfill facilities. For example:
    - Rhode Island has only one landfill;
    - There are only three landfill sites in Delaware, all of which already recirculate leachate;
    - Most landfills in South Dakota and Wyoming do not have prescriptive Subtitle D liners, limiting opportunities for bulk liquids addition; and
    - Connecticut relies almost entirely on waste-to-energy plants and thus lack landfills suitable for liquids application.

Finally, on the opposite end of the scale, it is interesting that three states (Maryland, South Carolina, and Texas) believe that they are legally entitled to issue RD&D permits without the need to specifically adopt the Rule. This is slightly different to states' perception of this issue reported by Gardner (2006) in which Kansas, Tennessee, and Texas expressed this opinion but Maryland and South Carolina did not, stating instead that they did not intend to adopt the Rule or were actively working on Rule adoption, respectively. This highlights some of the uncertainty that exists amongst states and even between agency personnel as to what exactly is meant by Rule adoption. Since enactment of the Rule in 2004, Texas reportedly issued a permit in 2009 for addition of stormwater to a landfill but there is no record of Maryland or South Carolina having issued any such permits.

5. Status of Bioreactor Projects in the U.S.

5.1 Number of Active Bioreactor Projects

As discussed in Section 3.1, the most comprehensive survey to date of full- and demonstrate-scale bioreactor projects in the U.S. was compiled by SWANA (2009), which lists 28 active projects in 17 states. Based on this, supplemented with independent review of the current status of these sites as well as reports of other active facilities using web-based resources, there may currently be as many as 40 bioreactor projects in the U.S. However, considerable uncertainty exists as to the true scale (i.e., pilot- or full-scale) and nature of many of these projects (i.e., conventional leachate recirculation may be reported as a bioreactor operation).

5.2 Number of Projects Currently Permitted under the Rule

Discussions were conducted with employees of the state solid waste division of all approved states to clarify the current extent of bioreactor RD&D permitting. This showed there are 30 active RD&D projects in 11 states, as well as one project on tribal lands. A summary is provided in Table 5-1.

The large number of projects in Wisconsin relative to other states is due to the fact that Wisconsin Administrative Code (WAC) NR 514.07(9) requires landfill owners to either eliminate landfill disposal of biodegradable materials or to achieve the complete stabilization of deposited organic waste at MSW landfills within 40 years after closure (Wisconsin DNR, 2007). Wisconsin's policies were developed mainly in consideration of PCC issues amid concerns that financial accruals may not be sufficient for longer-term care, and require landfill owners to submit a plan showing how to significantly reduce the residual amount of degradable organic matter in place after closure in order to meet this goal. Landfill organic stability is considered to have been achieved when LFG production has effectively ceased, the organic pollution load of landfill leachate is insignificant, the organic fraction of the waste mass will not readily decompose when placed in ideal moisture and temperature conditions, and there is no longer measurable settlement. Recommended approaches to achieve this goal are liquids addition or in-situ aeration, both of which require an RD&D permit. Invariably, landfill operators have elected to attempt to meet their goal using a liquids addition approach. Under the statutes, operators are required to submit regular status updates to estimate progress toward achieving their goals, and revise their operations plans accordingly if efforts are considered to be off target. This represents a unique opportunity to collect data from multiple sites on the long-term performance of bioreactor landfills in relation to a uniformly applied goal.

Table 5-1. Summary of bioreactor projects currently permitted under the Rule

State	Date Approved by EPA	Number of RD&D Permits Issued	Listing of Permitted Projects
Alaska	January 2011	3	Anchorage Regional Landfill, Eagle River Central Peninsula Landfill, Soldotna Palmer Central Landfill, Palmer
California	October 2007	2	CWM Kettleman Hills Facility, Kettleman City Yolo County Central Landfill, Woodland
Illinois	January 2006	1	River Bend Prairie Landfill, Calumet
Indiana	October 2005	0	None
Iowa	April 2009	0	None
Kansas	August 2009	4	Johnson County Landfill, Shawnee Plumb Thicket Landfill, Runnymede Seward County Landfill, Liberal Western Plains Landfill, Garden City
Massachusetts	January 2013	1	Fall River Landfill
Michigan	August 2006	2	Midland City Landfill, Midland Smiths Creek Landfill, St. Clair
Minnesota	January 2005	1	Spruce Ridge Landfill, Plymouth
Missouri	November 2006	1	City of Columbia Landfill, Columbia
Nebraska	January 2008	0	None
New Hampshire	August 2010	0	None
Ohio	June 2011	0	None
Oregon	April 2013	1	Columbia Ridge Landfill, Arlington
Virginia	January 2009	1	Maplewood Landfill, Amelia County[1]
Wisconsin	March 2006	13	Cranberry Creek Landfill, Wisconsin Rapids Deer Track Park Landfill, Johnson Creek Emerald Park Landfill, Muskego Glacier Ridge Landfill, Horicon (Williamstown) Hickory Meadows Landfill, Hilbert Lake Area Landfill, Sarona Metro Landfill, Franklin Orchard Ridge Landfill, Menomonee Falls Pheasant Run Landfill, Paris Ridgeview Landfill, Whitelaw Seven Mile Creek Landfill, Eau Claire Timberline Trail Landfill, Stubbs Valley Trail Landfill, Berlin
Salt River Pima-Maricopa Indian Community (Arizona)	March 2009	1	Salt River Landfill, Phoenix metropolitan area[2]

Notes:

1. RD&D permit is for leachate recirculation over alternative liner, no bulk liquids addition
2. Permitted by EPA Region 9

6. Documentation for Permitting under the Rule

6.1 Overview

Given the relatively low level of Rule adoption by states (i.e., 16/50 states, or 32%) and wide disparities in RD&D permitting approaches at the state level, a final objective of this report is to provide case study examples of permit applications, operating plans, monitoring plans, and performance evaluation reports that were used in successful RD&D permit applications. This is intended to give a "best practice" indication of the level of detail that an applicant should expect to provide. In general, a successful application will require clear, succinct documentation, be goals-oriented, and provide sufficient redundancy to allow for flexibility of operation within conservatively defined conditions for protecting health, safety, and the environment. It is also important also to remember that all RD&D permits are issued only on that basis; in other words, an application must clearly convey what is to be learned as a key motive for a demonstration project.

It is recommended that RD&D documentation prepared for bioreactor projects should broadly follow the structure outlined in the 2006 bioreactor guidance document prepared by the Interstate Technology and Regulatory Council (ITRC), as listed in Section 2.4.2. ITRC is a coalition of public authorities and industry stakeholders partially funded by EPA and dedicated to cooperative development of cost-effective, innovative environmental techniques; their guidance documents are thus intended to inform both applicants and reviewers of new and unfamiliar technologies as to what are the key elements of operation, maintenance, monitoring, and reporting.

6.2 Bioreactor Design Report

The main purpose of the design report narrative supporting a RD&D permit application is to provide clear understanding of site characteristics and future development plans, communication of planned activities and the engineering design, and explanation as to why planned liquids application activities are suitable (i.e., safe) and beneficial at the subject landfill. Component sections expected in a design plan include:

- Introduction
    - Purpose, overview of the facility and planned development, prior operational history of liquids application (if applicable), prior permitting history and current status
- Plan requirements
    - Site eligibility, goals and anticipated benefits of the demonstration project, expected process and schedule for RD&D permit approval
- Overview of liquid application system and operating parameters
    - Design and performance metrics and standards, sources and quantities of permitted liquids, proposed methods of operation and management of liquid application activities and systems, contingency measures
- Engineering calculations
    - Liquid application capacity and rate (average daily and maximum annual allowable), control of leachate head on liner, landfill gas collection, geotechnical stability analysis, effectiveness and performance of liner and LCS
- Potential implications of adopting the plan

  - Effects on site-wide leachate management, effects on the characteristics of the waste mass, protection of human health and the environment, warning symptoms and failure thresholds (above ground and subsurface)

- Operating plan (see Section 6.3)
- Monitoring and reporting plan (see Section 6.4)

At a minimum, engineering drawings should include a plan showing existing conditions and facility layout, a proposed project development plan, construction details for liquids application systems, and appropriate process flow diagrams for liquid application systems and dedicated infrastructure.

6.3 Bioreactor Operating Plan

The main component of a bioreactor operations plan is typically a liquid application plan (LAP). The LAP is intended provide details on existing and proposed liquid application activities and systems. The main intent is to support and simplify the day-to-day decision making process by landfill managers and site personnel on how and where liquid application should be performed in order to optimize operation and benefits of the RD&D program while minimizing disturbance of site waste disposal operations and maintaining compliance with permit conditions and monitoring and reporting requirements.

Component sections expected in a LAP include:

- Introduction
  - Purpose, overview of the facility and planned development, prior operational history of liquids application (if applicable), requirements for the LAP
- Liquids acceptance and management practices
  - Sources of permitted liquids (e.g., leachate, stormwater, sludge, commercial liquids), acceptance protocols for outside liquids, operational procedures for approved liquid application methods, limits on liquid application rates for each method and total daily/annual quantities for the facility, necessary restrictions on operation due to site conditions, inclement weather, etc.
- Procedures for monitoring and reporting (see details in Section 6.4)
- Warning symptoms and contingency measures
  - Leachate seeps and breakouts, side slope slopes or other signs of instability, leachate generation in exceedance of expectations, LFG management issues, odors, observation of elevated subsurface temperatures, fire
- Site, state, and emergency contacts list

Figures should include a plan showing project layout plan and features and appropriate process flow diagrams for liquid application systems and dedicated infrastructure. Daily field logs should be provided to track liquid application according to landfill area or infiltration system (e.g., trench, blanket, pond, etc.) as well as to allow observations on potential warning symptoms and noteworthy site conditions to be recorded.

6.4 Bioreactor Monitoring Plan

Bioreactor projects require additional monitoring above that routinely performed at Subtitle D landfills. In addition to monitoring the condition of the landfill and environmental media to avoid operational issues and impacts as a result of liquid application, a key component of any RD&D permit is a requirement to measure and report performance of the bioreactor demonstration against stated goals and anticipated benefits. To assess the performance of liquid addition to a landfill, the characteristics and properties of LFG, leachate, and the waste mass can be monitored and evaluated. To provide a basis for consistent data collection for future decision-making in support of the newly promulgated RD&D requirements, EPA developed a guidance document in 2004 to outline approaches for bioreactor landfill monitoring (as listed in Section 2.4.2). Preparation of monitoring plans for RD&D project should follow the guidelines set forth in that document.

Component sections in a monitoring plan developed for a liquids application project typically include:

- Introduction
    - Purpose, overview of the facility, overview of RD&D program goals and anticipated benefits, requirements for the monitoring plan
- Review of rationale for selection of monitoring parameters
    - RD&D project performance metrics and monitoring parameters
        - Physical parameters, including parameters necessary to perform an annual moisture balance such as monitoring of the waste (quantity, type, moisture content) disposed at the landfill, liquid added at the landfill, precipitation, and leachate generated
        - Leachate parameters used to identify the waste decomposition state and pollution potential, including temperature, pH, volatile fatty acids (VFA), BOD, COD, TOC, nitrogen compounds, metals, volatile and semi-volatile organic compounds, cations and anions (e.g., chloride), and phosphate
        - LFG generation rate and methane composition, which provide an estimate of the rate of waste decomposition in the landfill for inter-site comparison to published representative values for landfills in similar environments or intra-site comparison based on spatial or temporal differences in liquid addition
        - Sampling and analysis of either incoming or in-place waste for moisture content, biochemical methane potential (BMP), volatile solids, and cellulose/lignin content, all of which can provide a direct measure of the waste properties and decomposition state (in contrast to indirect measures from leachate and LFG monitoring) if practical limitations related to the large spatial and temporal variability of the waste stream can be accounted for
        - Settlement monitoring (settlement plates or land surveys)
    - Operational monitoring parameters
- Routine monitoring procedures established to measure RD&D project performance and/or site operational and safety conditions
    - Direct performance monitoring measures

    - Operational changes that occurred during the report period (e.g., opening of new cells, installation of addition LFG collector trenches, etc.), total leachate flow in the LCS, total volume of each type of liquid added to the landfill during the reporting period, location and volume of liquid added via each application method employed during the reporting period, volume of waste placed in the landfill during the reporting period, precipitation and other climatic data;
    - Geotechnical stability monitoring, including visual inspections as well as physical monitoring features such as settlement plates, piezometers, or inclinometers
  - Indirect performance monitoring measures
    - Total and average flow and composition of LFG, leachate quality parameters, waste settlement
- Supplemental environmental monitoring established to measure impacts to site operations and safety and allow corrective measures to be implemented as necessary
  - Leachate release through surface seeps, subsurface release to groundwater;
  - Side slope instability
  - Increase LFG and/or leachate generation
  - Reduced LFG collection efficiency due to watered out wells
- Monitoring in-situ moisture distribution using invasive or non-invasive techniques
- Recordkeeping and reporting protocols

Monitoring logs outlining routine and non-routine monitoring activities should be provided. These should clearly outline responsibilities for site personnel.

6.5 Annual Report

40CFR 258(c)(4) requires the owner/operator of a RD&D project landfill to submit an annual report to the state outlining to what extent the project is progressing in attaining its stated RD&D goals. As such, the contents of the annual report will vary between projects depending on the goals and expected benefits of the RD&D program. Sections that could be expected in a "typical" annual report include the list below, although it should be recognized that some sections will not require substantial revision but only updating on a routine basis. All reports must include a summary of all monitoring and testing results obtained in the preceding 12-month period as well as any other operating information specified by the RD&D permit.

- Introduction and technical background
  - Purpose, overview of the facility, overview of RD&D program goals and anticipated benefits, reporting requirements
  - Overview of liquid addition relative to waste decomposition and effects on landfill conditions and emissions, discussion of rationale for selection of monitoring parameters established for evaluation of RD&D program performance (i.e., physical parameters, leachate, LFG, solid waste, settlement, and stability)
- Review of site activities during reporting period

  - General description of pertinent site activities and waste disposal operations (in particular modifications since submission of last PER), liquid addition under RD&D program, leachate management, LFG management, data collected and available for assessment
  - Liquid feedstock assessment (i.e., types and amounts of applied liquids)
- Review of project performance against established metrics
  - Water balance analysis (total liquid addition quantities, leachate generation, water consumption in LFG production and extraction, storage in the waste mass)
  - Waste decomposition and settlement
  - Leachate and LFG generation and quality
- Performance issues and potential environmental impacts
  - Overall performance issues, including slope stability concerns, liner or LCS function, changes in leachate volume or head on liner, odor complaints, changes in differential settlement or waste moisture content
  - Leachate quality and potential groundwater issues
  - Seeps, runoff management, and potential surface water issues
  - Gas management issues, including changes in gas composition and collection, fugitive emissions
- Conclusions and recommendations for future project modification and/or data collection

7. Summary and Conclusions

7.1 Status of Rule Adoption by States

As discussed in Section 3, there is some uncertainty surrounding bioreactor permitting mechanisms and the extent of Rule adoption by states. For this report, the current status of EPA approval for states to issue RD&D Permits under the Rule was established on the basis of whether an announcement appeared in the Federal Register. Based on this, 16 states (i.e., 32%) were confirmed to have adopted the Rule and are approved by EPA to issue RD&D Permits as of March 2014. This is a fourfold increase over the four approved states reported by Gardner (2006). One bioreactor landfill on tribal land within Arizona was permitted under the Rule by EPA Region 9. Seven states were reported to be in various stages of Rule adoption and application for EPA approval, while a final 27 states have not adopted the Rule. Although 11 of these 27 states have their own provisions that allow RD&D-type permits using language similar to that in the Rule, it is not known the extent to which any such permits have been issued. Table 7-1 summarizes the current status of Rule adoption, and lists which non-approved states have individual RD&D-type statutes.

Table 7-1. Summary of current status of Rule adoption

Status of Rule Adoption	Number and List of States
Rule adopted, approved by EPA	16 States ▪ AK, CA, IL, IN, IA, KS, MA, MI, MN, MO, NE, NH, OH, OR, VA, WI
In process of Rule adoption and application for EPA approval	Seven States ▪ AZ ▪ LA, MS, MT, NM, VT, WA (unconfirmed)
Rule not adopted; however, non-approved RD&D statute exists at state level	11 States ▪ CO, DE, FL, KY, MD, NJ, NY, RI, SC, SD, WY
No Rule adoption or state RD&D statute	16 States ▪ AL, AR, CT, GA, HI, ID, ME, NV, NC, ND, OK, PA, TN, UT, WV ▪ TX (does not consider legal need exists for specific statute)

State laws were found to vary in terms of permit duration and renewability, reporting requirements, and the scope of allowable Subtitle D exceptions. Discussion is beyond the scope of this report; however, a summary of specific state regulatory codes relating to RD&D Permits, whether within or external to the EPA approval process, is provided in Appendix II.

7.2 Regulatory Challenges for Rule Adoption

Feedback received from RD&D permit stakeholders on how the process of Rule adoption and implementation could be improved was reviewed in Section 4. Most information compiled was obtained from interviews with employees of the solid waste division at state environmental agencies. As such, it should be recognized that information obtained is limited and may not be fully representative of the issues and problems experienced by all states with regard to Rule adoption and implementation.

The predominant single category of reasons cited for not adopting the Rule was lack of interest amongst facilities in the state. Other reasons cited related to concerns over increased time, cost, and complexity of the permitting procedure for both state personnel and individual applicant sites. However, this is unwarranted as EPA has developed a guidance briefing entitled "Procedures for State Modifications to Incorporate RD&D Final Rule," a copy of which is provided as Appendix I to this report. This guidance provides a simple overview of adoption and notification procedures, as well as examples of a formal state request for approval to modify their solid waste program for Rule inclusion, a listing of items that should be reviewed to ensure that the modification is consistent with federal provisions, and an example of a Federal Register notice approving a modified state program. However, many states seemed unaware that this level of support was available.

Some frustration was also expressed over the long lag time in the approval process following Rule adoption by states. Although some states (California, Nebraska, and Iowa) did wait over a year for approval, the average waiting time for the 16 approved states was only seven months, with four states (25%) waiting three months or less. It is noted also that delays are common in almost all new permitting processes: for example, the full process of states' adoption of Subtitle D after 1993 required an average of over two years. It is recognized that applications based on familiar designs are easily approved while those based on innovative, complex designs are slowed by the unfamiliarity of permit reviewers. This works against innovation, as recognized by ITRC, which is why that organization, with the support of EPA, prepares guidance documents to assist permit reviewers with new technologies.

Overall, few technical concerns over site stability, environmental protection, or public safety were raised. This is a generally positive finding. A negative finding is that a leading cause of delay or postponement of Rule adoption by states is low enthusiasm by site operators in seeking RD&D permits. Most operators appear satisfied with leachate recirculation as a method to control leachate disposal costs, and there does not appear to be significant market pressure or other economic incentives for accepting commercial liquids for landfill disposal. Whether this situation would change if more states were to adopt the Rule is not known.

7.3 Number of Projects Permitted under the Rule

As discussed in Section 5, there may currently be as many as 40 bioreactor projects in the U.S. However, several definitions of bioreactor operations exist, many of which differ from that selected for this research. This means that considerable uncertainty exists as to the true scale (i.e., pilot- or full-scale) and nature (i.e., leachate recirculation only versus application of bulk liquids) of many projects reported as bioreactors. Employees of the state solid waste division were asked to clarify the current extent of RD&D permitting amongst the 16 approved states. This showed that there are 30 active RD&D projects in 11 states, as well as one project on tribal lands.

7.4 Conclusions and Recommendations

A main objective of this report included identifying major hurdles for adoption of the Rule, both in adoptive and non-adoptive states. It is anticipated that by understanding the main hurdles experienced by states in adopting of the Rule, EPA may incorporate lessons learned in their future plans for modification or extension of the Rule. In the short term, there may be an opportunity to overlap any further investigations into updating the Rule with research or pilot studies related to other upcoming initiatives or regulations for landfill monitoring and permitting planned by EPA (e.g., methane emissions monitoring).

Available guidance on Rule adoption and the structure and contents of RD&D permit documentation and design and operations plans from existing projects were briefly reviewed in this report. Overall, it is concluded that development of new guidance materials for Rule adoption or RD&D permitting is not necessary. However, it would be useful to promote EPA's existing guidance on Rule adoption to non-adoptive states as this would highlight the extent to which the process can be streamlined and would help overcome current misconceptions over its high administrative and cost burdens.

Finally, it should be understood that it is not necessarily EPA's goal to have all 50 states approved to issue RD&D permits. Rather, EPA anticipated that during the 12-year period following initial Rule promulgation and adoption, the data gathered would be evaluated to allow consideration of general rulemaking with regard to the 40CFR Part 258 criteria. Over the longer term, therefore, it would be of significant interest to evaluate the actual performance of bioreactor projects against the stated goals and expected benefits of their RD&D programs, as all projects permitted under the Rule are required to include such goals. RD&D permits also require annual performance evaluation reports to be submitted to the state to summarize and evaluate data collected (see Section 6.5). Once a significant number of projects have completed their total RD&D permit approval period of 12 years, a substantial quantity of information should thus be available from state agencies, and collaborative research programs could be established to evaluate findings. A number of states were approved for RD&D permit issuance in 2006, which means the oldest permitted projects in those states could complete their 12-year RD&D term in 2018. Wisconsin appears to offer very significant potential for collaborative research, as it is one of the earliest approved states (March 2006) and has issued 13 RD&D permits. As was discussed in Section 5.2, Wisconsin DNR requires that operators submit regular status updates to estimate progress toward achieving organic stabilization goals, and revise their operations plans accordingly if efforts are considered to be off target. This represents a unique opportunity to evaluate data from multiple sites on the long-term performance of bioreactor landfills in relation to relatively uniform goals and stable factors such as climate and waste generation and disposal patterns.

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Appendix I

Procedures for State Modifications to Incorporate RD&D Final Rule

Since the final RD&D rule provides more flexibility than existing federal Criteria, states are not required to amend permit programs which have been determined to be adequate under 40 CFR Part 239. States have the option to amend statutory or regulatory provisions pursuant to the final RD&D. If a State adopts a law, regulation, or guidance to provide authority for RD&D permits, Section 239.12(c) requires that the State notify the Regional Administrator of the modification. It seems appropriate that this **notification** can be simple and straightforward.

Section 239.12(d) does not impose any required time-frame for submission of such modification. Since States are electing to pick up the RD&D provision at their discretion, any submission of a permit modification should be when the State is ready to submit its modification.
It seems appropriate that the State solid waste staff work with the Regional solid waste staff prior to any formal submission of a modification in order to ensure that most issues have been worked through and to ensure that the formal submission is a quick and pain-free process.

Once a State submits its RD&D modification to the Part 258 program, the Regional staff will perform a review. If the Region believes that the submission **is consistent** with the Federal RD&D language then the review would be finished and the Region would draft a FR notice indicating approval of the modification language, ask for public comments and the determination would become final in 60 days **if** no adverse comments were received on the FR notice in the first 30 days. The Regional Counsel can assist the Regional staff in determining when an "adverse" comment is received and provide guidance as to the appropriate process to follow when an "adverse" comment is received. Section 239.12(g)(2) requires that the Regional Administrator review any "adverse" comments and publish another FR notice either affirming or revising the initial determination. If the Regional review determines that the submission **is not consistent**, it would work with the State to make it consistent with the Federal RD&D Criteria prior to issuing the FR notice approving of the modification..

Attached are some Appendices. Appendix A is an example of a formal State request for approval for an RD&D modification to Part 258. Appendix B is a listing of items that should be reviewed by the Region to ensure that the State modification is consistent with the Federal RD&D provision. Appendix C is an example of a FR notice approving a state program for their RD&D permit modification.

Appendix A

Example Submission of Formal State Request for Regional Review of an RD&D Modification

Regional Administrator
U.S. EPA
Region XX

Dear Regional Administrator:

This is to inform you, that the State of XXXXXX has decided to amend its existing permit program for municipal solid waste landfills and, as such, has modified its regulations to include language that allows owners/operators of municipal landfills in the State to apply for RD&D permits. We are hereby formally requesting approval of this modification. We are providing the citations and regulatory/statutory language that we believe are consistent with the recently promulgated Federal RD&D change for your review. We have worked with your solid waste staff to ensure that the modification language is appropriate. We are requesting that your review and subsequent decision by made within **90 days**. If your staff have any questions regarding this modification, please contact Xxx Xxxxxx of my staff at (xxx)-xxx-xxxx. Thank you and I look forward to hearing from you regarding this request.

Sincerely,

State Director
XXX Department of Environmental Control

Appendix B

In the Regional review of a State modification under the RD&D provision, the following provides a listing of items that should be reviewed for consistency:

-Does the state have the authority to issue a permit (or other enforceable approval document) for a RD&D permit?

- Does the modification only allow variances to the run-on, liquids, and final cover provisions?

-Does the modification require that any RD&D facility have a leachate collection system that will be designed and constructed to maintain less then 12 inches of head on the liner system if a variance from the run-on system (Section 258.26) or liquids restrictions in section 258.28 (a) is allowed?

- Does the modification require that any RD&D facility demonstrate that the infiltration of liquid through an alternative cover will not cause contamination of ground water or surface water or cause the leachate dept h on the liner to exceed the 12 inch limit?

- Does the modification prohibit any RD&D permit from exceeding 3 years, any renewal from exceeding 3 years, or from exceeding a total of 12 years?

- Does the modification require the submission of an annual report that documents the performance of an RD&D operation?

- Does the modification have provisions included to terminate or provide for corrective action at a unit operating under an RD&D permit?

- Does the modification require a detailed assessment of the RD&D project for a permit renewal?

- Does the modification prohibit the applicability of an RD&D permit to small landfills operating under 258.1(f)(1)?

The questions below were thought about but were not considered essential components of a State RD&D review because 1) only approved states will be seeking approval and it can be assumed that approved States are going to require that 258 protectiveness be met and 2) the determinations of what waste streams and what type of testing to require are up to the states to determine.

- Does the modification require that any RD&D project be at least as protective as the criteria for municipal solid waste landfills to assure protection of human health and the environment?
- Does the modification discuss the appropriate waste streams and quantities for inclusion in a unit operating under the RD&D permit?

- Does the modification include requirements for testing and providing information to the State Director regarding the performance of the unit?

- Does the modification require the continue compliance with all other parts of the 258 Criteria for a unit operating under an RD&D permit?

Appendix C

Example FR Notice Approving a State RD&D modification request

ENVIRONMENTAL PROTECTION AGENCY

40 CFR Part 258

[*insert STATE name*]:Approval of Research, Development, and Demonstration (RD&D) Permit Requirements for [*insert State name*]'s Municipal Solid Waste Landfill Permitting Program

AGENCY: Environmental Protection Agency (EPA)

ACTION: Notice of final determination of adequacy of [*insert STATE name*]'s Research, Development, and Demonstration (RD&D) Permit Provisions for Municipal Solid Waste Landfills.

SUMMARY: On [*insert Date of Publication of final RDD Rule*] the U.S. EPA issued final regulations allowing research, development, and demonstration (RD&D) permits to be issued to certain municipal solid waste landfills by approved states (40 CFR Part 258.4). On [*insert date*] [*insert STATE name*] submitted an application to the U.S. EPA seeking Federal approval of its RD&D requirements per the procedures in 40 CFR Part 239.12. Subject to public review and comment, this notice approves [*insert STATE name*]'s RD&D permit requirements.

DATES: This final determination of RD&D program adequacy for [*insert STATE name*] will become effective [*insert date 60 days after the date of publication in the FR*] unless adverse comments are received on or before [*insert date 30 days after the date of publication in the FR*].

If adverse comments are received a second **FR** notice responding to the adverse comments will be subsequently published.

ADDRESSES: You may inspect and copy *[insert STATE name*]'s application for a RD&D permit program during business hours at the following addresses: [*insert STATE agency name, address, and primary contact person*] and U.S. EPA Region 5, 77 West Jackson Boulevard, Chicago Illinois 60604, Attention: Susan Mooney, mail code: DW-8J. Send written comments on this determination of adequacy to the U.S. EPA Region 5 mailing address. Comments on this determination of adequacy may also be submitted electronically to mooney.susan@epa.gov. Please submit electronic submittals as ASCII files and avoid the use of special characters and any form of encryption.

FOR FURTHER INFORMATION CONTACT: Susan Mooney, mailcode DW-8J, Waste Management Branch, U.S. EPA Region 5, 77 West Jackson Boulevard, Chicago, Illinois 60604, telephone (312) 886-3585, mooney.susan@epa.gov.

SUPPLEMENTARY INFORMATION:

On [*insert date*] the U.S. EPA issued final regulations allowing RD&D permits to be issued at certain municipal solid waste landfills (40 CFR Part 258.4). This new provision may only be implemented by an approved State. While States are not required to seek approval for this new provision, those States that are interested in providing RD&D permits to municipal solid waste landfills must seek approval from EPA before issuing such permits. Approval procedures for new provisions of 40 CFR Part 258 are outlined in 40 CFR Part 239.12. On [*insert date*], [*insert STATE name*] submitted an amended application for approval of its RD&D permit provisions. ([*insert STATE name*] received full approval for all other 40 CFR Part 258 provisions on [*insert date*] (see [*insert FR citation*]). After a thorough review, U.S. EPA Region 5 determined that [*insert STATE name*]'s RD&D provisions as defined under [*insert state rule citation*] are adequate to ensure compliance with the Federal criteria as defined at 40 CFR Part 258.4.

AUTHORITY: This notice is issued under the authority of section 2002, 4005 and 4010(c) of the Solid Waste Disposal Act, as amended, 42 U.S.C. 6912, 6945 and 6949(a).

Dated:

NOTE: REGION 3 HAS DEVELOPED STREAMLINED LANGUAGE FOR ALL OF THE EXECUTIVE AND STATUTORY BOILERPLATE STUFF THAT GOES AT THE BACK END OF FR NOTICES.

Appendix II

State	Status of State RD&D Regulation[1]	State Regulatory Code	State	Status of State RD&D Regulation[1]	State Regulatory Code
Alabama	None	NA	Montana	In Application[2]	Mont. Admin R 17.50.507
Alaska	Approved	18 AAC 60.213	Nebraska	Approved	Neb. Admin. Code Title 132 Chpt. 2.014
Arizona	In Application	ARS 49-723	Nevada	None	NA
Arkansas	None	NA	New Hampshire	Approved	ENV-Sw 806.05
California	Approved	27 CCR 2-1	New Jersey	Non-Approved	NJAC 7:26-1.7
Colorado	Non-Approved	6 CCR 1007-2 2.1.14	New Mexico	Approved[2]	20.9.4.17 NMAC
Connecticut	None	NA	New York	Non-Approved	320 NYCRR 1.13
Delaware	Non-Approved	NA	North Carolina	None	NA
Florida	Non-Approved	FAC 403.70715	North Dakota	None	NA
Georgia	None	NA	Ohio	Approved	OAC 3745:27-80 to 89
Hawaii	None	NA	Oklahoma	None	NA
Idaho	None	NA	Oregon	Approved	ORS 459.245
Illinois	Approved	35 Ill. Adm. 807.203	Pennsylvania	None	NA
Indiana	Approved	329 IC 10-11-6.5	Rhode Island	Non-Approved	CRIR 2-3-06
Iowa	Approved	567 IAC 113.4(10)	South Carolina	Non-Approved	SC Code Regs 61-107.19
Kansas	Approved	KAR 28-29-2	South Dakota	Non-Approved	Tenn Comp R & Regs 0400-11-01.2
Kentucky	Non-Approved	401 KAR 47:150	Tennessee	None	NA
Louisiana	In Application[2]	LAC 33:VII.117	Texas	None[3]	NA
Maine	None	NA	Utah	None	NA
Maryland	Non-Approved	COMAR 26.04.07.03	Vermont	In Application[2]	Not found
Massachusetts	Approved	310 CMR 19.062 & 19.080	Virginia	Approved	9 VAC 20-80-485D
Michigan	Approved	MAC r Act 451 Part 115 324.11511b	Washington	In Application[2]	WAC 173.351.710
Minnesota	Approved	MN r 7035.0450 & 7035.2861	West Virginia	None	NA
Mississippi	In Application[2]	Not available[4]	Wisconsin	Approved	NR 514.10
Missouri	Approved	10 CSR 80-2.021	Wyoming	Non-Approved	Solid Waste Rules Ch.2 Sec. 3

Notes:
1-Absent of confirmation of EPA approval via the Federal Register, the status of state RD&D-like provisions is based on individual investigation of the solid waste regulations for each state and
2-Unconfirmed.
3-According to state officials, Texas considers 40 CFR 258.28 to restrict liquid "waste", not liquids in general, and therefore they feel they can selectively allow liquids addition without violati
4-State is presently revising the regulation.