tHE BIOREACTOR LANDFILL - An innovation in solid waste management

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Introduction

Sanitary landfilling in the United States has made monumental strides in the last 20 years, moving from open dumps with little or no control to "state of the art" controlled facilities with sophisticated containment systems, environmental monitoring, improved operational practices, and increased regulation. The modern sanitary landfill is truly an important component of today's integrated solid waste management system. However, in order to advance the field of solid waste management, new and innovative ways of managing solid waste disposal need to be continually evaluated. One idea that has gained significant attention in the last several years is the "bioreactor landfill." The concept is seen as a way to significantly increase the extent of waste decomposition, conversion rates and process effectiveness over what would otherwise occur within the landfill. Other benefits include maximization of landfill gas (LFG) capture for environmental recovery projects; increased landfill capacity; improved opportunities for leachate treatment and storage; reduction of post-closure activities; and abatement of greenhouse gases.

This "White Paper" presents an overview of the bioreactor landfill concept, including existing relevant regulations, benefits to be derived, design and operational issues and possible solutions to many of these issues. In addition, the paper addresses the numerous non-technical and non-environmental barriers to acceptance of the bioreactor landfill concept. This paper is intended to raise reader awareness that the bioreactor landfill is an emerging viable option for solid waste management. It is hoped that landfill owners and operators, policy makers, regulators, others concerned with the environment, and the public at large will use this paper as a focal point for future discussion.

Background

The predominant municipal solid waste disposal option in use today is the sanitary landfill. Landfills must meet the requirements of the Resource Conservation and Recovery Act (RCRA), Subtitle D, the Clean Water Act, the Clean Air Act and numerous other Federal, State and local regulations. The intent and guiding principle of these regulations is to keep wastes "dry," thus minimizing production of leachate and LFG, two of the major by-products of waste degradation.

The underlying assumption is that a 30-year post-closure period is the minimum necessary to effectively manage the very long-term environmental liabilities of the organic components, salts and heavy metals contained within conventional "dry" Subtitle D landfills. The containment provided by these landfills offers environmental protection initially; however, at some point beyond the 30-year period, there may be partial failure(s) of the containment lining system (underlying and overlying the waste). The primary environmental issue associated with partial containment system failure and moisture infiltration is the potential associated increase in gas and leachate production and the resulting impact of uncontrolled leachate and/or LFG releases to the environment. The nature and magnitude of the releases exiting the landfill and their resulting impacts is directly related to the amounts of organic waste not yet decomposed.

How a Bioreactor Landfill Differs from a Conventional Landfill

As defined in this paper, a bioreactor landfill is a sanitary landfill that uses enhanced microbiological processes to transform and stabilize the readily and moderately decomposable organic waste constituents within 5 to 10 years of bioreactor process implementation. The bioreactor landfill significantly increases the extent of organic waste decomposition, conversion rates and process effectiveness over what would otherwise occur within the landfill. Stabilization means that the environmental performance measurement parameters (landfill gas composition and generation rate and leachate constituent concentrations) remain at steady levels, and should not increase in the event of any partial containment system failures beyond 5 to 10 years of bioreactor process implementation.

The bioreactor landfill requires certain specific management activities and operational modifications to enhance microbial decomposition processes. The single most important and cost-effective method is liquid addition and management. Other strategies, including waste shredding, pH adjustment, nutrient addition, waste pre-disposal and post-disposal conditioning, and temperature management, may also serve to optimize the bioreactor process. Successful implementation also requires the development and implementation of focused operational and development plans.

In effect, the bioreactor landfill is merely an extension of the accepted Subtitle D leachate recirculation landfill option. However, the bioreactor process requires significant liquid addition to reach and maintain optimal conditions. Leachate alone is usually not available in sufficient quantity to sustain the bioreactor process. Water or other non-toxic or non-hazardous liquids and semi-liquids are suitable amendments to supplement leachate (depending on climatic conditions and regulatory approval). Other process amendment strategies may also be included, subject to regulatory approval. Although Subtitle D does permit recirculation of leachate and condensate from a specific landfill, many states have not yet endorsed the leachate recirculation option, let alone permitted the addition of water or other liquid amendments needed to facilitate the bioreactor activity.

Shortly following closure of a bioreactor landfill, the landfill gas generation rate will usually be at its highest. It will then quickly decline over the next 5 to 10 years to a stable and relatively low and declining rate. Similarly, shortly after landfill closure, many leachate contaminant concentrations will change from levels regarded as highly polluted to much lower levels normally characteristic of extended stabilization. The leachate quantity at closure will be a finite amount, amenable to on-site treatment with limited need for off-site transfer, treatment and disposal. In the event of post-closure partial containment system failure, the quality of the leachate generated from infiltration into a bioreactor landfill will be much better than other drier Subtitle D landfills.

Evidence suggests that bioreactor landfills can meet Subtitle D requirements. A 1997 SWANA survey of 130 US bioreactor landfills indicates that most environmental and other relevant concerns have been resolved; information on leachate recirculating landfills in existence worldwide is similarly positive.

Existing Regulations, Policy, and Activities

Present regulations generally encourage landfills to remain relatively dry. In most cases, the final moisture content remains close to that of the entering waste.

The Federal Code most pertinent to liquid addition is 40 CFR 258.28, which only allows reintroduction of leachate and condensate into Subtitle D lined landfills, described in 40 CFR 25.40 (a)(2). Subtitle D does not expressly bar amendments, and is in fact silent on the issue. Some states interpret 40 CFR 258.28 to mean that liquid addition, other than leachate and condensate, is not allowed into landfills. Despite this oft-taken position, Federal Code may be interpreted to prohibit only the addition of *bulk liquid wastes*, and not *amendments*, to landfills. Thus water and other amendment additions to landfills appear permissible within regulations. For example, the US EPA, Region 10, approved an amendment to Washington State's solid waste regulation that specifically allowed water addition in a controlled manner to a specific composite lined, subtitle D Landfill.

The bioreactor and leachate recirculating landfills differ from the "dry" Subtitle D landfill in that they each receive managed liquid additions to augment waste stabilization. The bioreactor landfill differs from the leachate recirculating landfill in that it can obtain rapid and complete stabilization by use of water and other amendments. For the bioreactor landfill, water is clearly not a waste but an amendment. Other potential bioreactor additions such as sludge and nutrients could also be categorized as amendments. Federal Code is open to necessary amendments providing that other statutory constraints are met, e.g., leachate head limits on the base liner and inclusions of a single composite liner.

Favorable federal policy toward the bioreactor landfill has begun to develop. In the Federal Climate Change Action Plan (CCAP) of 1993, Action Item 37 contains, among others, the following relevant recommendations:

- Creation of a joint state/federal coordination program to facilitate siting/permitting of enhanced recovery (i. e., bioreactor) landfills.

- Modification of environmental performance standards and regulatory requirements to remove unnecessary barriers to bioreactor landfills.

In addition to support apparent in these policy statements, federal support seems implicit in long-standing US EPA sponsorship of bioreactor experimental work. One representative compendium of work may be found in the EPA seminar publication, "Landfill Bioreactor Design and Operation," proceedings of the EPA Symposium in Wilmington, Delaware, March 1995. A large body of other work has been sponsored and published under EPA auspices over the past three decades.

With respect to states, a 1997 SWANA data collection effort included a survey of state regulatory agencies to determine their position on leachate recirculation and landfills as bioreactors, (Gou and Guzzone, 1997). Of 50 distributed surveys, 37 were returned.

The survey indicates that approximately 130 MSW landfills are currently employing leachate recirculation. More than half (21) of the respondents cited specific state regulations on leachate recirculation. For the most part, the state requirements closely follow those stipulated under RCRA Subtitle D, i.e., a composite liner system and leachate collection system (LCS) to maintain leachate head levels below 1 foot (30 cm).

Six states supplement their regulations with additional specific requirements, including gas collection, runoff controls, leak detection systems, and double liner systems (i.e., Delaware and New York.) In other states, survey responses list no specific requirements, save a requirement to obtain Department and state approval. For example, Ohio and Wyoming allow leachate recirculation, however, there are no specific state rules pertaining to the practice. Finally, three states do not permit recirculation at all. In these cases, either leachate production is not a primary concern (dry climate), or most of the state's landfills are unlined, or the state environmental agency simply does not find the practice researched and studied adequately for implementation.

At the time the survey was administered (mid 1997), fourteen states indicated either that they accept bioreactor landfills, approval was pending, or they would consider a proposal. States favoring, considering, or accepting bioreactor landfills include: Alabama, Alaska, Arkansas, California, Colorado, Delaware, Florida, Iowa (one project pending), Michigan, Mississippi, Montana, New Jersey, New York and Washington.

Eleven states (Arizona, Illinois, Kansas, Kentucky, Massachusetts, Maryland, Nebraska, New Hampshire, Ohio, and Pennsylvania) indicated that they would **not** approve a bioreactor landfill. Others gave no answer, or indicated they were in the process of evaluating the technology. A primary reason cited by those not approving of bioreactor landfills was that most landfills were unlined. Those that did permit bioreactor landfills usually classified the practice under recirculation, rather than as a separate category. In many of the states lacking specific bioreactor regulations, the practice had never even been requested. However, the topic had been considered internally through permit modifications or alterations.

Example Bioreactor Landfill Activities

- **California:** For three years, Yolo County has been operating a bioreactor demonstration cell that contains 9,000 tons of refuse. Yolo County is negotiating with concerned state regulatory agencies to permit and then operate the next 15-acre landfill cell of the Yolo County Central Landfill as a bioreactor.
- **Delaware:** The Delaware Solid Waste Authority has operated the major landfill (largest in the state) at Sandtown as a bioreactor for more than 10 years.
- **Florida:** The state recently allocated more than 3.2 million dollars to establish a demonstration bioreactor landfill.
- **Georgia:** Two aerobic bioreactor landfill projects are operational; one at the Live Oak Landfill in Atlanta, the other at the Baker Road Landfill in Columbia County
- **Iowa:** The Bluestem Solid Waste Authority has received a $500,000 state grant for its bioreactor project at the Bluestem #2 Landfill near Marion. Waste placement commenced in December 1998 and the demonstration project should receive final cover in June 1999.
- **New York State:** An anaerobic bioreactor operation is being carried out at the Mill Seat Landfill; a pretreatment aerobic bioreactor activity is operational at Elmira.
- **South Carolina:** The State Research and, Development and Demonstration Program is sponsoring an aerobic activity at the Aiken County Landfill.
- **Washington State:** Washington Administrative Code 173-351-200(9) specifically permits bioreactor landfills. The pertinent section on operating criteria on liquid restrictions states, "Bulk or non-containerized liquid waste may not be placed in MSWLF units unless: (ii) the waste is leachate or gas condensate derived from the MSWLF unit, or water added in a controlled fashion and necessary for enhancing decomposition of solid waste, as approved during the permitting process of WAC 173-351-700, whether it is a new or existing MSLF or lateral expansion."

Potential Benefits of the Bioreactor Landfill

Numerous benefits can be derived from the bioreactor landfill. These are situation-dependent and can affect different parties or stakeholders in different ways. They can accrue in the form of environmental, regulatory, monetary and social benefits. Some of the key benefits include:

Rapid organic waste conversion/ stabilization

- Rapid settlement - volume reduced and stabilized within 5 to 10 years of bioreactor process implementation.
- Increased gas unit yield, total yield and flow rate – almost all of the rapid and moderately decomposable organic constituents will be degraded within 5 to 10 years of closure.
- Improved leachate quality - stabilizes within 3 to 10 years after closure.
- Early land use possible following closure.

Maximizing of landfill gas capture for energy recovery projects

- Significant increase in total gas available for energy use, which provides entrepreneurial opportunities.
- Potential increase in total landfill gas extraction efficiency (enabled over a shorter generation period).
- Increased greenhouse gas reduction from lessened emissions.
- Increase in fossil fuel offsets due to increased gas energy sales.
- Assistance in defraying landfill gas non-funded environmental costs.
- Significant economy of scale advantage due to high generation rate over relatively short time.

Increased landfill space capacity reuse due to rapid settlement during operational time period

- Increase in the amount of waste that can be placed into the permitted landfill airspace (effective density increase.)
- Extension of landfill life through additional waste placement.
- Deferred capital and financing costs needed to locate, permit and construct replacement landfill results in capital and interest savings.
- Significant increase in realized waste disposal revenues.

Improved leachate treatment and storage

- Low cost partial or complete treatment; significant biological and chemical transformation of both organic and inorganic constituents, although mostly relevant to the organic constituents.
- Reintroduction of all leachate over most of the operational and post-closure care period significantly reduces leachate disposal costs.
- Absorption of leachate within landfill available up to field capacity.

Reduction in post-closure care, maintenance and risk

- Rapid waste stabilization (within 5 to 10 years) minimizes environmental risk and liability due to settlement, leachate and gas.
- Landfill operation and maintenance activities are considerably reduced.
- Landfill monitoring activities can be reduced.
- Reduction of financial package requirement.
- In the event of partial liner failure, there should be no risk of increased gas generation, worsening leachate quality, increased settlement rate or magnitude.

Another major benefit of bioreactors may come from greenhouse gas abatement. Bioreactors can generally rapidly complete methane generation while attaining maximum yield. This can be combined with nearly complete capture of generated gas using the bioreactor landfill in combination with a landfill gas energy project (Augenstein et al, 1997). With this approach, the high generation level and gas capture efficiency maximizes landfill greenhouse gas offset potential.

Additional goals and benefits may also accrue, including: 1) transformation of certain resistant organics (dehalogenation, etc.) and sequestration of certain inorganics (precipitation, etc.); and 2) pollutant removal processes of filtration, capture, sorption, etc. that are promoted by leachate recirculation (Pohland, 1995).

BIOREACTOR LANDFILL ISSUES

Design

For the most part, state and federal regulations (primarily RCRA Subtitle D), dictate the design of the modern landfill. Required design components include the liner, leachate collection facilities, gas collection and management facilities, and the final cap. These same components must be adapted during the operational period of the bioreactor landfill to manage leachate, including liquid introduction, and to handle enhanced gas generation. The following issues must be addressed to produce a successful project that satisfies regulatory concerns.

Cell Size.

For economic and regulatory reasons, an emerging trend in traditional landfill design is to build deep cells (or phases) that are completed within two to five years. This trend bodes well for bioreactor landfill evolution. Phased cell construction can more easily take advantage of emerging technological developments, rather than committing long term to a design that may prove to be inefficient. Once closed, methanogenic conditions within the cell (phase) are optimized and gas generation and extraction is facilitated. However, extremely deep landfills may be so dense in the lower portions that refuse permeability will inhibit leachate flow. In these instances, it may be necessary to limit addition and/or recirculation to the upper levels, or develop adequate internal drainage management capability.

Maximum Allowable Leachate Head on the Bottom Liner.

Federal regulations prescribe a one-foot maximum allowable leachate head on the bottom liner. This criterion may be readily achieved by appropriate design and specifications of bottom liner slopes, drainage layer flow distances, and hydraulic conductivity of the leachate drainage layer. The design can be aided by use of mathematical models such as HELP3 developed by the Corps of Engineers (Schroeder et al, 1994). Since leachate head predictions are based on mathematical models, regulatory agencies may require monitoring to verify performance.

Liquid management

An estimate of the design flow rates and liquid storage and supplementation capacity must be developed for the liquid management system. Sufficient storage will be required to ensure that peak leachate generation events can be accommodated. Sufficient liquid supply (i.e., leachate, water, wastewater, or sludge) must be assured to support project goals. The volume of liquid needed to reach waste field capacity can be based on prior field studies, model predictions, or landfill specific measurement. Expressed as a volume per mass of solid waste, the range of liquid addition to reach field capacity is 25,000-50,000 gallons per 1,000 tons of solid waste (Reinhardt and Ham, 1974).

There are various methods of adding liquid. Methods that directly apply the leachate and water to the solid waste can target moisture supplementation levels (desired gallons/ton or cubic yard) during active landfilling. One option is to apply the liquid at the working face as refuse is placed into the landfill. In this case, however, operators must be prepared to deal with increasing gas generation shortly thereafter.

Another option is to add moisture after waste placement, which controls the onset of rapid gas generation. Applying leachate and water to solid waste already in place can be accomplished by using surface irrigation systems, infiltration ponds, injection wells, or trenches. Selection considerations include climate, malodors, worker exposure, environmental impacts, evaporative loss, reliability, uniformity and aesthetics. Buried trenches or vertical wells offer advantages of minimum exposure pathways, good all-weather performance, and favorable aesthetics. However, they may be adversely impacted by differential settlement. Guidance on liquid addition, alternative design and performance can be found in Reinhart and Townsend (1997).

Solid Waste Density Considerations

Adding liquid to solid waste will increase its density, which can be of critical importance in the design of load-bearing structural members in the landfill. Most notably, the leachate and LFG collection system must be designed to accommodate the increased load, which may be as much as 30% heavier because of expected moisture uptake and settlement. The design process for determination of the buried leachate pipe load bearing capacity is described in Harrison and Watkins (1996).

Landfill Gas Control System

A bioreactor landfill will generate more landfill gas in a much shorter time than a drier landfill. To efficiently control gas and avoid odor problems, the bioreactor landfill gas extraction system may require installation of larger pipes, blowers and related equipment early in its operational life. Horizontal trenches, vertical wells, near surface collectors, or hybrid systems may be used for gas extraction. Greater gas flows are readily accommodated by increased pipe diameter, as capacity increases as the square of pipe diameter. Liquid addition systems should be separate from gas extraction systems to avoid flow impedance. The porous leachate removal system underlying the refuse should be considered for integration with the gas extraction system.

Enhanced gas production can negatively impact side slopes and cover if an efficient collection system is not installed during active landfill phases. Uplift pressure on geomembrane covers during installation may cause ballooning of the membrane and may lead to some local instability and soil loss. Temporary venting or aggressive extraction of gas during cover installation may facilitate cover placement. Once the final cover is in place, venting should be adequate to resist the uplift force created by LFG pressure buildup. The designer should consider the pressure buildup condition on slope stability when the collection system is shut down for any significant time.

Landfill Stability

Addition of liquid into the refuse to increase biological activity will increase the total weight of the refuse mass and may cause an increase in internal pore pressure. This stability issue can be readily assessed and resolved with standard geotechnical analyses (Maier, 1998). Seismic effects should also be considered during geotechnical analysis when appropriate.

Settlement

A bioreactor landfill will experience more rapid, total and complete settlement than a drier landfill. Accelerated settlement results from both an increased rate of decomposition of the solid waste and increased compression through higher specific weights. Settlement during the landfilling operations will impact the performance of the final surface grade, surface drainage, roads, gas collection piping system, and leachate distribution piping system. Because of the significant increase in settlement magnitude and rate, it could be very beneficial to overfill the refuse above design grade before placement of the final cover. Alternatively, a significant benefit may accrue if final cover and final site improvement installations are postponed and the rapid settlement is used to recapture airspace. Settlement impacts can be readily accommodated by the project design. Since settlement will be largely complete soon after landfill closure, long-term maintenance costs and the potential for fugitive emissions will be avoided.

Operations

The bioreactor landfill is a waste treatment system. During landfill operations, it requires closer attention to system performance than the drier landfill. Successful operation of a bioreactor landfill depends upon control and monitoring of biological, chemical, and hydrologic processes occurring within the landfill. Operational and maintenance programs addressing settlement, landfill gas, and leachate may be reduced to a minimal level once the landfill is closed and the refuse is largely stabilized.

Solid Waste Pre-treatment or Segregation

Bioreactor operations are most efficient and effective where the refuse has high organic content and high exposed specific surface area. For this reason, bioreactor operations should be concentrated on waste segregated to maximize its organic content and shredded, flailed, or otherwise manipulated to increase its exposed surface area. Waste segregation could include separation of construction and demolition (C&D) wastes from MSW. Limited shredding can be obtained by spreading refuse in thin lifts and using landfill equipment to break open plastic bags and break down containers. Mechanical shredding can be efficient and effective in reducing particle size and opening bags, however it is an intensive, high maintenance and high cost activity, which may not be cost-effective. Moreover, shredded wastes may become exceedingly dense after placement, thereby limiting moisture penetration.

Leachate Seeps

Adding liquids to solid waste landfills increases the potential for leachate seeps or breakouts; and the landfill must be operated to minimize such possibilities. Leachate must be precluded from contaminating storm water runoff. Monitoring for leachate seeps is mandatory, and the operations plan must include a rapid response action to correct leachate seeps as they develop. Such measures as installation of slope and toe drains, surface regrading, filling and sealing cracks as necessary to reduce surface water infiltration, and reducing the liquid addition rate, are some of the standard methods used to address this condition. Potential for slope seeps can also be limited by managing liquid addition rate, amount, and location.

Daily and Intermediate Cover

The use of soil cover in a bioreactor landfill requires special attention. A cover more permeable than the waste can direct leachate to the sides, where the leachate must be properly collected and drained. Low permeability daily cover can create barriers to the effective percolation of leachate and water (Miller et al, 1991). It can also impede leachate distribution and landfill gas flow to collection and distribution systems. Where low permeability soil is used as cover, its ability to serve as a barrier should be reduced by scarifiying, or partial removal, prior to placing solid waste over it. Where low permeability soil cover is placed within 50 feet of the slopes, it should be graded to drain back into the landfill to preclude leachate from reaching the slope and emerging as a seep. Use of alternative covers that do not create such barriers can mitigate these effects. In many cases, alternative covers have been found to be quite cost effective when compared to soil.

Management of Nutrients and Other Supplement Addition

Nutrient requirements are generally supplied by waste components (Barlaz et al, 1990), but research suggests that nutrients and other biological and chemical supplements may be considered to enhance biological activity. Addition of such additives has not yet been attempted in the field. As with waste segregation, or shredding, the costs of nutrient and supplement additions will need to be justified.

Optimum pH for methanogens is approximately 6.8 to 7.4. Buffering of leachate in order to maintain pH in this range has been found to improve gas production in laboratory studies. Particular attention to pH and buffering needs should be given during early stages of leachate recirculation. Careful operation of the landfill bioreactor initially through slow introduction of liquids should minimize the need for buffering.

Bioreactor Management Program

It is important that operators of each bioreactor project develop a detailed and thorough management plan that addresses the project goals; design, operation and maintenance, training, monitoring, contingency considerations, and QA/QC elements. All issues and solutions should be addressed in detail within these programs to the satisfaction of regulators and the public. The bioreactor landfill is possible now that Subtitle D mandates an environmentally secure environment. Within Subtitle D, some management flexibility is allowable to optimize the benefits available through controlled management of the organic decomposition process. Under certain conditions, the bioreactor landfill may be a viable technical option for landfill management.

Non-Technical Barriers to the Bioreactor Landfill

Research and limited field-scale experience offers solid technical evidence of the efficacy of the bioreactor landfill. While resolution of remaining technical and the environmental issues appears assured by implementation of RCRA Subtitle D and the CAA, the bioreactor landfill also faces the challenge of numerous non-technical barriers. Principal among these are:

- Limited regulatory awareness and negative perception.
- Dearth of site-specific performance quantification.
- Limited availability of project economic assessments.
- Insufficient project sustainability experience.

- Lack of financing experience.
- Extended time expectations for planning permitting and licensing.
- Increased regulatory constraints and conditions.

These non-technical issues and uncertainties must be further addressed to fully evaluate the viability of potential projects and gain acceptance for the concept. It is hoped that an improving understanding of the technical issues will` lead to resolution of many of the non-technical barriers.

Summary and Conclusion

It is now time to seriously consider acceptance and adoption of the bioreactor landfill as a key strategy for deriving short and long-term environmental, regulatory, monetary and societal benefits. The bioreactor option is a direct result of engineering and building a new generation of environmentally sound landfills; it provides environmental security while permitting and encouraging rapid stabilization of the readily and moderately decomposable organic waste components. It is hoped that the emerging bioreactor landfill technology will point our solid waste industry towards taking a new look at a very effective option to manage our waste disposal.

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