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California Integrated Waste Management Board

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Contractor's Report

To The Board

Technologies and Management Practices for Reducing Greenhouse Gas Emissions From Landfills

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Introduction

Objectives

The objective of this project was to develop a guidance document (Report) that landfill operators and regulators can use to evaluate potential actions that can be implemented to achieve additional greenhouse gas (GHG) emission reductions from landfill gas (LFG) beyond what are currently occurring with existing landfill practices. The study is based on an evaluation of existing state-of-the-practice technologies, as reflected in published literature, reports to regulatory agencies, and the Project Team's familiarity and experience with specific landfill and LFG practices and projects. The Report provided herein evaluates various technologies and practices and recommends practical and cost-effective site-specific measures that can be used on a voluntary basis to reduce GHG emissions from landfills in California.

Please note that the study is not designed to compare and contrast the different elements of the solid waste industry (e.g., landfilling versus recycling) nor make any value judgments regarding the preferred method(s) for waste management. Rather, the Report is intended to provide practical best management practices (BMPs) for the landfill sector for GHG emissions reductions related to the methane contained in LFG.

Project Team

The California Integrated Waste Management Board's (CIWMB's) Project Team was managed by SCS Engineers (SCS), which acted as the prime contractor for this project. The Project Team's approach to this study was to use its expertise in landfill, LFG, air and GHG emissions, composting, and recycling to develop a series of BMPs for GHG emissions reductions at landfills. The internal expertise of the Project Team was supplemented with published, credible literature on these topics to ensure that the study encompasses the most current and state-of-the-practice methods to achieve these objectives.

The CIWMB Project Team includes the following team members:

- CIWMB staff.
- SCS, overall team leader and experts in LFG and landfill design, operations, and construction.
- Integrated Waste Management Consulting, LLC, expert in organic waste recycling, composting, and use of biocovers.
- Pacific Waste Consulting Group, Inc., experts in landfill operations.
- GC Environmental, Inc., experts in LFG design, operations, and construction.

Background

By Executive Order S-3-05 filed June 1, 2005, California set ambitious goals to reduce GHG emissions to 2000 levels by 2010; to 1990 levels by 2020; and to 80 percent below 1990 levels by 2050. The interagency California Climate Action Team (CAT) was created to recommend strategies to achieve these goals and is chaired by the California Environmental Protection Agency (Cal/EPA) Agency Secretary. The climate change program in California was further strengthened by the passage of AB 32, also known as the "California Global Warming Solutions Act of 2006." It is the first law to comprehensively limit GHG emissions at the state level and was signed into law by Governor Schwarzenegger on September 27, 2006. Among other things, it establishes annual mandatory reporting of GHG emissions for significant sources, sets forth early action measures for near-term GHG emissions reductions from certain sources (including landfills), and sets emission limits to cut the state's GHG emissions to 1990 levels by 2020. Both the legislation and the CAT currently estimate that the solid waste industry, particularly landfills, is a significant source of the total net GHG emissions in California and should be a major focus of any efforts for GHG emissions reductions.

As an example, options for reducing methane emissions from landfills account for the majority of potential non-CO_2 GHG emissions reductions (California Energy Commission [CEC], PIER Final Project Report, July 2005, CEC-500-2005-121), which may be possible in the state. However, the estimates of landfill GHG emissions are based on factors and assumptions poorly understood and highly debated. Many researchers and stakeholders conclude that although there are opportunities for further reductions in GHG emissions from landfills, the baseline emissions are much lower than currently estimated because of advancements in solid waste management and LFG control efforts over recent decades. Other stakeholders believe that landfill GHG emissions are higher than currently estimated and that reduction estimates are exaggerated.

In response to the debate over landfill GHG emissions estimates, the CEC is conducting a study on landfill methane emissions and capture efficiencies to improve overall estimation of landfill GHG emissions and reductions. The study summarized herein is considered a complement to the existing CEC study by providing guidance on ways to actually achieve landfill GHG emissions reductions, which then could be measured by the methodologies being evaluated in the CEC study.

The California Air Resources Board (CARB) approved a 2020 emissions limit in December 2007 which is equivalent to the 1990 emissions baseline level. In addition, CARB is also developing the various regulatory programs necessary to achieve the objectives of AB 32, which includes early action measures for GHG emissions reductions. Landfill emissions are one of the prime focuses of these potential early action requirements, and this Report is intended to provide useful information for development and implementation of these early action measures.

At this time, there is no overall practical guide or roadmap to reduce GHGs from landfills in California. The lack of such guidance or roadmap presents a significant barrier toward achieving GHG emissions reductions targets for the industry. The Report sets forth landfill technologies and practices that can be used for GHG emissions reductions and recommends practical and cost-effective site-specific measures to reduce GHGs from landfills in the state.

Workplan

Under the first task of this project, the Project Team developed a detailed work plan to submit to the CIWMB contract manager for approval for the subsequent tasks on this project. The work plan identified and described the specific tasks to be performed, schedule for completion, deliverables including draft and final reports, and itemized costs per task. As part of the work plan, the Project Team prepared a detailed outline of the final report that would be produced on this project, and this outline became the basis for the Report contained herein. The final work plan was approved by the CIWMB before work commenced on the remainder of the project.

Technical Advisory Group

Background

The CIWMB convened an advisory group to review the project deliverables in consultation with CIWMB staff. The CIWMB believes that it is critical that the final work product on this study gain the approval of the overall solid waste industry and that it represent the state-of-the-practice for proposed GHG emissions reduction strategies. The Project Team proposed a list of nominations to the CIWMB for inclusion on the technical advisory group (TAG), and the CIWMB staff made the final selection of TAG members.

TAG Members

The individuals on the TAG include representatives from both the private and public solid waste industry in California (i.e., landfill owners/operators), the regulatory community, environmentalist groups, and other technical experts on landfills and/or GHG emissions. The TAG members are listed below:

- Regulatory Agency: Renaldo Crooks, CARB
- Environmentalist: Scott Smithline, Californians Against Waste
- Landfill Owner/Operator:
  - Large Public: Tim Israel, Sacramento County
  - Small Public: Mary Pitto, Rural Counties ESJPA
  - Private: Chuck White, Waste Management, Inc.
- Technical Experts:
  - Randy Masukawa, Power Management, Inc. (LFG engineering and operations expert)
  - Rich Haughey, Shaw Environment & Infrastructure, Inc. (landfill engineering expert)
  - Ramin Yazdani, Yolo County (bioreactor expert)
  - Jim Bier, Ameresco, Inc. (LFG-to-energy and LFG operations expert)

TAG Duties

The duties of the TAG members include the following:

1. Review proposed TAG nominations and provide comments via e-mail on the duties of the TAG members, including confirmation of participation on TAG.
2. Provide an alternate TAG member to act in their place and serve as point of contact and coordinator of any outside comments on the draft report from associates or colleagues within their represented group. Note that any member from the public may comment as they see fit to the CIWMB Board when this Report is presented, and TAG members themselves may provide their own comments above and beyond their TAG duties.
3. Provide assistance on specific data sources and information, if available, as part of the literature review task.
4. Review an initial list of technologies and BMPs and aid in selection of specific BMPs for inclusion in the final report.
5. Review draft final report, provide comments, and attend one meeting or conference call on the draft final report.

The TAG reviewed the project work plan, an initial listing of BMPs, and this final Report, and their comments on each of these documents have been addressed to the extent practical and consistent with the objectives of the project.

Literature Review

Background

The Project Team reviewed available literature on the technologies and practices for reducing GHG emissions from landfills. This task began with a compilation of literature and other sources of information where these issues have been addressed or covered in a relevant way. This included, but was not limited to, the topics of collection efficiency for active and passive LFG collection and control systems; LFG-to-energy; landfill design, construction, and operations; landfill covers, including alternatives; use of recycled materials as covers at landfills; landfill closure and post-closure activities; and other landfill practices as they relate to potential GHG emissions reductions.

Summary of Literature Review

To complete the literature review, the Project Team used in-house sources (the Project Team members collectively maintain a substantial library of solid waste documents), regulatory information, academic literature, environmental journals, industry supplied data (e.g., from industry groups, individual landfill companies, etc.), and any other available and relevant sources of information. Specific requests of recognized experts, including the TAG members, in this field were also made to obtain the data sources from their collections, if available. In this way, the Project Team ensured that the majority of the applicable and relevant information on the topics was available for review.

After compilation of the literature, the Project Team conducted a detailed review of the collected data. The focus of the review was on making the most defensible and up-to-date conclusions regarding the GHG emissions reduction potential from these various LFG and landfill practices and technologies being considered. However, a large percentage of the necessary information was not available from published literature and instead was drawn from the experience and expertise of the Project Team members. This is especially true for the BMPs related to LFG and landfill design, construction, and operations.

In summary, the following general conclusions were made based on the literature review:

- Although there is substantial published literature on methane emissions from landfills, there was a clear deficiency in practical measures for GHG emissions reductions at landfills.
- The various BMPs are very site-specific in nature, and therefore, it is very difficult to develop a technology that could apply to all landfills.
- The most useful literature was derived from the landfill industry in the form of technical papers presented at industry conferences, such as the annual LFG Symposium of the Solid Waste Association of North America (SWANA).
- Literature from academia tended to be very theoretical in nature and focused more on measuring or estimating methane emissions from landfills rather than practical measures that can be implemented in the field to reduce these emissions.
- There is a very limited amount of information from regulatory agencies on the relevant topics.
- The areas where the most study has been conducted recently included biologically active covers and bioreactor landfills. This research was very useful in developing BMPs;

however, both of these technologies have had limited real world application and field experience.

- The majority of the BMPs developed for this Report were derived directly from the actual experience from the Project Team and TAG members. In these topic areas, there appears to be no substitute for actual field experience and personal expertise.

A listing of all literature sources and documents is provided in the Bibliography section of this document. The Bibliography includes an entire listing of literature sources reviewed; however, only a small fraction of these documents were used in the direct development of the BMPs.

Summary of Technologies and BMPs

General Summary

The Project Team developed and evaluated technologies and management practices for applicability, cost and overall effectiveness in GHG emissions reductions, including, but not limited to design, construction, and operational practices for:

- LFG collection and control systems;
- Landfill waste management unit design and construction practices;
- Landfill operational practices including: daily cell development and construction; waste acceptance and placement; leachate recirculation and bioreactor landfill operation; and daily, intermediate, and final cover materials and practices;
- Use of compost and other recycled materials as landfill biocovers for GHG emissions reduction;
- Landfill closure and post-closure maintenance practices including partial closure.

For the LFG collection and control system BMPs, the Project Team assessed the following topics:

- LFG design techniques that could be used to maximize methane collection and destruction.
- LFG system operational strategies to enhance the efficiency, uptime, and overall effectiveness of the LFG system.
- LFG construction techniques and materials to ensure the highest level of LFG control, performance, system longevity, and operational ease.
- Early installation of LFG collection systems into new landfills, existing landfills, and/or expansion areas ahead of current regulatory requirements and criteria for implementation.
- The efficacy of installation of LFG control systems for smaller and/or older landfills, which are currently not required to have LFG control, and the possible criteria that could be used to determine when this would be warranted.
- Potential enhanced monitoring strategies to assess methane emissions and to measure the increased GHG emissions reduction through the BMPs.

For the landfill design and operational BMPs, including closure and post-closure operational aspects, the Project Team assessed the following topics:

- New cell design and impacts on LFG collection, including design of gas collectors in bottom liner systems, protection against gas escaping through liner anchor trenches, etc.
- Use of leachate collection and removal system (LCRS) components for LFG control.
- Landfill construction impacts on LFG systems and how to minimize.
- Landfill operational and phasing impacts on LFG systems and how to minimize, including waste acceptance practices, waste placement activities, and cell development.
- Designing, constructing, and operating LFG systems at sites with leachate recirculation or at bioreactor landfills and minimizing liquids impacts while enhancing LFG system design to accommodate increased gas production.
- Cover design and practices and impacts on LFG collection, including daily cover, alternative daily covers (ADCs), intermediate cover, final cover, synthetic versus soil covers, and closure phasing.
- Closure and post-closure activities and how to minimize impacts on the LFG system.

For the organics recycling and biocovers BMPs, the Project Team assessed the following topics:

- Types of biocovers and their comparative value for methane oxidation.
- Biocover design criteria.
- A brief qualitative analysis of the GHG emissions reduction potential from organic waste diversion based on published literature on the subject.

Alternatives to landfilling were also considered as possible BMPs since these waste management strategies would serve to reduce landfill methane emissions by waste diversion.

To complete BMP listing, the Project Team utilized its experts in each topic area to develop strategies for GHG emissions reductions under each area of landfill or LFG practice. The strategies were based on information developed from the literature review as well as the personal expertise and experience of the experts on the topic. This resulted in the development of an initial list of all of the available and feasible options. From this initial list, the Project Team selected certain technologies or strategies that were fully developed and selected as primary BMPs for reduction of GHG emissions from landfills.

In the information provided below, the Project Team has summarized each of the primary BMPs and how it could be implemented at landfills. The detailed description of the BMP includes applicability, rationale for inclusion in the final study report, technical feasibility, logistics of implementation, relative cost, and relative potential for GHG emissions reductions, if feasible. For the purposes of this Report, these topics were defined as follows:

- The description of the BMP provides details on what the BMPs encompass and how they serve to create potential GHG emissions reductions. Sufficient detail is provided to outline the unique nature of each BMP and various components that comprise it.
- The feasibility discussion includes general criteria that could be used to determine under what circumstances the BMP would be technically feasible (or not) without regard for cost or other factors.
- Recommendations for implementation are included to provide specific instructions for use of the BMP in actual landfill situations.
- Cost information is provided in one of two ways for the various BMPs. Where practical, actual cost information for implementation of the BMP is provided in 2008 dollars. This information could be in unit costs, cost ranges, and/or percentage increases in costs relative to the likely costs that a landfill owner/operator would incur for implementation of the BMP. In other cases where actual cost information is not available and/or would not be representative for a majority of the cases where the BMP is being considered, then relative cost is provided as a criterion for comparison of the various BMPs on a generalized cost basis. Because landfills come in varying sizes and degrees of complication, it can be difficult to provide any meaningful absolute cost information that could be used to assess the actual cost for implementation of a particular BMP on a site-specific basis. In these cases, costs are ranked on a low, medium, or high basis relative to other BMPs that are included herein. In all cases, the Project Team recommends that a detailed cost-effectiveness analysis be conducted on a case-by-case basis as detailed in the Screening Process summarized below before final selection of any BMP.

- The relative potential for GHG emissions reduction is also graded on a low, medium, and high basis relative to other BMPs. It is extremely difficult, albeit impossible, to provide numeric values for the anticipated amounts of GHG emissions reduction that can be realized with any one BMP. The success of a BMP is truly a site-specific phenomenon, which is driven by many different factors. As such, a qualitative assessment of the GHG emissions reduction potential is probably the only way to assess the potential success of a BMP. Actual quantitative estimates of GHG emissions reduction may be possible as part of a detailed site-specific analysis as envisioned under the Screening Process detailed below.

The BMP listing was originally submitted to the CIWMB and TAG for a pre-review prior to inclusion in this Report. The BMPs are summarized in Table 1 and described in more detail in the text below.

Table 1. Summary of Best Management Practices

BMP	Description	Feasibility	Implementation Recommendations	Relative Cost	Relative GHG Emissions Reduction Potential
LFG Design-Related BMPs					
Horizontal Collectors	Horizontal collectors collect LFG before vertical wells are installed.	This BMP can provide appreciable gas collection before vertical wells become feasible but it may not be feasible in wet conditions.	Horizontal collectors can be installed during the filling process but vacuum should not be applied until they will be effective for gas collection. Installation must be coordinated with fill planning to avoid damage.	Low	Medium
Surface Collectors	Surface collectors collect gas from a landfill where traditional wells fail due to water infiltration	Surface collectors are feasible where traditional horizontal and vertical collectors fail	Collectors are installed after filling is complete and are most effective with synthetic or low permeability cover	Low where synthetic cover already exists, high elsewhere	Low
Tighter spacing of LFG wells	Vertical wells are closely spaced to increase the overlap of the ROI.	Feasibility should be based on monitoring data. If data shows potential surface leaks, tighter spacing is more likely to be feasible.	Conservative assumptions should be made during the design of collection systems. Tighter spacing can be employed on a limited basis to ascertain success.	Medium	Medium
Mixed horizontal/ vertical well systems	Horizontal collectors are installed in active areas while vertical wells are placed where they are not at risk of damage from operations.	This BMP is feasible for most landfills but may be costly for some and requires coordination with landfill operations.	This BMP is recommended for deep landfills that take years to fill each section.	High	Medium
Connection of LCRS layer to GCCS	The LCRS is connected to the GCCS to collect LFG along the bottom of the landfill.	This BMP is feasible for most landfills with a LCRS and GCCS where the LCRS contains LFG.	The high side of the LCRS is connected to the GCCS to prevent the blockage. The LCRS may be monitored for gas quality to determine when vacuum should be applied.	Low	Medium
Deep multi-depth vertical wells	Wells are placed at multiple depths in the same borehole and deep wells are operated preferentially. Alternatively, wells alternate between shallow and deep.	This BMP is most feasible for deep unlined or clay lined landfills or wells operating near the landfill slope.	The use of alternating shallow and deep wells or multi-depth wells should be determined in the design phase.	Low for multi-depth wells, medium for alternating depths	Low for shallow landfills, medium for deep landfills

Table 1. Summary of Best Management Practices (cont.)

BMP	Description	Feasibility	Implementation Recommendations	Relative Cost	Relative GHG Emissions Reduction Potential
Maximize borehole well diameters	Pipe diameters of 4" or 6" are used for wells, with larger diameters if high LFG production is expected.	This BMP is feasible for the construction of all vertical well systems.	It is recommended to err conservatively and select the largest diameter.	Medium	Low
Enhance seals on LFG wells/ boreholes	Improved seals allow more vacuum to be applied to LFG wells.	Up to 3 types of seals can be placed on wells.	At least 2 seals are recommended for wells. Alternate seals are recommended in arid regions where bentonite seals can crack.	Low	Medium to high
Dewater gas wells	Various methods are employed to prevent water from blocking the flow of gas to LFG wells.	Pumps can remove water from wells that contain water, but pumping can be difficult.	Large diameter pipes make installing automated pumps easier.	High for pumping, low for designing wells and collectors to drain by gravity.	High for flooded wells, low otherwise
BMP for LFG System Piping	System piping is designed so it does not limit LFG flow.	This BMP is feasible for all LFG systems, but specific elements must be chosen on a site-specific basis.	This BMP should be implemented after an engineering review and should use conservative assumptions.	Low to medium	Low to medium
<u>BMPs for Gas Mover Equipment and Vacuum Control</u>					
Barometric control of LFG system	Vacuum applied to wells is changed based on the change in barometric pressure.	This BMP is more feasible for systems designed to run with lower vacuum.	The best implementation of this BMP would use blowers and destruction devices that allow a wide range of operation.	Medium to high	Low
Redundant flare station equipment	Spare equipment is available for less downtime.	Most flares have little downtime and do not keep spare equipment. This BMP is feasible for all sites with GCCS.	A good supply of spare parts, possibly including low quality replacements for expensive parts, should be available.	Low to medium for blowers, high for flares	Low
Maximize capacity of gas mover equipment	The blower system is designed so it does not limit the gas collection.	More uncertainty in the LFG generation requires sizing the blower higher on the performance curve.	Evaluate performance of several units and include the manufacturers' representative in the selection process.	Medium	Medium where blower capacity limits LFG recovery

Table 1. Summary of Best Management Practices (cont.)

BMP	Description	Feasibility	Implementation Recommendations	Relative Cost	Relative GHG Emissions Reduction Potential
BMPs for LFG Control Systems					
Maximum Capacity of Gas Control Equipment	Increases flare capacity and destruction efficiency, typically by increasing the flare size.	It is feasible to require that manufacturers use a 6:1 turndown ratio. Rather than using large flares, multiple smaller flares can be used.	There are two approaches: (1) Install the largest flare with the highest turndown. (2) Install multiple small flares.	Medium to high	Low if the existing flare is adequate, medium to high if it is not adequate
BMPs for LFG Enhanced LFG Operations and Maintenance					
Enhanced O&M	Training of operators, maintenance, and monitoring are increased.	This BMP is feasible for all LFG systems, but specific elements must be chosen on a site-specific basis.	This BMP should be implemented after site specific conditions are available.	Low	Unknown, expected low
General LFG BMPs					
Early installation of LFG systems	LFG systems are installed earlier than currently required by regulation.	This BMP expands the number of landfills required to install LFG systems and requires earlier expansion of LFG systems at landfills with existing systems.	Constraints to this BMP are budget, mobilization costs and economy of scale, landfill operations, and filling rates.	High for new systems, low for expansion of existing systems	High for new systems, low to medium for expansion of existing systems
LFG Master Planning	This BMP recommends the implementation of a LFG Master Plan for long term gas management planning.	This BMP is feasible for all landfills.	This BMP should be implemented with certain minimum requirements outlined in the body of the report, but those minimum requirements should be exceeded where possible.	Low	Low to medium
Energy Recovery from LFG	LFG is combusted for energy, displacing fossil-fuel use	This BMP is most feasible for large projects where and when fuel and energy costs are high.	This BMP is recommended for implementation at any landfill where the project can be shown to be economically viable.	Low, over the project lifetime	High
Enhanced Monitoring, Modeling, and Testing BMPs					
Enhanced surface emissions monitoring	SEM is conducted more frequently and under more stringent limits to detect and control lower level emissions.	This BMP is feasible for any landfill.	This BMP increases the stringency of existing landfill practices.	Medium	Low to medium

Table 1. Summary of Best Management Practices (cont.)

BMP	Description	Feasibility	Implementation Recommendations	Relative Cost	Relative GHG Emissions Reduction Potential
Enhanced gas migration monitoring	LFG migration monitoring is conducted more frequently and under more stringent limits to detect smaller emissions.	This BMP is feasible for any landfill.	This BMP increases the stringency of existing landfill practices. Siting additional LFG probes should follow CIWMB standards and guidance.	Medium	Low
Improved monitoring and testing for LFG design	LFG system design is enhanced by improved modeling and testing	This BMP is feasible for any landfill and is most feasible at landfills where there problems optimizing LFG recovery.	This BMP includes elements that can be included on a site specific basis.	Low to medium	Low to medium
Design-Related BMPs for Landfill Systems					
Cover LCRS layer	The LCRS layer is covered with waste as timely as possible.	This BMP is feasible unless waste is not available.	Cover the LCRS with at least 20 feet of waste when possible.	Low	Low
Blockage of permeable layer with landfill footprint	Blockage is created in the geocomposite near the top of the slope.	This BMP is feasible for new cell construction, but is difficult in existing cells.	This BMP is recommended for sites with a geocomposite LCRS layer which extends into the anchor trench.	Low	Low
Designing for closure and post-closure	Closure design operations take LFG systems into consideration.	These practices are typically well known and documented.	The landfill operator should develop a comprehensive O&M plan for the LFG system when closing a landfill.	Low	Low
Promote deeper landfills	Deeper landfills are allowed without requiring a larger footprint.	Landfill heights are frequently limited due to visibility, and top deck size becomes a limiting factor.	Landfills could be evaluated to determine optimum geometry.	Low	Medium to high
BMPs for Landfill Cover Systems					
Designing covers for LFG collection	The type of cover is chosen to control LFG. Synthetic final cover system.	This BMP is feasible, well known, and proven.	Cover system design should accommodate the LFG collection system components. Final cover system of lowest permeability possible.	Low on LFG items. High for synthetic final cover	Low for LFG items. High for synthetic final cover system

Table 1. Summary of Best Management Practices (cont.)

BMP	Description	Feasibility	Implementation Recommendations	Relative Cost	Relative GHG Emissions Reduction Potential
Limit delays on final cover systems	Final cover is applied to landfills sooner.	This BMP is feasible for sites that do not expect additional refuse.	Placement of final cover should be strongly considered for landfills of sufficient size and elevation.	Medium to high	Moderate
Limit or remove intermediate cover systems	Remove daily and intermediate cover immediately prior to waste filling to create more uniform gas flow through the landfill.	This approach is technically feasible and can be done by removing daily or intermediate cover in the morning or by the use of ADC such as tarps.	Implementation could be accomplished by bulldozers and scrapers.	Low to medium	Low
BMPs for Landfill Operations					
Avoiding Impacts from landfill operations	The impacts of daily operations on the LFG system are reduced.	The materials and procedures are well known and proven.	Fill placement operations and LFG collection system installation and operation must be planned out.	Low	Low
BMPs for Enhanced Landfills					
Designing LFG systems for leachate recirculation	Horizontal and vertical LFG collection wells are used to recirculate leachate.	LFG collection systems are commonly used to recirculate leachate.	Only landfills that are approved for leachate recirculation will use them.	Medium	Medium
Bioreactor landfills	Liquids are added to the landfill to bring moisture content to levels to allow enhanced waste degradation.	Bioreactor landfills are in the RD&D phase. They are likely feasible at large sites.	Bioreactor landfills require earlier installation of LFG systems.	Low	Medium to high
Biocovers	Biocovers are installed to increase methane oxidation in the landfill cover.	This BMP is feasible at sites with available organic material (e.g., compost) and/or onsite organic material processing.	This technology would first need to be demonstrated in a pilot project before it could be fully implemented.	Low	Medium
Other Solid Waste Management Strategies					
Compost	Methane generating waste is diverted from landfills thereby not generating methane.	Composting is well demonstrated and technically feasible.	Landfill owners should analyze the feasibility of developing compost on site.	Highly variable	Highly variable
Anaerobic digesters	Organic waste is anaerobically digested in vessels with a high level of methane control.	The technology has been demonstrated.	Will require programs to collect and transport the organic material. Likely to be done in conjunction with an energy-producing facility.	High	High

Table 1. Summary of Best Management Practices (cont.)

BMP	Description	Feasibility	Implementation Recommendations	Relative Cost	Relative GHG Emissions Reduction Potential
Bale waste prior to disposal	Waste is mechanically compacted into bales with LDPE and placed in the landfill. Bailing with LDPE would impede methane production.	Many landfills already bale waste.	Rectangular bales result in more GHG emission reductions than cylindrical bales.	Low	Low to medium
Segregate organic wastes in dedicated cells	Organic waste is stored separately from inorganic waste, which allows enhanced LFG collection in a limited area.	The facility must be large enough to manage organic waste separately and maintain multiple active cells.	This program should be implemented at landfills where wet/dry collection programs are already established.	High	Low to medium

BMP = best management practice
LFG = landfill gas
ROI = radius of influence
LCRS = leachate collection and removal system
GCCS = gas collection and control system
SEM = surface emissions monitoring
CIWMB = California Integrated Waste Management Board
O&M = operations and maintenance
RD&D = research development and demonstration
LDPE = low density polyethylene

Landfill Gas

Design-Related BMPs for LFG Collection Components

The most common approach to LFG collection is to wait until a landfill cell is complete and then install vertical gas extraction wells using a standard design for the well placement and spacing. This approach usually results in adequate gas collection in spite of the fact that landfills are not homogeneous. Other approaches to enhance early or more comprehensive gas collection are discussed in this section. When LFG systems are unable to control LFG emissions to the degree required or when additional LFG control is desired, modified designs can also be used. This section discusses some of the methods employed for enhancing a typical LFG collection and control system through specific design features. These BMPs are not necessarily additive, and the selection of a particular BMP must be based on site-specific conditions. BMPs for LFG design are provided below.

Use of Horizontal Collectors---

<u>Description</u>

Horizontal collectors can be used in the early life of a cell or landfill to control surface emissions. The horizontal collectors are installed across the landfill surface in trenches within the refuse and connected to the piping system at the outside slope of the landfill. A horizontal collector is usually comprised of perforated pipe laid horizontally in a trench and surrounded by gravel or other permeable substrate. The pipe is sloped to promote drainage of condensate and leachate to designated collection points, and designed to accommodate settlement (as much as practicable) of the waste. The wellheads for the horizontal collectors are installed at the outside of the fill area to allow for monitoring. By burying these collectors they are sufficiently protected to allow them to collect gas while the cell or landfill is in active filling mode. However, the collectors are not brought online until adequate refuse has been placed above them to limit air infiltration into the landfill, which may be up to 30 feet of waste thickness. This BMP allows for gas collection in the deepest portion of the waste if employed in the earliest stage of cell development as well as gas collection much earlier than waiting to install vertical collectors after the landfill cell is filled with refuse.

A variation of a horizontal well collection pattern is to use varying lengths of pipes spaced according to waste density in a particular area, such as, piping near the landfill perimeter would have a tighter spacing requirement than within the landfill interior. This would be accomplished by alternating the length of adjacent horizontal collectors between short and long. A long horizontal collector could traverse across the length of the landfill surface, even “day-lighting” (i.e., coming to the surface) out of the back side of the landfill. A short horizontal collector would protrude 50-100 feet into a landfill. The purpose of variable spacing is to place more collectors in areas where gas is most likely to leak from the landfill (e.g., side slopes caused by the greater horizontal permeability of refuse than the vertical permeability), while reducing installation costs of a more comprehensive system. Horizontal collectors are in use at many sites in California (e.g., Chiquita Canyon Landfill, El Sobrante Landfill, Potrero Hills Landfill, etc.). Figure 1 provides a schematic diagram of a landfill with a layout of horizontal collectors and details for a typical horizontal collector.

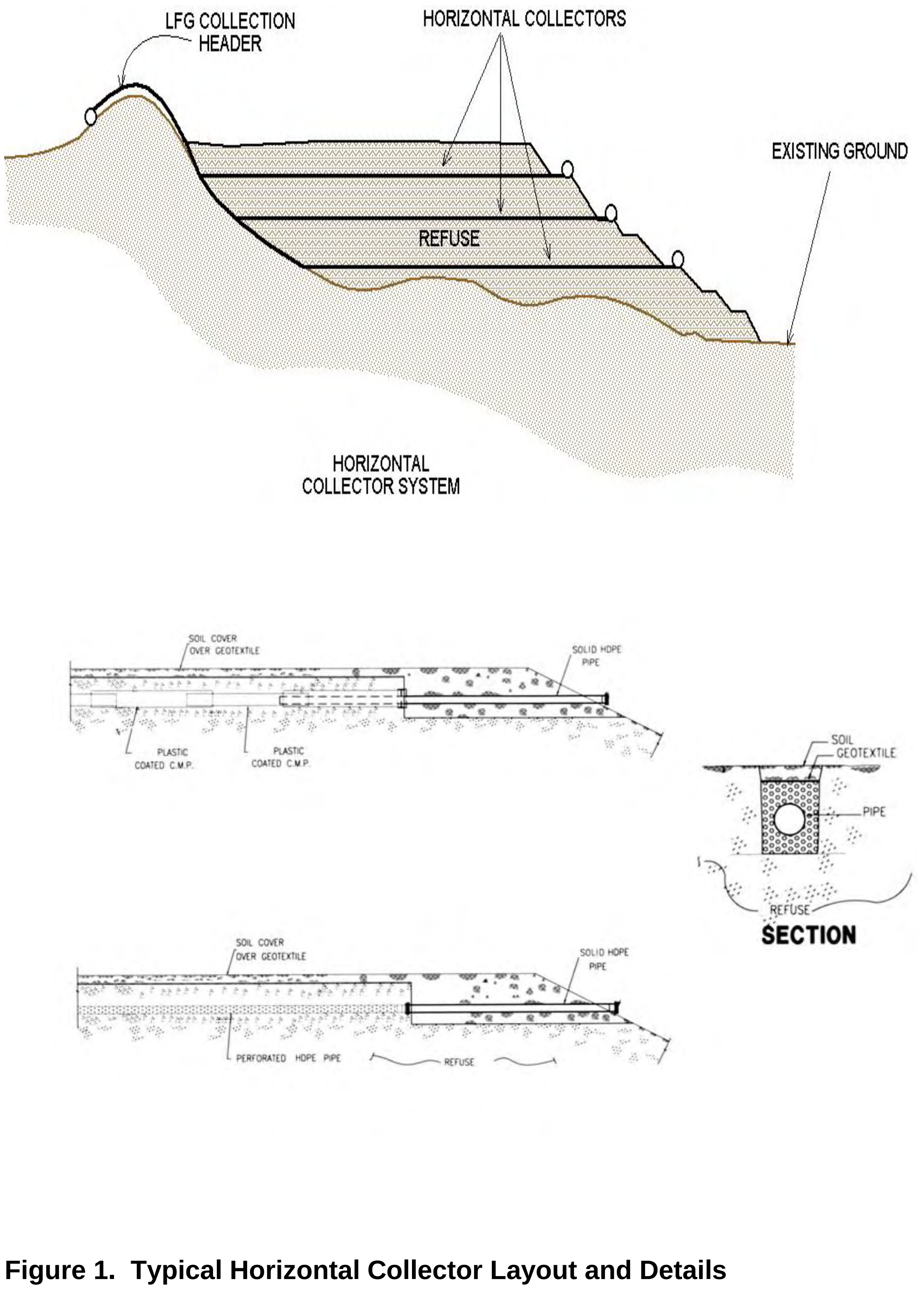


Figure 1. Typical Horizontal Collector Layout and Details

A continuous planar layer of permeable material located higher in the waste mass has also been shown to provide efficient LFG collection (e.g., Yolo County, University of Delaware, Waste Management, Inc.) and can be used in lieu of or in concert with a comprehensive horizontal collector system. This technology is discussed in further detail below.

Feasibility

The feasibility of using horizontal collectors is based on whether a landfill cell or area will remain in active filling mode into the time period when the refuse will begin to produce collectable quantities of LFG. While this is ultimately dependent on the size of the cell (i.e., amount of waste) and the precipitation levels (i.e., moisture in the refuse), appreciable gas production can begin as early as six months and up to five years from initial waste placement in a conventional landfill. Geometry of the fill sequence can also be a limiting factor in placement of horizontal collectors. Long, relatively consistent lifts are needed to effectively install the collectors. Horizontal collectors can provide a valuable level of gas collection during the interim period before the cell or landfill reaches a final or interim grade when vertical wells would become more feasible and/or in landfills where LFG production is slow to mature (i.e., dry sites). A horizontal collector may not be the best practice in cells which reach final or interim grade quickly and where vertical wells can be employed because it may not provide as much benefit in LFG control. They may also not be feasible in refuse areas with high liquids content in the waste since the horizontal alignment of the collector is more susceptible to inundation with water.

Implementation Recommendations

Horizontal collectors or permeable layers are installed as the filling progresses so the collectors are geometrically distributed throughout the thickness of the waste; however, vacuum is not initially applied to them immediately after installation. This is because at their shallowest point, the collectors are too close too surface of the landfill and air will likely short-circuit into the refuse when a vacuum is applied. The short circuiting reduces horizontal collector effectiveness and radius of influence and increases the potential for landfill fires due to oxygen intrusion. In many cases, the horizontal collectors are monitored for gas quality, quantity, and/or pressure build-up prior to applying a vacuum to them to determine anaerobic conditions have established before implementing gas collection. Horizontal collectors should be activated when the depth of waste above the collector reaches an adequate thickness to prevent excessive air intrusion, after the cell begins to generate sustainable quantities of LFG, and when logistical considerations with the cell construction will allow connection of the collector to the LFG system. The installation of horizontal collectors must be coordinated with fill planning since its construction has the potential to impact landfill operations, and poor coordination can result in damage or destruction of the collector.

Horizontal collectors are at risk of failure due to air short circuiting into the well from landfill settlement, and because of the weight of multiple lifts of refuse on top of them. If horizontal wells fail, they can be supplemented with vertical wells to collect LFG.

Relative Cost

The use of horizontal collectors would increase the cost of the LFG system versus simply waiting to install vertical wells when final or interim grade is reached and/or when regulations mandate installation. Horizontal collectors are a potentially cost-effective way to achieve control during the early life of a landfill or cell, and may result in some avoided costs for managing vertical wells with above grade piping in active filling areas. Overall, the relative cost for implementation of horizontal collectors is expected to be low because of some of the avoided operational impacts in the LFG system. Horizontal wells may also reduce the need for vertical wells offsetting some of the increased costs of this approach. The 2008 unit price for installation of horizontal collectors is expected to range from $40/foot to $55/foot for 6-inch HDPE collectors in a 6-foot deep trench.

Relative GHG Emissions Reduction Potential

When used properly, horizontal collectors can control methane generated during the early life of a landfill or cell. They can also collect LFG which has escaped collection throughout the rest of the system and is moving toward the surface of the landfill. Properly utilized horizontal collectors are expected to have a relative GHG emissions reduction benefit that is medium.

Use of Surface Collectors---

Description

Surface collectors can be used to collect gas from a wet landfill where traditional horizontal and vertical wells fail due to water infiltration. The surface collectors are installed across the landfill surface above the refuse. A surface collector is usually comprised of perforated pipe laid across part of a landfill covered by an impermeable geomembrane. Gas flow below the geomembrane is promoted by installing a permeable layer. The wellheads for the surface collectors are installed at the outside of the membrane to allow for monitoring. By burying these collectors, they are protected from the weather.

Feasibility

The feasibility of using surface collectors is based on the lack of feasibility of more conventional vertical and horizontal LFG extraction wells. Surface collectors can provide gas collection when other well types fail due to flooding.

Implementation Recommendations

Surface collectors are installed after filling is complete. Because of their shallow installation air will likely short-circuit into the refuse when a vacuum is applied. The short-circuiting reduces collector effectiveness and radius of influence. Therefore, these collectors are most effective when a synthetic or very low permeability landfill cover in installed. These collectors can provide either passive or active gas control through connection into the LFG system. Surface collectors are at risk of failure due to air short-circuiting below the geomembrane cover if too much vacuum is applied.

Relative Cost

The use of surface collectors would increase the cost of the LFG system versus by requiring the installation of an additional collection layer above the refuse. Overall, the relative cost for implementation of surface collectors is expected to be low at sites where geomembrane covers are already being installed and high at other sites because of additional cost for geomembrane material, which would be needed to prevent air intrusion. The 2008 unit cost for the installation of a surface collector would be approximately $25 to $35 per foot for a 6-foot deep trench and rock pack. The 2008 unit cost for installation of a geomembrane cover could range from $40,000 to $50,000 per acre of landfill surface.

Relative GHG Emissions Reductions

Surface collectors can control methane from a landfill surface following landfill completion. They would not be effective in collecting gas while a landfill is being filled. They will not place vacuum directly into the refuse, hence they would only control LFG that has escaped collection and has moved toward the landfill surface. Properly utilized surface collectors are expected to have a relative GHG emissions reduction benefit that is high in their immediate vicinity but overall low.

Tighter Spacing of Vertical LFG Wells---

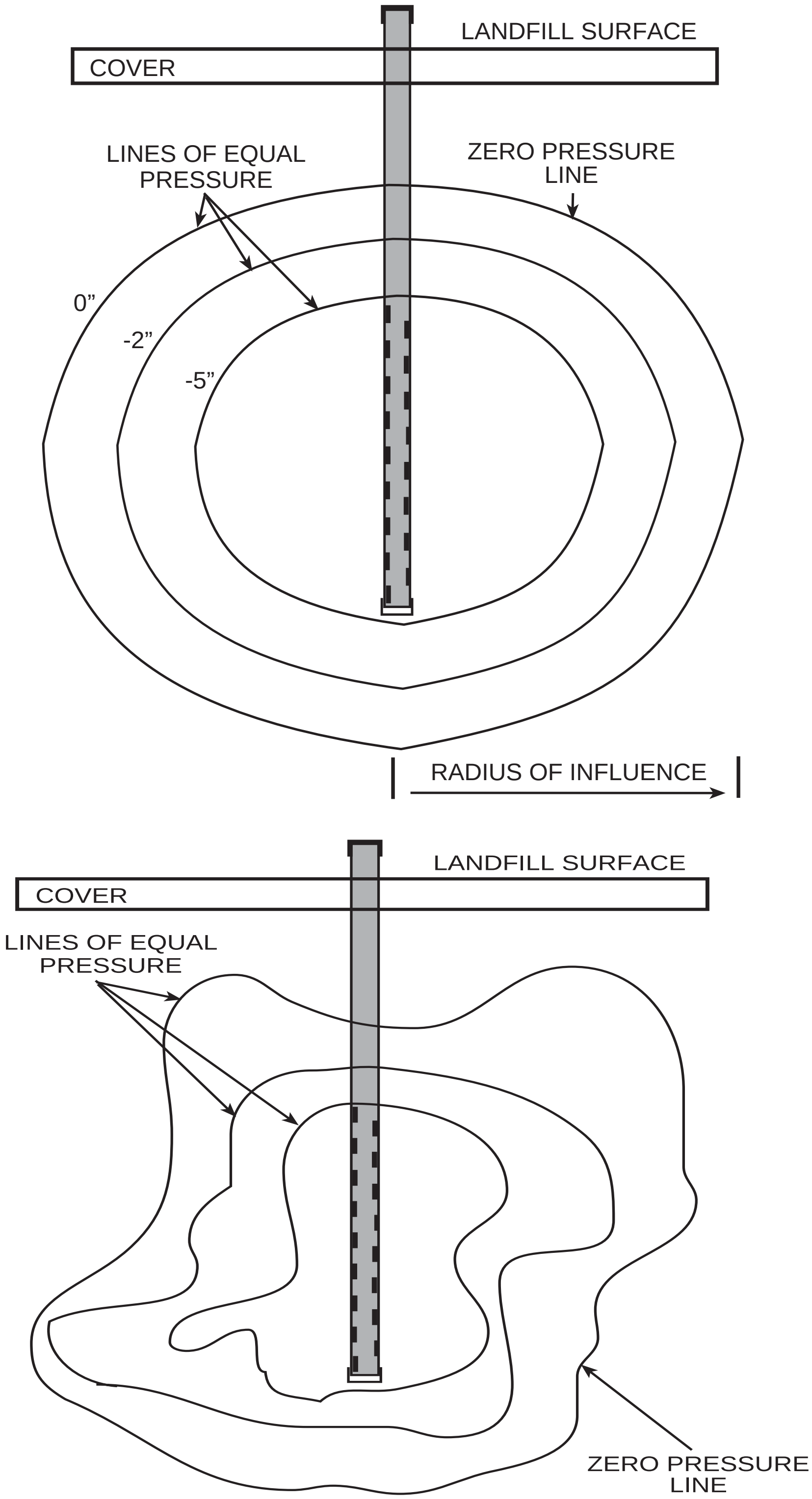
Description

Vertical LFG wells are the primary method of LFG collection for the majority of California's landfills. The spacing of these wells depends on various parameters, including the thickness of the waste, water content of the waste, type of daily and intermediate landfill cover, the length and placement of the perforated well pipe, the diameter of the well, the use of well bore seal(s), the distance from the top of the perforations to the landfill surface, and the vacuum available. LFG system designers use various tools, models and experience to estimate the expected radius of influence (ROI) for particular wells and use this value to determine the number and spacing of wells to provide adequate coverage in a landfill or cell. This design generally uses some degree of overlap of the radii of influence for neighboring wells to provide vacuum throughout the waste. However, wells can fail for a variety of reasons, and there is always uncertainty in estimating the radius of influence, and therefore, there may be room for reducing the spacing of wells (and increasing the overlap of the radii of influence) in a conservative LFG system design.

A variation that can be implemented to improve LFG collection but may reduce installation costs is to use a variable well spacing. Wells near the perimeter or edge of a landfill are more prone to air short-circuiting into the landfill and therefore less likely to operate at high vacuum. Therefore, these wells would be installed at a relatively close spacing and operated at lower relative vacuum then interior wells. However, wells on the interior of a landfill do not have the same air short-circuit potential hence it may be possible to operate these at much higher vacuum, and as such, not as many vertical wells are required. Therefore, fewer interior wells could be installed and still place adequate vacuum on the landfill. It must be shown that any reduced spacing in the interior does not jeopardize control of LFG within the entire extent of the refuse.

Vertical wells are in use at the majority of landfills in California with active LFG systems. Figure 2 shows a theoretical and actual ROI for a vertical extraction well. Figure 3 depicts a typical vertical extraction well. Figure 4 shows a network of vertical well types.

Figure 2. Theoretical and Actual ROIs



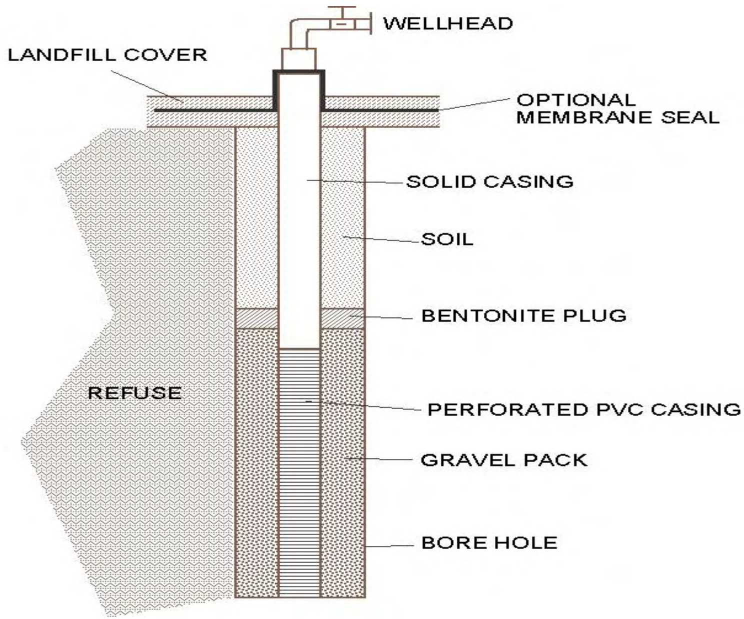


Figure 3. Typical Vertical Extraction Well

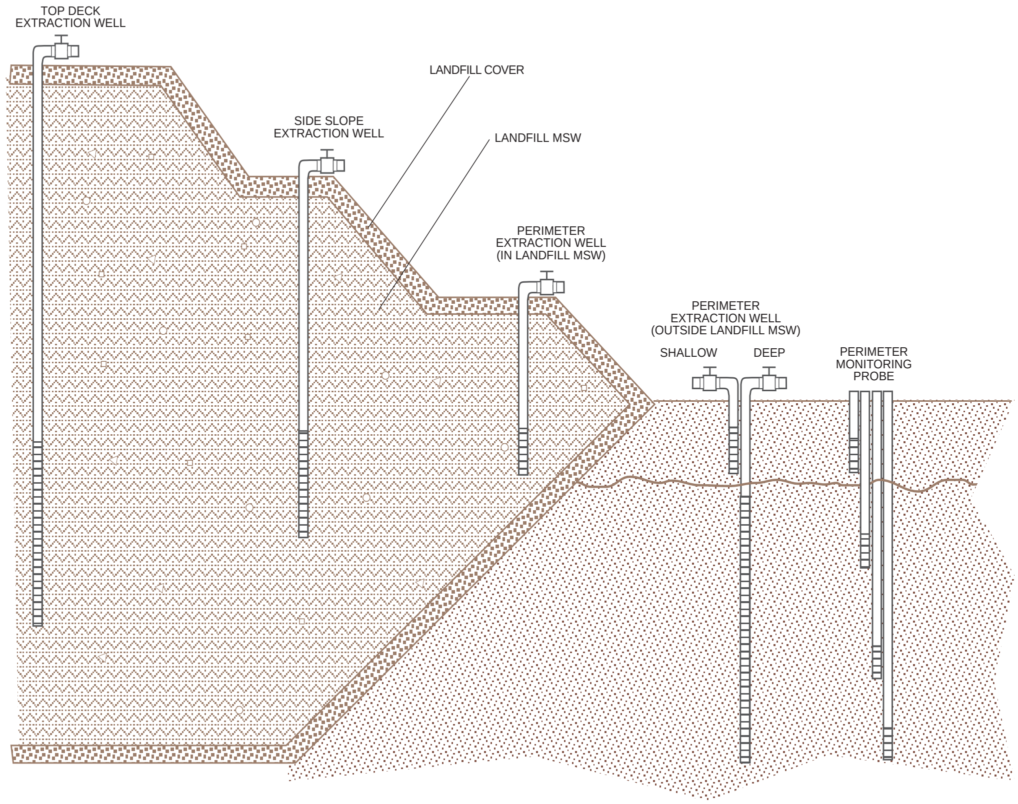


Figure 4. Network of Vertical Extraction Wells Types

Feasibility

The feasibility of using tighter spacing of vertical wells should be based on monitoring data, which suggest the LFG system is not collecting the amount of LFG expected (e.g., excessive surface emissions, subsurface migration, odor, recovered gas flows less than model predictions, or other evidence of gas emissions). Tighter well spacing is likely more feasible in these cases where data indicate the need but is generally feasible at any landfill to achieve a greater degree of coverage throughout the refuse. It should be noted that vertical well installation should be avoided in active landfilling areas. Extension of the wells is difficult and the survival rate of wells is not good. These wells are prone to damage or destruction due to the driver's limited visibility from the cabs of dozers and compactors during active landfill operations.

Implementation Recommendations

To implement this BMP, the designer must employ conservative assumptions when selecting the radius of influence for well spacing. Every design method generally derives a range of possible values, and the engineer should select a value or criteria at the conservative end of that range. For initial LFG systems at a landfill or within a cell, this would be employed as part of the design development. For existing landfills, this strategy could be implemented as part of a planned expansion and/or when data suggest complete LFG coverage does not exist. Tighter spacing can be employed on a limited basis at first to ascertain whether it will be successful on a larger scale by tracking the increase in total and per well gas flows. There is a point of diminishing return with this BMP whereby additional collectors do not increase the amount of extracted methane because the additional wells are simply drawing gas from other wells rather than from an uncollected reservoir. Competing vacuums between neighboring wells can also increase operations and maintenance costs.

Relative Cost

The use of tighter well spacing would increase the cost of the LFG system versus systems with less comprehensive landfill coverage. The cost-effectiveness of this BMP is ultimately dependent on the amount of LFG not collected under the existing or less conservative design. Many times this can only be determined through trial and error. Overall, the relative cost for implementation of tighter vertical well spacing is expected to be medium. This increased cost can be somewhat offset by using variable well spacing on the landfill perimeter vs. the interior. The 2008 unit cost for drilling and installation of vertical wells is $65 to $85 per foot for 4- to 6-inch Schedule 80 PVC wells in up to 36-inch boreholes. Additionally, the 2008 unit cost for each wellhead assembly is expected to range from $400 to $650/each for 2-inch wellheads with piping and valves.

Relative GHG Emissions Reduction Potential

When applied appropriately to sites with inadequate well coverage, tighter well spacing may increase methane recovery while reducing air infiltration (e.g., the closer spaced wells can be operated at reduced vacuum levels in comparison to wells spaced farther apart and reduced vacuum can reduce or eliminate the tendency to pull air into the wells from the landfill surface or adjacent side slopes). Conservative LFG designs for well spacing are expected to have a relative GHG emissions reduction benefit that is medium for this condition.

Mixed Horizontal/Vertical Well Systems---

Description

Horizontal collectors offer the benefit of early gas collection, but they are not as efficient as vertical wells at collecting LFG because the permeability of refuse is greater horizontally than vertically. Therefore, horizontal wells create a horizontal layer of efficient gas collection, but vertical vacuum distribution is not as good. This requires horizontal wells on a tighter vertical spacing so they can cover gas collection throughout a landfill. Vertical wells are more efficient at collecting LFG in general; however when installed in an active landfill zone, they can interfere with filling operations because of above grade well heads and lateral piping. A hybrid system consist of horizontal collectors to collect gas across the horizontal plane of active landfill areas, including near surface gas, and vertical wells to collect gas from areas of the landfill that are at or near final or interim grade or are in areas which are not active for filling. This offers the advantage of interim control with horizontals in active areas, including sufficient surface emission control, while keeping wells out of the way of landfill operations. Vertical wells are installed when they are not at risk for damage from operations. Figure 5 depicts a mixed horizontal and vertical well system at a landfill in California. Most landfills in California that utilize horizontal collectors also use vertical wells in conjunction (e.g., Chiquita Canyon Landfill, El Sobrante Landfill, Potrero Hills Landfill, etc.).

A variation of this approach is to drill a vertical hole below a horizontal collector and backfill it with rock thus creating a rock column that can be used to vent deep gas to the horizontal collector. The rock column would operate at the same vacuum as the horizontal collector. Because horizontal collectors typically operate at much less vacuum than vertical wells, this system would not collect gas as efficiently as a vertical well. A continuous permeable layer as discussed above under horizontal collectors overcomes this disadvantage to some extent as LFG moving upward from any location would typically encounter the continuous permeable layer.

Feasibility

While this BMP is feasible for most active landfills, it is inconvenient at many sites because vertical wells are installed in smaller increments as areas reach grade or become inactive. Multiple drill rig mobilizations can be expensive depending on where the equipment is stationed, and is more costly than single mobilizations for installation of a larger number of vertical wells. The installation of horizontal collectors will need to be coordinated with landfill operations, and the collectors must be accurately surveyed to prevent future damage from operations or drilling into the refuse.

Implementation Recommendation

This BMP is recommended when dealing with large, deep landfills that take years to fill a section of the landfill. This approach would provide good gas collection and surface emission control throughout the life of this type of landfill. Upon closure, vertical wells could supplement horizontal collectors across the landfill surface.

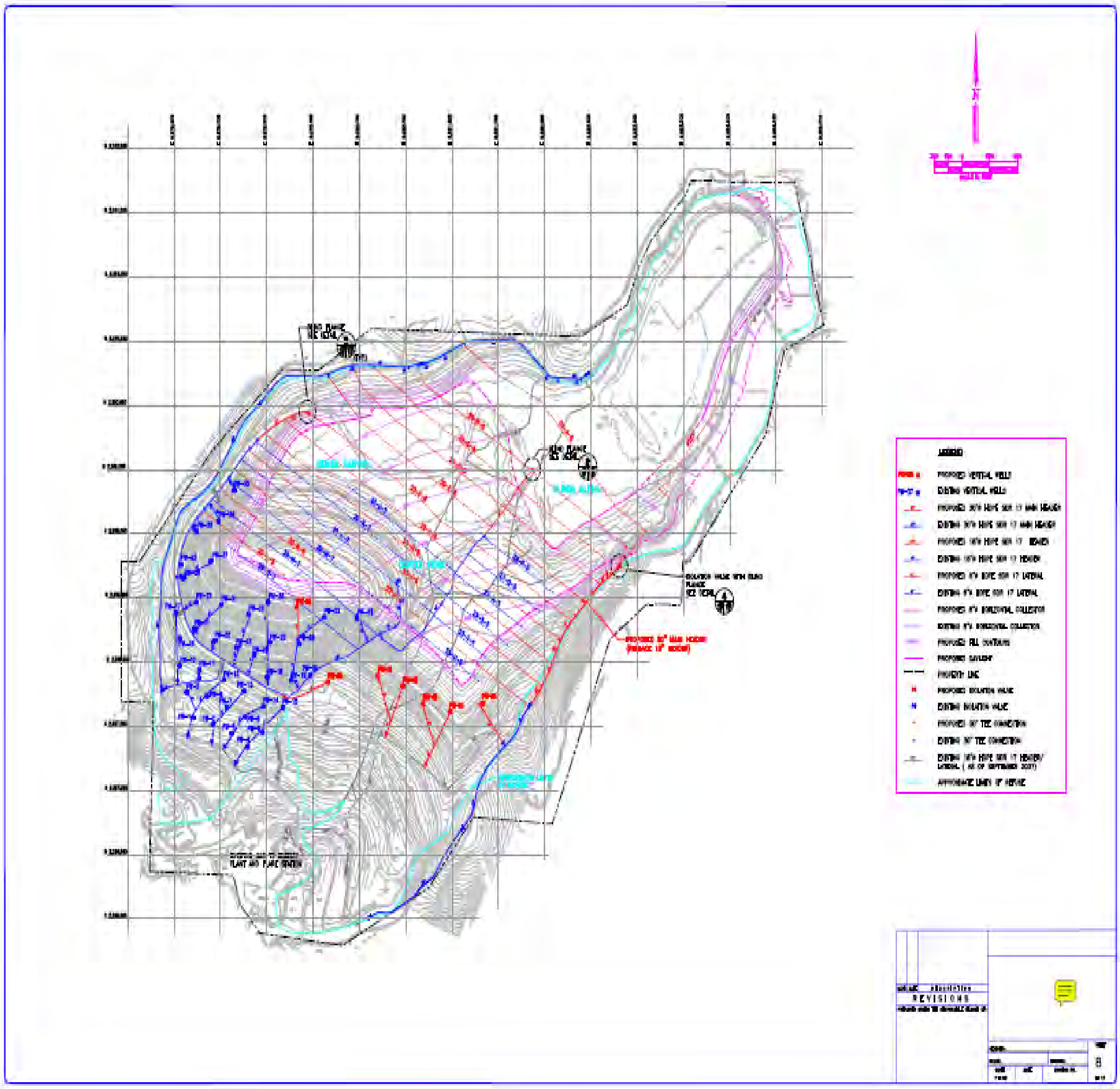


Figure 5. Example of Combination of Vertical Well and Horizontal Collector System in California

Relative Cost

It is expected that this system would be more expensive because of the higher costs of horizontal collectors and the multiple drill rig mobilizations for vertical wells, which are installed at strategic times in the landfill life. If the landfill is hundreds of feet deep, then this system could have some cost savings because some very deep vertical wells could be avoided. However, horizontal collectors are many times sacrificial because of the crushing effect of the weight of the refuse (corrugated metal pipe can be used to help overcome the crushing issues with HDPE or PVC but the construction cost can be greater). As such, the ultimate loss of function for these collectors must be factored into a cost analysis. We expect the relative cost to be medium to high for full implementation of the combined systems approach. The 2008 unit costs for horizontal collectors and vertical wells were provided above and are also applicable to this BMP.

Relative GHG Emissions Reduction Potential

Properly used combination systems are expected to provide good early LFG collection and provide the greatest benefit during this time. The relative GHG emissions reduction is expected to be medium.

Connection of LCRS Layer to LFG Collection System---

Description

Connection of the leachate collection and removal system (LCRS) to the LFG collection system is a way to collect LFG beneath the refuse along the bottom of the landfill. The LFG collection system is connected to the LCRS by installing a lateral pipe connection, with corresponding wellhead, to an LCRS riser pipe, clean-out, or other access point. Figure 6 provides photographs of an LCRS connection to the LFG system. The connection of the LCRS to the LFG system is becoming more commonplace in California (e.g., Pacheco Pass Landfill, Ostrom Road Landfill, etc.)

Feasibility

This BMP is feasible for a landfill with an existing LFG collection system that can be connected to the LCRS at strategic points. It is the most effective when there is a known presence of appreciable quantities of LFG in the LCRS, which can be determined through testing. This BMP should also be considered for newer lined landfill cells as means of control from beneath the deepest layer of waste. It performs best in drier climate sites when the LCRS is not constantly filled with liquid; however, with California requirements to limit or eliminate head on the liner, it has proven feasible at most landfills in the state.

Implementation Recommendation

This BMP should be implemented by connecting the high side of the LCRS to the LFG system to avoid leachate blockage at the collection point. The LCRS well is brought online when it is buried by waste; otherwise, excessive oxygen will be drawn into the LFG system through short-circuiting with ambient air. The short-circuiting reduces LFG collection effectiveness and increases the potential for landfill fires due to oxygen intrusion. Some cleanout/riser pipes run along the bottom perimeter so that there may be vacuum influence on the side slope drainage layer as well, which is an added value in preventing LFG migration or escape of gas over the liner anchor trench. In many cases, the LCRS connections are monitored for gas quality, quantity, and pressure build-up prior to applying vacuum.

Figure 6. Photos of LCRS Connections to LFG System

Relative Cost

This BMP is not costly and is easy to implement, so the relative cost is considered low. Each connection would include the costs of a LFG wellhead (2008 unit price of $400 to $650 each) and some above grade piping with a 2008 unit cost of $10 to $15 per foot for a 3- to 4-inch HDPE pipe that is staked.

Relative GHG Emissions Reduction Potential

Connection of the LCRS system is an effective way to capture additional LFG from beneath the waste mass along the landfill bottom. It has a medium to high GHG emissions reduction potential early in a cell's life where the LFG preferentially moves into the LCRS, and the LCRS cleanouts continue to be excellent collectors of LFG in the deep portions of landfills (subsurface migration prevention). As a cell ages, the reduction potential will decrease.

Deep Multi-Depth Vertical Wells---

Description

The deeper a well is imbedded in refuse, the greater vacuum that can be applied. With this BMP, a two-depth or three-depth vertical wells (i.e., multiple nested well pipes in the same borehole or adjacent wells of varying depths) may be advantageous by operating the deep zones at greater vacuum than the shallow zones. Deep zones would be operated preferentially over shallower zones. If additional gas is present as evidenced by positive pressure in the well, shallower wells can be brought online sequentially from bottom to top. This pressure condition can exist because of the reduced vertical permeability of refuse vs. horizontal permeability.

A variation of closely spaced deep multi-depth vertical wells is to alternate the pattern between deep wells and shallow single depth wells. This pattern helps take care of the problem of shallow wells having a reduced radius of influence compared to deep wells. It also reduces the construction cost caused by drilling deep vertical wells.

Sometimes vertical wells are installed in the active fill area of a landfill. These wells cause special problems because they can interfere with landfill operations. There are several ways of dealing with this issue. The simplest is to bury the vertical wellhead in refuse and extend a lateral pipe to a valve that is accessible at the edge of the landfill. This system is prone to failure by the well being crushed or by differential settlement causing the lateral pipe to fail. Another option is to extend the vertical well by the height of a refuse lift, place dirt around the well, and fill refuse around the dirt. Wells extended in this manner have the advantage of being deep in refuse, however they are costly to protect and prone to failure. Dual-depth vertical wells at in use at some of the deeper landfills in California with refuse depths over 100 feet (e.g., Otay Landfill, Ox Mountain Landfill, etc.). Figure 7 depicts a typical dual-completion extraction wells installed at different depths within the same borehole.

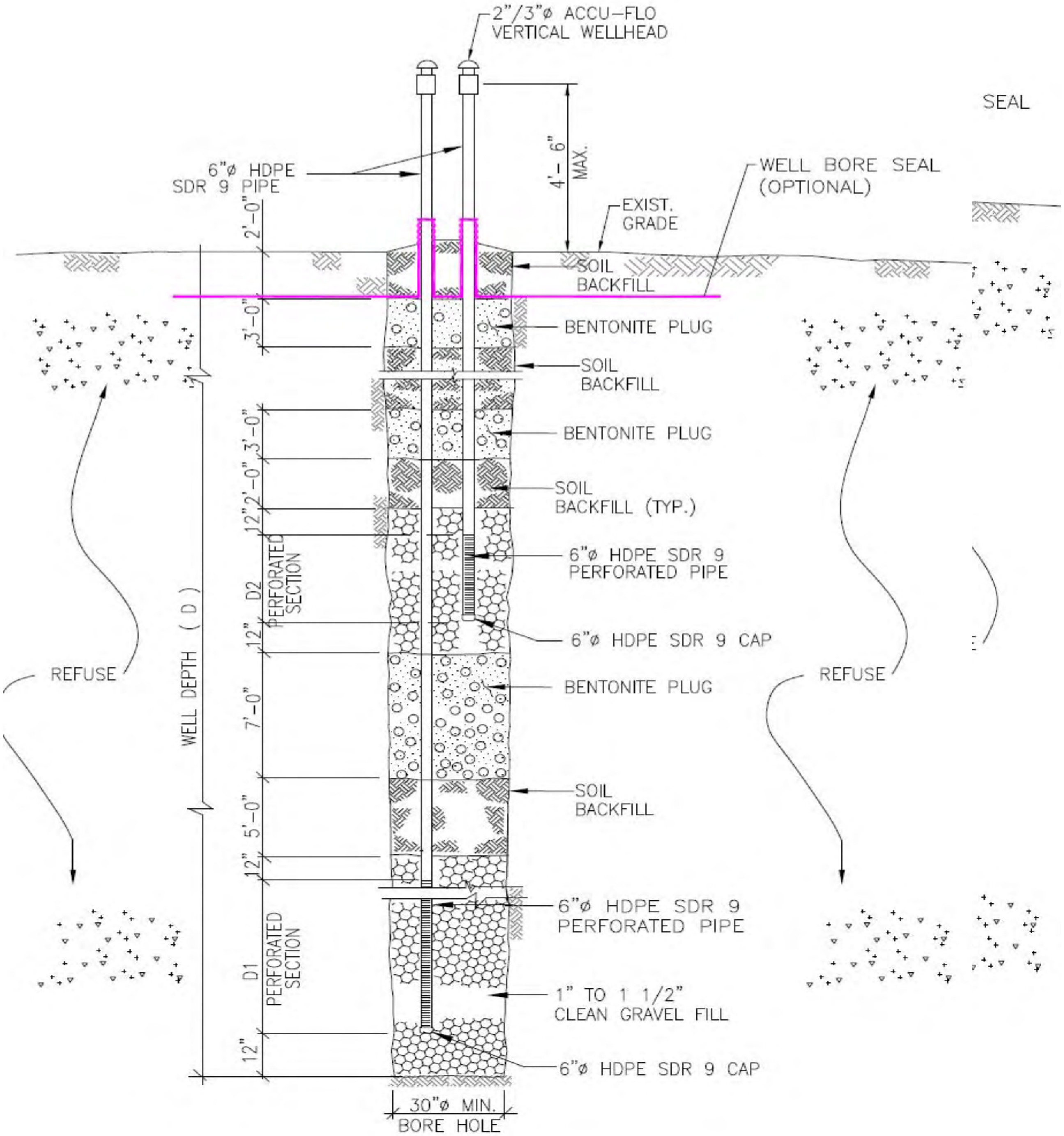


Figure 7. Typical Dual-Completion Vertical Extraction Well

Feasibility

The feasibility of using multi-depth vertical wells is dependent on the depth of the landfill and the need for deep LFG migration control. This installation would be most applicable to deep unlined or clay-lined landfill cells with evidence of lateral gas migration or LFG wells operating near a landfill slope where shallow wells are prone to short circuiting. In this latter case, the landfill slope creates a variable air short-circuit path with the shortest distance being at the top of the perforated pipe. This short-circuit path length then limits the vacuum that can be applied to the well. By splitting the well into multiple depth casings and maintaining greater depth to the perforated sections, the short-circuit path for deep wells is longer hence greater vacuum can be applied to them.

Implementation Recommendation

The designer would start by applying conservative design assumptions for the spacing of the shallow wells. This dictates the spacing of the wells. Next an evaluation of possible vacuum that can be applied to a deep well zone would be made. If the ROI of a deep zone could be doubled based on the longer short-circuit path then alternating deep and shallow wells could be constructed. A positive benefit of increasing the air short-circuit path is reduced air infiltration into a landfill.

Relative Cost

Multi-depth vertical wells of similar depth to single depth wells can be implemented for a nominal cost increase over traditional vertical wells. The nominal cost would include additional materials of construction, and additional wellhead(s), monitoring port(s), and control assemblies. Deep vertical wells can get expensive when they exceed 120 feet. There are some economies of scale because one borehole is essentially used for two wells, except when using the alternate pattern type design where two boreholes are used. The 2008 unit cost for drilling and installation of dual-depth vertical wells is $80 to $120 per foot for 4- to 6-inch PVC wells in up to 36-inch boreholes with the cost increasing as the well gets deeper. This is a total cost and can be compared to the single depth well cost provided above to get an incremental cost. Additionally, the 2008 unit cost for each wellhead assembly is expected to range from $400 to $650/each for 2-inch wellheads with piping and valves.

Relative GHG Emissions Reduction Potential

There are two benefits to variable vacuum within a landfill. First, it may be possible to have some improvement on GHG emissions reductions through better application of vacuum throughout the refuse depths. The second benefit is to reduce air infiltration in a landfill, thus potentially improving LFG quality and quantity. The estimated amount of GHG emissions reduction is rated as low at shallow landfills, but medium at landfills with refuse thicknesses greater than 100 feet.

Maximize Borehole and Well Diameters---

Description

One way to help maximum production and life of each individual vertical well is to increase the pipe diameter and install the well in a larger borehole. LFG extraction wells are commonly constructed with pipe diameters ranging from two to six inches within boreholes that range from eight to 36 inches. However, the smaller diameter wells may ultimately limit the amount of LFG flow that can be achieved in the well. As such, in the design of vertical well systems, it is preferred to use the larger diameter pipe with a minimum of four inches with a provision to increase to six inches or more if high LFG production is expected. Larger diameter wells will also be more resistant to pinching and can accommodate the insertion of pumps for liquids removal. However, in shallow, dry landfills, smaller diameter boreholes and casings may be acceptable and more effective in conjunction with closer well spacing.

Larger diameter boreholes ensure that the well is protected to the maximum degree against settlement and help to avoid the plugging of piping perforations due to fine material passing through a thin gravel pack layer. They also decrease the likelihood that refuse will fall back into the borehole before the well is placed decreasing the amount of gravel pack around the well.

Large diameter boreholes also offer greater surface perimeter area to apply vacuum to the refuse. Deep vertical extraction wells should be installed in a minimum of a 24-inch borehole with a provision to increase the borehole to as large as 36 inches in areas with excessive liquids. It is also important to use a high quality pipe for wells, including Schedule 80 PVC, higher grade, i.e., thicker wall HDPE (e.g., SDR 9 or 11), or steel pipe in areas with expected high gas temperatures consistently over 150 degrees F.

Feasibility

This BMP is feasible for all vertical well systems. It is most feasible for extraction wells where high gas production is expected.

Implementation Recommendation

This BMP should be implemented after an engineering review of the site conditions and selection of the appropriate pipe and borehole sizes. If there is uncertainty in the design, it is recommended to err on the conservative side and select the largest diameters for both.

Relative Cost

The added cost of this BMP is in more expensive pipe and potentially increased drilling costs for the larger boreholes and backfill materials. The relative cost is considered medium compared to LFG systems where this BMP is not implemented. Deep wells may actually benefit by large diameter boreholes because it is less likely that refusal will limit the depth of a well because larger items can be extracted through the borehole. The expected costs for this BMP would include actual costs on the high end of the ranges presented above for vertical wells.

Relative GHG Emissions Reduction Potential

The use of larger pipe and borehole diameters is an effective way to maximize the amount of gas that can be recovered from an individual well or series of wells. This BMP ensure that the design of the well itself will not become a limiting factor in the LFG system's ability to collect methane. The expected methane reduction potential is low compared to other LFG BMPs.

Enhanced Seals on LFG Wells/Boreholes---

Description

LFG extraction wells function by applying vacuum to the landfill. The amount of vacuum that can be applied is limited to a great extent by the seal between the perforated collection zone and the nearest source of air infiltrating the landfill. One source of air infiltration is through the well borehole for vertical wells or through the well trench for horizontal collectors. The design for vertical wells typically includes the use of bentonite or bentonite soil mixtures near the surface as part of the well boring backfill to reduce the potential for air to be pulled into the well. Compacted backfill soil can also be considered but may not be practicable and adds risk of damaging the well casing pipe.

Well connecting pipes are typically sealed using three different techniques: 1) bentonite clay seal, 2) compacted clay seal, and 3) plastic well bore seal. Often times multiple seals are used because of the critical need to have a good seal on the well so it can perform properly. Los Angeles County Sanitation District research showed that a geomembrane at the surface extending a few feet from the well effectively increased collection efficiency. Figure 8 depicts a typical detail for a well bore seal.

Feasibility

All of the above methods are feasible for sealing vertical wells. Methods 1 and 2 above are feasible for sealing horizontal wells. The key question is what redundancy is reasonable and appropriate. Many engineers require 2 and sometimes 3 seals in a well. Combination seals could include the specifications in the table below.

The first bentonite seal is placed deep in the borehole. Other seals are typically installed closer to the landfill surface. Landfills closed using a clay cap will typically have a clay seal in the well borehole that matches the cap depth. A good surface seal appears to be more effective at minimizing surface emissions and borehole air intrusion.

Two Seals	**Three Seals**
Bentonite – Bentonite	Bentonite – Clay – Bentonite
Bentonite – Clay	Bentonite – Clay – Well Bore Seal
Bentonite – Well Bore Seal	Bentonite – Bentonite – Well Bore Seal

Implementation Recommendation

Because of the critical nature of seals, a minimum of two seals is recommended. Additional seals do not cost a lot but provide an additional measure of security against failure. In arid landfills alternate seals may be preferable in addition to the bottom bentonite seal in case the arid conditions cause the bentonite to desiccate and crack.

Relative Cost

The relative cost is low, typically only requiring additional materials and labor for installation. The 2008 unit costs cost to install a well bore seal can range from $500 to $2500 per well depending on the type of seal chosen.

Relative GHG Emissions Reduction Potential

For wells to have the proper radius of influence they need to be properly sealed. Compared to improperly sealed wells, this BMP would have a medium to high GHG emissions reduction potential.

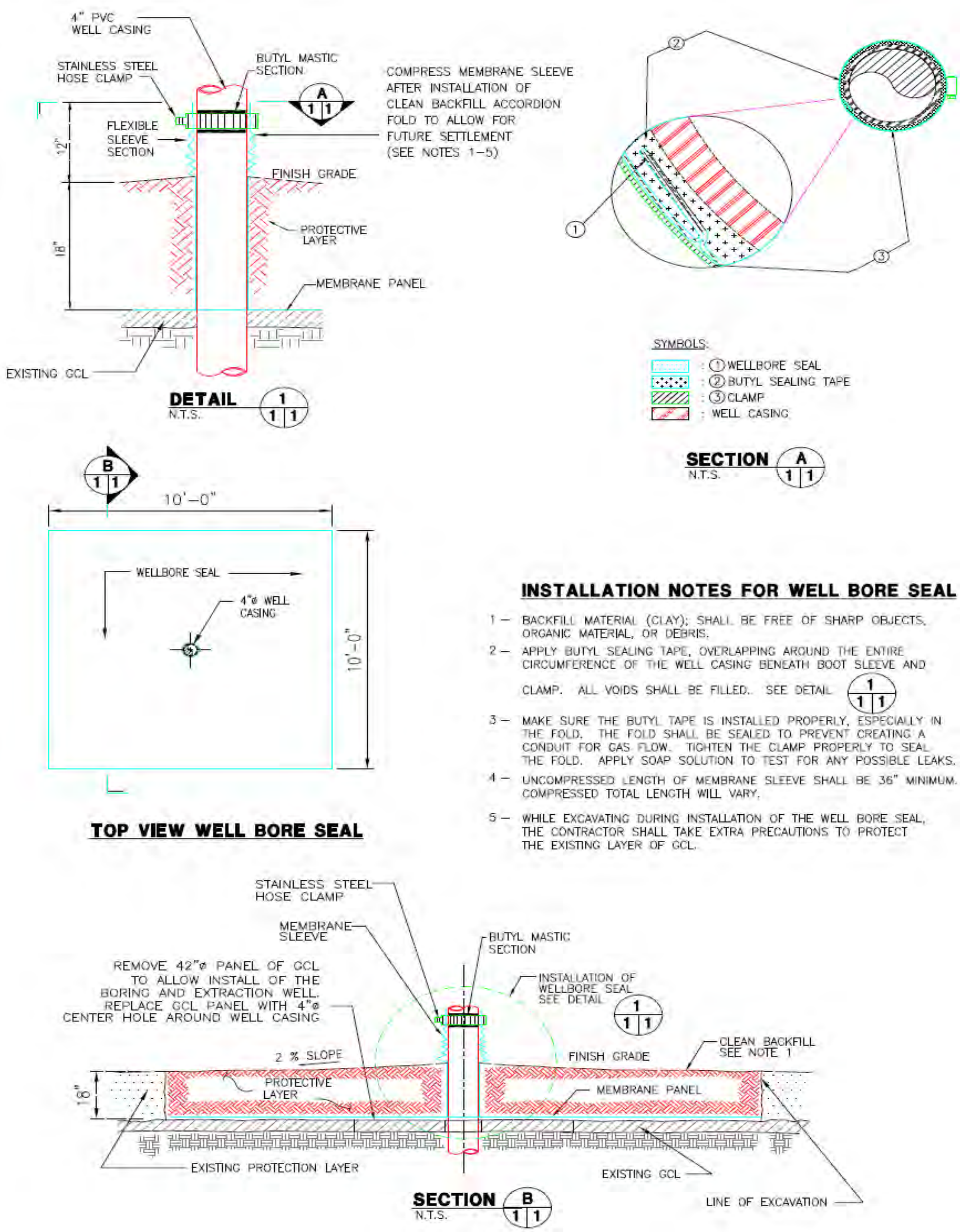


Figure 8. Typical Well Bore Seal

Dewatering of Gas Wells---

Description

Wells are unable to pull gas through liquid. In some cases, leachate or LFG condensate can perch within the refuse and create wet zones in the landfill. Keeping well screens free of liquid is essential for proper performance. The most practical method of keeping liquid out of wells is to prevent its entry. Perched water can be found in landfills that use clay for daily or intermediate cover.

One method that has been used with some success is to place a bentonite seal opposite perched water in the refuse. The problem is identifying the perched liquid levels (this is best done using a down-hole camera) and the ability to accurate place the seal. Another method is to conduct field investigations of liquids levels in the waste prior to installation and avoid those areas in the design. A third method is to utilize solid pipe at depths where liquids levels are suspected. Also, laterals should always be sloped away from the well head to avoid condensate backflow. Another issue is biological build-up on well screen or filter pack due to the liquids passing into the screen. Methods are also available for flushing out the screen and filter pack and can be employed to improve both the dewatering and subsequent gas collection from the well.

If liquid is hindering the performance of a well, another alternative is to install a leachate pump. Leachate pumps can be successful in removing liquid; however, the process is typically very slow.

Horizontal collectors are also prone to flooding in landfills with high water addition (by rain or waste). The easiest way to prevent this is to request the landfill operator to build a high point on the deck for the horizontal well installation. This would require significant planning and coordination with the designer of the landfill's stormwater drainage. All landfill decks must drain and "high" spots could introduce complications in the fill sequence. Assuming the coordination can be accomplished, water on the deck will drain away from the horizontal wells to the low points on the deck during installation. To prevent flooding after the collector is buried, it is best to design the ends of the collector (i.e., the solid pipe portion near the edge of the landfill) with proper slope to drain liquids out of the collector. The minimum slope for the collector ends is approximately 5%.Horizontal well pipes should be installed at the top portion of the trench excavated for its placement to allow liquid to drain below them. At very wet landfills, a drainpipe can be installed at the lowest point of the horizontal collector trench to drain accumulated leachate. The horizontal permeable layers, as an alternative to horizontal collectors, can also serve to mitigate this problem. LFG system components are dewatering on a continuous basis at numerous landfills in the state, which have problems with accumulating leachate in the waste (e.g., Bradley Landfill, Palo Alto Landfill, Pacheco Pass Landfill, etc.).

Feasibility

Removing leachate from landfills tends to be slow because landfills do not readily give up liquid. Pumping liquid from vertical wells is costly because of the required pump maintenance. Whenever possible it is best to keep liquid out of wells or construct wells with perforations above liquid zones. If liquid removal is required, pumps can be used with some effectiveness. However, a difficulty occurs when infiltrating leachate brings silt into a well and around the pump. This condition can cause pumps to fail. In addition to added pump maintenance, it may be necessary to remove silt from the well.

Implementation Recommendation

This BMP could be implemented by increasing the well pipe size to allow for installation of automatic pumps specifically designed for leachate removal and providing the required above ground utilities such as power and compressed air to facilitate pump operation. Installing pumps would need to be measured in terms of cost and performance against installing a well with perforations above the leachate level.

Relative Cost

Long-term costs for pumping can be high. These costs include capital costs for the pumping systems, operation and maintenance of the pumps as well as collection and disposal costs of the leachate. The cost to gravity drain leachate from horizontal collectors is low; however differential settlement, silt, inorganic precipitates (i.e. $CaCO_3$), or bacterial fouling can cause the collectors to fail.

Relative GHG Emissions Reduction Potential

A well that is flooded cannot collect gas; hence, this BMP could salvage non-functioning wells. In this case GHG emissions reduction would be high in cases where wells have become watered in.

BMPs for LFG System Piping

Description

Beyond the LFG extraction wells and other collectors, it is also critical to design the LFG piping to carry the necessary volume of LFG so it does not become a limiting factor in the ability to collect gas. LFG piping is comprised of lateral piping that connect the wells to the main headers, and main header piping, which conveys large quantities of gas to the control system. This BMP includes provisions for ensuring that LFG piping is properly designed and installed, including the following elements:

- **Maximize Piping Sizes.** Specific pipe sizes (i.e., diameters) have limitations on the amount of gas that can be moved through the pipe. With LFG, there is always some uncertainty in the amount of gas that will be generated and recovered and the variability in applied vacuum levels can also affect gas flow. As such, it is critical to design piping systems for the high end of the range of expected gas flows for the area of the landfill that the pipe will serve. The design can take into consideration the expected life of the piping so that the pipe sizing is not based on future flows beyond the life expectancy of the piping, as long as provisions are made to upgrade the piping when needed. Larger pipe sizes also help against condensate formation and blockage by allowing gas flow to continue with moderate condensate buildup.

- **Install Piping on Native Soil.** Wherever possible, LFG piping, particularly main header lines should be installed on native soil to prevent undue affects of landfill settlement. For piping installed on refuse settlement can cause unintended low points in the piping where condensate can collect and block gas flow. Piping on native soil outside the boundary of the refuse avoids this problem and also allows the piping to be installed with a shallower slope, which makes design and installation easier.

- **Increased Pipe Slopes.** In all cases, it is considered a BMP to maximize the pipe slopes for all LFG system piping. For piping that is installed on native soil, the piping should be installed with a minimum slope of 1% to promote condensate water flow with a provision to increase slope to 2% whenever feasible. For piping on refuse, the minimum slope should be 3% for areas expected to have low to moderate differential settlement and 5% for piping in areas expected to exhibit heavy settlement. Where these slopes cannot be achieved, the piping should be designed with multiple access points and cleanouts for inspection and dewatering of piping and be subjected to a more rigorous and frequent pipe inspection program. Pipes can be run down or across landfill slopes to increase slope.

- **Above Grade Piping.** Above grade piping systems are preferred over below grade systems in most cases. Above grade piping can be more easily inspected, repaired, and upgraded, which can promote maximum effectiveness. However, above grade piping systems must be protected against weather effects by staking of piping to control movement due to thermal expansion and contraction or landfill erosion, UV protection to protect plastic pipe against the sun’s influence, etc. The only exception to the above would be cold weather locations where frequent freezing temperatures would necessitate burying the pipe or in active areas where above grade piping could be damaged. If piping must be buried, it should be designed in accordance with the BMPs noted above for buried pipe. A photograph of an above grade header pipe that is staked to prevent movement down the slope is contained in Figure 9.

Figure 9. Staked Above Grade Header

- **Looped Piping Systems.** Despite the best design and construction standards, LFG piping may fail due to damage, breakage, or settlement. As such, LFG piping systems that include looped headers can be considered. These looped systems allow vacuum to reach all areas of the landfill from more than one direction. Each LFG system would have a primary piping loop around the entire refuse area; however, for large landfills, multiple interior loops, including temporary, movable ones, may be warranted. Looped piping systems equalize vacuum throughout the gas system and reduce downtime for portions of the gas system affected by non-functioning piping. With these looped systems, isolation valves are included so that non-functioning pipe sections can be isolated for repair and flow directions changed to restore vacuum to the problem area. A rough schematic of a lopped header system and well network is provided in Figure 10.

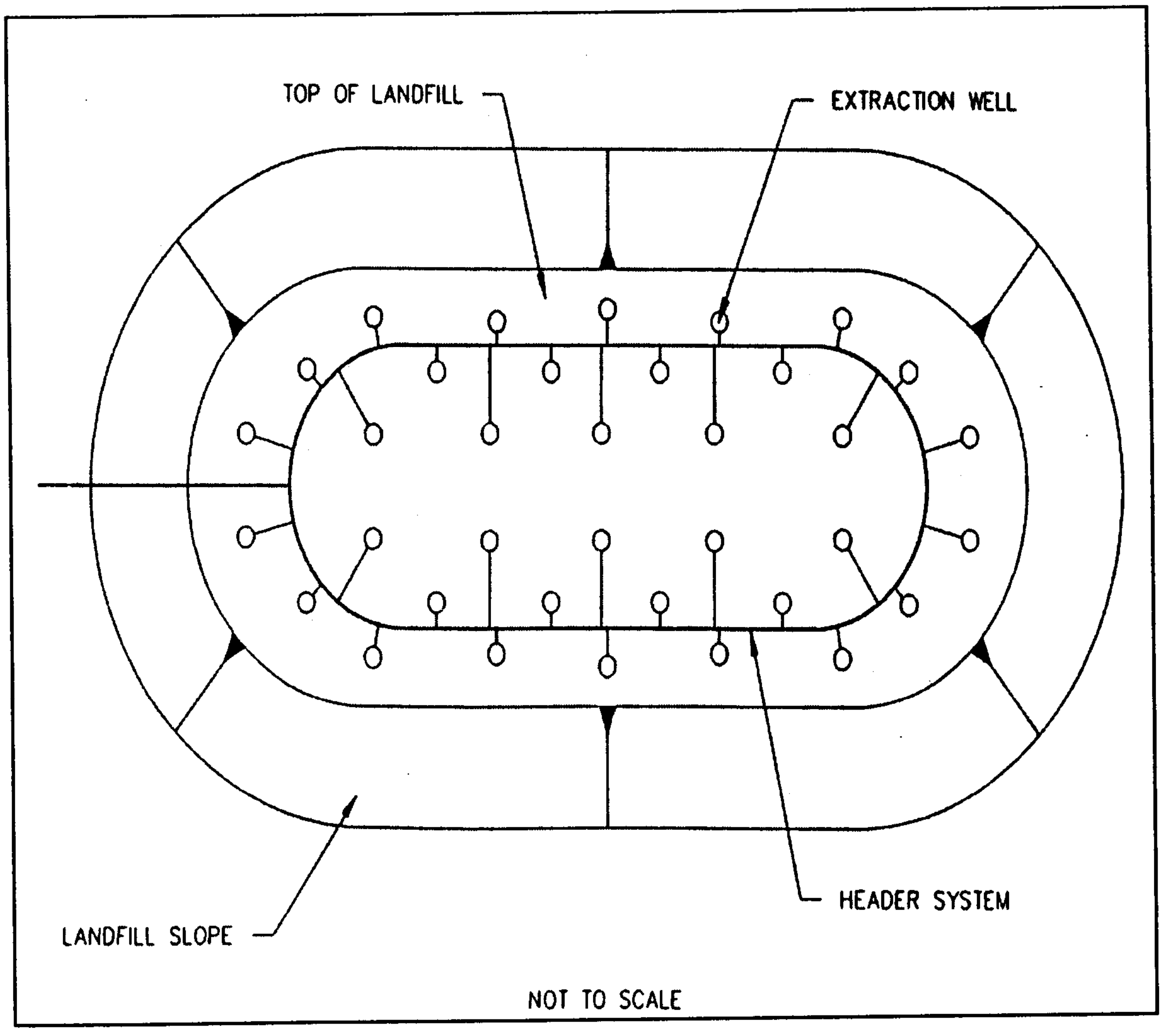


Figure 10. Schematic of Looped Header System

- **Pipe Specifications.** Beyond the size and slope of the pipe, the specification for the type of grade of pipe is important as well. Plastic piping systems are commonplace in the LFG industry and still considered BMPs. However, specification of high grade pipe is important for effectiveness and longevity of the piping system. This would include use of Schedule 80 PVC over Schedule 40 and use of higher quality HDPE pipe (e.g., SDR 17). Above grade PVC pipe must be protected against UV radiation, and above grade HDPE should be staked to prevent movement when the pipe is exposed to temperature extremes. Special allowance should be made for HDPE thermal expansion and contraction because of its substantially greater coefficient of thermal expansion than PVC.

- **Adequate Condensate Systems.** LFG piping systems should be designed with an adequate number and size of condensate sumps and traps to remove condensate from the gas lines in a manner so that it does not affect gas system operation. Automated condensate systems are preferred with either electric or pneumatic pumping systems, which continuously drain sumps, traps, and tanks and move the condensate to its final point of disposition. A schematic for a typical condensate sump is provided in Figure 11.

Feasibility

This BMP is feasible for all LFG systems; however, the selection of specific elements of the piping BMP must be site-specific selection.

Implementation Recommendation

This BMP should be implemented after an engineering review of the site conditions and selection of the appropriate pipe design and features. If there is any uncertainty in the design, it is recommended to err on the conservative side and select the largest pipe diameters, slopes, and other elements.

Relative Cost

The cost of this BMP is in more expensive pipe and other components and construction costs for installation of the piping systems. There are also increased operational costs for maintaining these systems; however, some elements of the BMP will actually reduce long-term maintenance and repair costs by expending more upfront capital to design and install a high quality system. The relative cost is considered low to medium compared to LFG systems where this BMP is not implemented, depending on the amount of avoided maintenance costs. Also, above grade piping is less expensive than below grade piping that has to be trenched. Overall, the cost to implement this BMP is expected to include an increase of 15 to 40% of the capital costs as compared to LFG piping systems that are not optimized, depending on site-specific conditions.

Relative GHG Emissions Reduction Potential

The use of these piping BMPs is an effective way to maximize the amount of gas that can be recovered from a LFG wellfield and ensure that the piping will not become a limiting factor in the LFG system's ability to collect methane. The expected methane reduction potential is low to medium compared to other LFG BMPs, with a higher potential at sites that are already experiencing low gas production due to poor piping design.

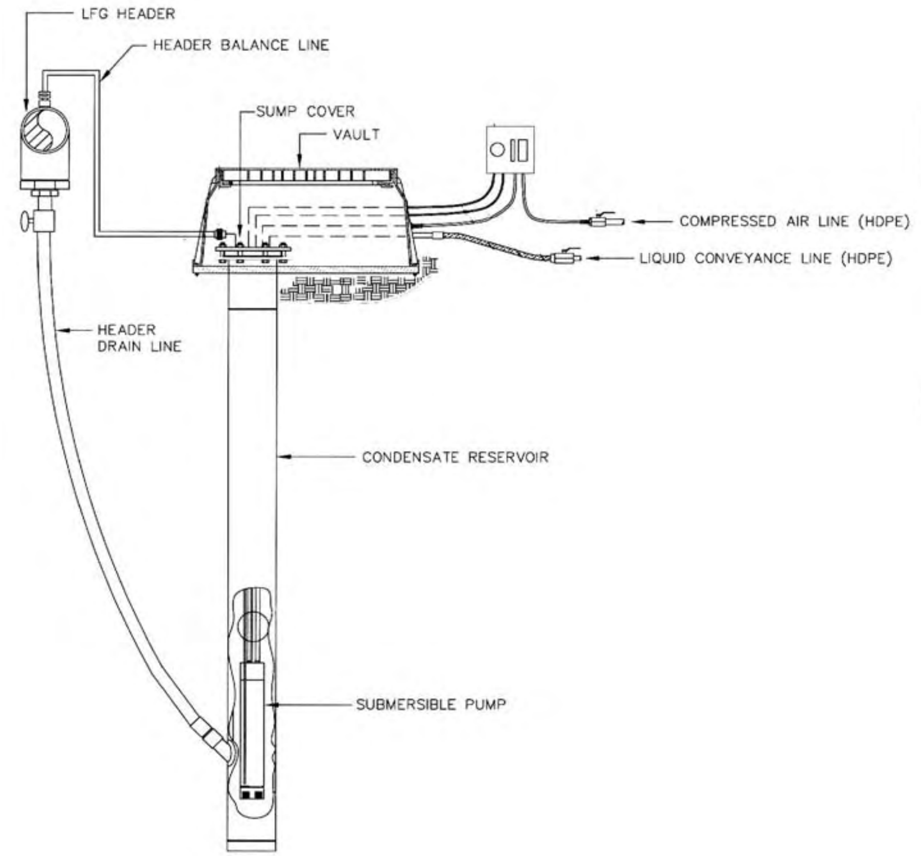


Figure 11. Schematic of Typical Automated Condensate Sump

BMPs for Gas Mover Equipment and Vacuum Control

Barometric Control of LFG System---

<u>Description</u>

The amount of gas stored within the void volume of refuse changes depending on the atmospheric pressure. When the atmospheric pressure is high, greater quantities of LFG are stored in the void volumes because the gas is compressed. When atmospheric pressure is low, the amount of gas stored in the void volumes is less because the gas loses some of its compression and vents from the refuse. One way to help reduce gas emissions is to increase the gas flow when barometric pressure is dropping due to weather event with large barometric fluctuations. Conversely, air infiltration can be reduced by decreasing gas flow when barometric pressure is increasing. This procedure is accomplished by using automatic controls that throttle the rate of LFG extraction inversely to the rate of barometric pressure change.

There are several methods of implementing this control. The simplest method is to increase and decrease LFG collection system flow rate based on the rate barometric pressure is changing. The flow rate can be changed by automatically increasing and decreasing the blower speed using a variable speed drive. Variability frequency blower equipment is becoming the norm in California when new blowers are purchased or existing systems are upgraded (e.g., Ox Mountain Landfill, Sonoma Central Landfill, Ostrom Road Landfill, etc.).

Feasibility

The feasibility of implementation is dependent upon the flow rate required to collect LFG and remain in compliance, and the ability to increase and decrease this flow rate. Additionally, the blowers and LFG combustion device need to be able to operate over a wide operating range to accommodate flow changes caused by variations in barometric pressure, and flow changes caused by LFG generation increasing or decreasing as the landfill is filled or as LFG generation decreases after closure. Operating equipment outside of its design range can cause poor performance and possibly even equipment failure.

Implementation Recommendations

Implementation requires a method of changing the gas extraction rate from the landfill. There are several methods of automating this process, the easiest of which is to control the blower speed using a variable frequency drive (VFD) to increase and decrease vacuum according to the desired changes in LFG flow rate. Simultaneously, the flare or disposal device will also need to be able to accommodate the increases and decreases in LFG flow.

The recommended procedure is to use blowers with a wide range of operation coupled with a flare that also has a wide range of operation to allow as much variability in LFG collection and combustion as practical.

Relative Cost

The capital cost for implementation can range from medium to high depending on the desired maximum and minimum equipment performance. The cost of installing a variable frequency drive (VFD) will often pay for itself by saving power. However, if the system requires substantially more vacuum to function properly then electrical costs could increase. Also, the capital cost of blower systems can increase by 15% to 25% when the costs of a VFD are included.

Relative GHG Emissions Reduction Potential

The varying barometric pressure may increase the collection of LFG when LFG is normally trying to vent while limiting air infiltration when air would normally be infiltrating a landfill. This could potentially improve gas quality while restricting gas vent rates. The improvement in GHG emissions reduction is considered low; however the benefit of reduced air infiltration may make this BMP practical.

Redundant Flare Station Equipment---

Description

Flare stations are designed to operate 24 hours per day, 365 days per year; however, no matter how good the equipment, there will be times when shutdowns and service are required. Some shutdowns will be short duration while others could involve replacement or rebuilding key equipment that could require several days to repair. A few examples of shutdowns include:

Short Duration Shutdowns	Long Duration Shutdowns
Adjust or replace belts on rotating equipment	Rewind an electrical motor
Calibrating meters	Repair or overhaul a blower
Greasing equipment	Repair or replace flare insulation
Replacing Thermocouples	Rebuild a flare burner
Replacing U.V. scanners	Repair/replace failed electrical equipment and controls

Nothing can be done to eliminate shutdown, however a lot can be done to reduce the downtime. Notification of a shutdown is critical. This is normally accomplished using an automatic dialer. The simplest and least costly approach to controlling the time required for repairs is to have a thorough spare parts inventory. This way when a failure does occur, it won't be necessary to try to find replacement parts. Spare parts inventory can include consumable parts (i.e., thermocouples, U.V. scanner tubes) as well as entire replacement assemblies (i.e., a motor blower assembly). Most of the time, the thoroughness of the inventory has to do with the importance of the operation. For instance, LFG collection at a park is more critical for safety than LFG collection at an old and rural landfill that isn't generating much gas. Back-up blower and control equipment is an important part of any BMP for redundant flare station equipment.

The next level of redundancy is to have spare equipment installed and ready to run. Sometimes the controls can be programmed to start spare equipment if a failure of the operable equipment occurs. Many landfills in California have full or partial backup capacity for blower and flares (or other control devices) (e.g., Newby Island Landfill, Kiefer Landfill, El Sobrante Landfill, etc.). A photograph of a redundant blower system is provided in Figure 12.

Feasibility

Provisions for a thorough spare parts inventory and redundant equipment installed and ready to operate are feasible as a BMP, although redundant equipment in flare stations is less common. This is because most flare systems are quite reliable having less than 10 days downtime per year.

Implementation Recommendation

The key recommendation is to have at a minimum a good spare parts inventory. This would include all small parts that require replacement or repair and possibly some critical parts (i.e., LFG blower) required for operation. A spare blower does not always have to be an exact replacement if its cost is high. A low quality blower with adapters could be used in an emergency to help the system stay operational while the primary blower is repaired.

A spare flare is uncommon and not recommended because these are typically very reliable and a good spare parts inventory is usually adequate to make quick repairs.

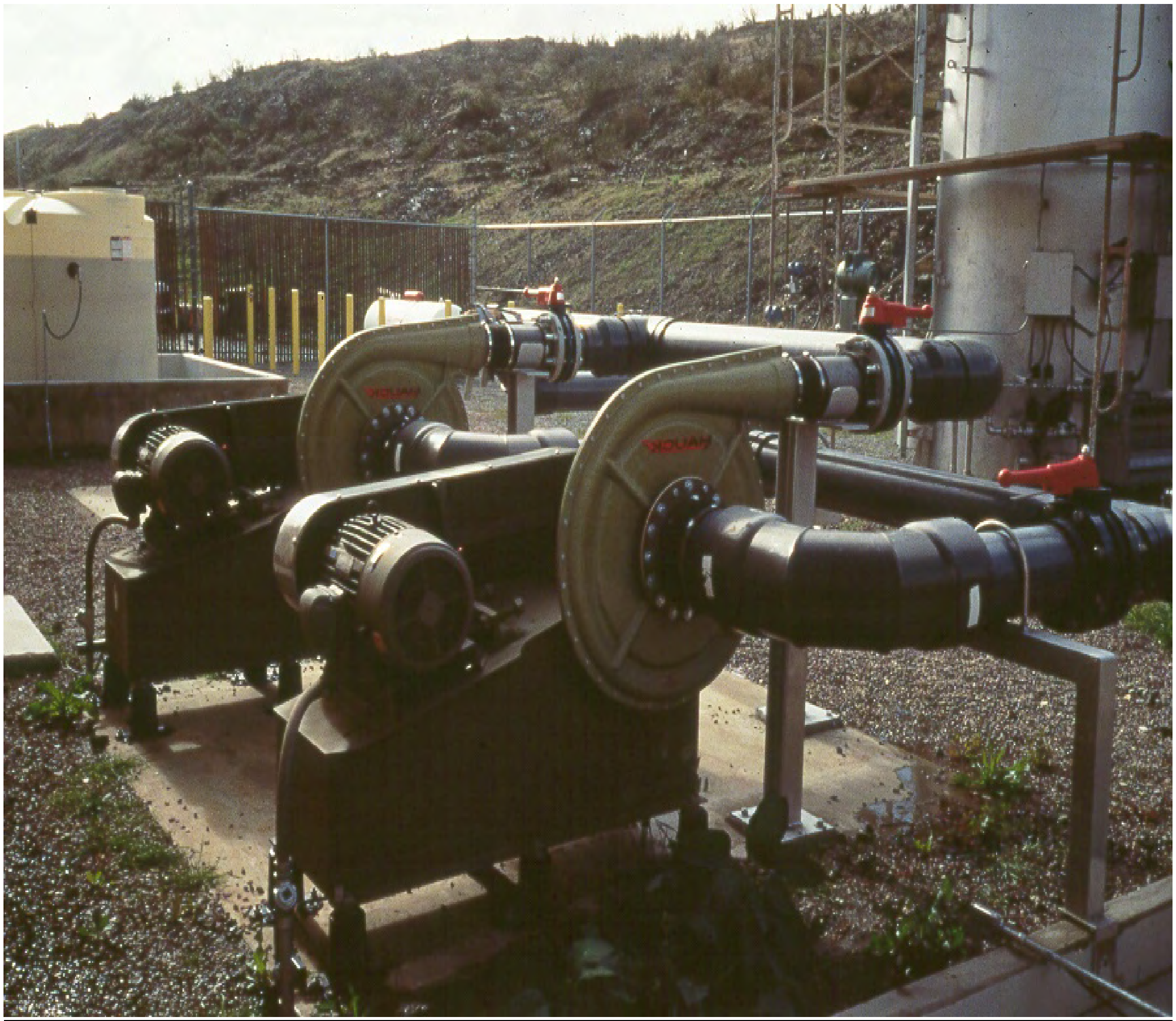


Figure 12. Photo of Redundant Blower Assembly

Relative Cost

Providing a good spare parts inventory could cost 5-10% of the flare station capital cost depending on its thoroughness. Installing redundant blower or flare equipment would be relatively expensive, often times costing more than the original installation because of the additional pipe, valves, and controls to make the connections. Though capital cost of a redundant blower may be high, with proper maintenance, the total available blower life should be additive and the contingent cost of emergency repairs deductible. The net cost will be only slightly higher assuming the full life is obtained from both blowers. Redundancy of blowers and flares can be very expensive because of the costs of equipment with blowers considered low to medium and flares considered high. The cost of a new blower can range from $10,000 to $50,000 depending on the size and type of blower. The cost of a new flare could range from $120,000 to $400,000 depending on the size of flare, assuming an enclosed flare type.

Relative GHG Emissions Reduction Potential

The relative GHG emissions reduction is considered low because modern flares, blowers, and controls are highly reliable normally contributing less than 3% total downtime per year. When flares are used as backup equipment for energy recovery devices, which generally have higher rates of downtime (approximately 5 to 10%), then the GHG reduction benefit is expected to be medium.

Maximize Capacity of Gas Mover Equipment---

Description

Blowers have multiple operating limitations including maximum flow, minimum flow, maximum vacuum, minimum speed to dissipate motor heat and blower surge considerations. The designer needs to carefully consider blower selection to make sure that the LFG collection rate falls within blower operating range with some cushion to increase flow in the future. The goal is to provide sufficient blower capacity (including motor horsepower) to collect all gas generated and available for collection from a landfill. This BMP also includes adequate pipe sizes to and from the blower to avoid flow restrictions.

Feasibility

The feasibility of increasing the blower size is dependent on having a reasonable handle on the expected LFG collection rate. The more uncertainty in the collection rate means the blower will be sized for operation closer to the blower's mid-range. If the expected flow can be reasonably well predicted, then the blower can be sized so that the LFG flow is at the low end of its performance curve.

The blower pipe size is usually determined once the LFG flow is estimated. One option is to increase the pipe size to avoid this from being a flow bottleneck.

Implementation Recommendations

When selecting a blower, the designer should review the performance data for numerous units to determine which one will be best for application with strong consideration for having sufficient capacity for future gas collection. The designer should include the blower manufacturers' representative in the selection process.

Relative Cost

Depending on the type of blower used, increasing the blower size can have two costs. The first is the cost for the blower, pipe, wire, and motor controls. The second is higher operating costs by operating the blower at low flow which may equate to low efficiency. In this case, the designer may want to use a smaller blower with provision to drop in a larger blower in the future if it proves that this approach is more cost effective. This BMP could increase the costs of the blower by 25 to 40% over a smaller blower.

One option to help mitigate this cost is to use a VFD to turn the blower at a lower speed. This can provide a substantial horsepower savings and help the turndown performance of a larger blower. The relative cost of this approach is medium.

Relative GHG Emissions Reduction Potential

Provided a blower is adequately sized, having a larger blower would create no reduction in GHGs. This BMP becomes most relevant when gas capacity exceeds the blower capacity, and an owner/operator has not upgraded the system to keep with the increased capacity. In these cases, the GHG reduction benefit is expected to be medium.

BMPs for LFG Control Systems

Redundancy on Gas Control Equipment---

Included above under "Redundant Flare Station Equipment"

Maximize Capacity of Gas Control Equipment---

Description

For this discussion, it is assumed that the gas control equipment is an enclosed ground flare. This is the most common type of flare required by California Air Quality Management Districts and Air Pollution Control Districts. Activated carbon is not considered a BMP for GHG emissions reduction because methane is not removed, and it vents to the atmosphere.

The function of a flare is to destroy methane and non-methane organic compounds. This is accomplished by burning the gas at a sufficient gas temperature with adequate oxygen present in the exhaust and holding the combustion products for sufficient time to allow adequate destruction.

There are several goals of this BMP. The first is to increase the gas combustion capacity, and the second is to improve the destruction efficiency. Increasing the capacity is achieved by making the flare larger. Increasing the destruction efficiency is usually achieved by increasing gas mixing with oxygen, increasing the combustion temperature, or increasing the combustion retention time.

The common element between increasing capacity and increasing destruction efficiency is increasing the flare size (i.e., longer flame retention time). Increasing a flare size is practical provided the manufacturer can simultaneously increase the flare turndown. This then provides improved combustion capacity without penalizing the low flow performance.

Feasibility

Flare manufacturers are generally able to make flares with between 4:1 and 6:1 turndown ratios. The turndown ratio is the ratio of the flare's maximum capacity and the minimum amount of heat input that is necessary to achieve proper combustion and operate the flare. It is feasible to require manufacturers adopt a 6:1 turndown thus allowing the flare size to be increased.

One challenge of very large flares is shipping. If a flare size is too large, then it is practical to split the capacity into multiple smaller flares. This approach has the benefit of increasing the minimum flare performance and providing partial combustion capacity when one of the flares is down.

Implementation Recommendation

The recommendation is to consider one of two approaches. The first is to install the largest flare with the greatest turndown that is practical. The second is to install multiple reduced size flares (i.e., two 60% flares).

Relative Cost

The relative cost is medium to high because of the increased flare capacity requiring a larger flare, and the increased turndown. Multiple flares will typically cost even more. This BMP could increase the costs of the flare by 25 to 40% over a smaller flare.

Relative GHG Emissions Reduction Potential

Provided the flare is adequately sized, the relative GHG emissions reduction will be small until the flare's capacity is exceeded. Then, the GHG emissions reduction could be medium to large until a larger flare is constructed.

BMPs for Enhanced LFG Operations and Maintenance

The objective of these operational strategies is to maximize LFG collection and flaring to minimize methane emissions by enhancing and expanding the manner in which LFG systems are operated and maintained.

Definitions---

In the context of this BMP, the following definitions are applied:

Efficiency is the measure of the amount of LFG collected versus the amount generated. The most efficient system would collect gas at the same rate it is generated.

Uptime is the percentage of time the system is operational. For most systems, partial operation is possible as when a portion of the wellfield is shutdown for repairs. Thus, 100 percent uptime would equate to continuous operations of the entire system. Sites that are sensitive to offsite odors, require compliance with emission standards, and/or are implementing a beneficial end use are less tolerant of downtime.

Effectiveness is related to efficiency but not the same. Sometimes, in order for a system to be effective, it may need to be somewhat inefficiently operated as when the landfill configuration and status of gas collection and control system "build-out" (i.e., expansion of gas system to coincide with the landfill expansion) warrants some over-pulling (i.e., drawing air into the landfill) to control LFG emissions.

Descriptions of Strategies----

System efficiency, uptime and effectiveness are greatly affected by LFG system operations. Operations factors that have the most impact include:

Monitoring/Adjustment Frequency

The best monitoring frequency for the LFG system is determined after careful consideration of the operational goals of the LFG system. Monitoring frequency should be established by the operational staff in conjunction with the engineer. The minimum monitoring frequency is monthly. Generally, more frequent monitoring and well adjustment enhances emissions reductions. This BMP recommends twice per month monitoring for active LFG systems at active landfills where LFG flow rate is changing and monthly for closed landfills. Twice per month may not be needed in many cases at active landfills. A well established and balanced system will have many wells that require little adjustment each monitoring round. A better approach is to require monthly and more frequent monitoring if the wells are actively being adjusted too often.

LFG system startup should be followed by a period of intensive monitoring. The LFG system should be monitored every other day, for a period of at least two weeks. The best practice is to open each wellhead valve from 10% - 20%, being careful to not exceed 25% open. Review of the blower curve and LFG system design report should be conducted to determine the expected rate of LFG recovery. Locate the value on the gas curve to estimate the percent open position on the inlet valve to the individual blower(s). Open the discharge valve 100%. Once gas flow and composition is stabilized, both at the control device inlet and at each well, the monitoring frequency can be cut in half, until each subsequent round of monitoring results in minor modifications to the individual wells (i.e. flow adjustments < 10%). Once the startup period is complete, the site can revert to the recommended monitoring frequency.

Coordination/Communications with Landfill Operations

The extent and frequency of communications with landfill operations is determined by the site specifics. For example, if the system is installed in a capped area, communications with landfill operations may not be as extensive as a site where an LFG system is installed in an active fill area. When a system is operated in an active disposal area, care needs to be exercised by operations to avoid damaging the existing LFG collection infrastructure. It is valuable to ascertain the filling sequence and the proposed duration of each “staging” or “lift” area. The LFG system operator should be notified immediately if damage occurs.

Maintenance Schedule/Spare Parts

Maintenance is a critical component of any best management practice. Due to the high variability of gas composition, trace gases, waste composition, leachate system and collection system design, it is difficult to create a standard maintenance schedule for some LFG system components. Though a maintenance schedule is typically provided for various components by the manufacturer, the aforementioned variables will ultimately dictate the maintenance schedule. Essentially, any manufacturer’s recommendation should be viewed as the minimum monitoring frequency, and this BMP recommends establishing a maintenance schedule for all LFG system components beyond the manufacturers’ minimums through the creation of a preventative maintenance plan. As part of this plan, it is suggested to divide the LFG system components into two classes, fixed and variable.

The LFG system components which should be maintained on fixed intervals with a minimum frequency as defined by manufacturers’ specifications are as follows:

- Replace chart recorder paper or electronic storage device
- Calibrate flow meters
- Replace thermocouple assemblies
- Inspect pilot assembly
- Blower bearing lubrication
- Blower vibration test

The LFG system components which should be maintained on a variable frequency are as follows:

- LFG collection system maintenance– monitor system pressures during monitoring event, conduct maintenance when evidence of air leaks (i.e. oxygen: balance gas ratio = 1:4, loss of header vacuum) is observed.
- Blower maintenance – monitor inlet pressure, outlet pressure, current (amp) draw, motor frequency and vibration during monitoring event, maintain as changes occur.
- Demister pad – monitor differential pressure across demister pad, clean when differential pressure rises beyond the manufacturer's recommendation. Also, differential pressure that does not increase during time may be an indication that the pad is not fouling, and may need to be inspected.
- Flame arrester – monitor differential pressure across flame arrestor element, clean when differential pressure increases by 1.0" water column (w.c.)
- Isolation valves – actuate valves to verify that they are operating during periods of downtime for maintenance.
- A spare parts inventory should be stored at the landfill to minimize downtime in the likely event of component failure due to wear, settlement, etc.

Spare parts for a LFG system should include items such as: monitoring port quick-connects; flex hose and clamps; chart paper or digital storage device for a chartless data recorder; pilot gas solenoid valve; igniter spark plug; igniter transformer; louver actuator; flare stack thermocouple elements; ultraviolet flame detector; vacuum/pressure gauges; temperature gauge; flame arrester element assembly with gaskets; blower grease; blower shaft couplings; pumps (adjusted for the number of on-site condensate and down well pumps; air regulators (if using pneumatic pumps); coalescing filters and dryers for air compressor, if site is equipped; and pipe and fittings with diameters representative of existing system sizes.

<u>Methods for Wellfield Adjustments</u>

There are many methods which can be utilized for wellfield adjustment. Specific wellfield adjustment strategy is not as critical as a implementing a consistent approach. The adjustment strategy should also consider the goals and design of the LFG system. Irrespective of the adjustment strategy, a monitoring event should always start and end at the blower station. The best method of wellfield adjustment consists of small adjustments in wellhead flow, considering the individual well's flow, percent methane, percent carbon dioxide, percent balance gas, gas temperature and static pressure. A simple method of wellfield adjustment is to use the gas composition at the blower inlet as the baseline or target, making small flow reductions on individual wells with quality less than the gas stream at the blower inlet. Conversely, small flow increases should be made on wells with quality greater than the gas stream at the blower inlet. Any time that wellhead adjustments are made, the adjustment should be documented along with the gas composition. Also, a second round of monitoring data should be collected after any adjustments have been made, to test the short-term effectiveness of the adjustment. It is good practice for the monitoring technician to carry the previous 6 months monitoring data with him during the monitoring event to be able to compare the data with historical values.

<u>Data Interpretation</u>

Common ratios should be examined to determine if additional wellfield modifications are warranted. Common ratios to consider are oxygen: balance gas and methane:carbon dioxide. An oxygen to balance gas ratio of 1:4 is an indication of air infiltration, either due to overlyaggressive extraction or a cracked/damaged well casing. An oxygen to balance gas ratio of less than 1:4, coupled with a decrease in percent methane and an increase in temperature suggests that drawn in oxygen is creating pockets of aerobic activity, which retards methanogenesis and creates a subsurface fire risk. A second ratio to support this is methane:carbon dioxide.

Typically methanogenesis in a landfill results in a higher concentration of methane compared to carbon dioxide. A byproduct of aerobic decomposition is carbon dioxide, thus, aerobic decomposition will shift the methane:carbon dioxide ratio to show a higher concentration of carbon dioxide than methane. If an aerobic condition is suspected, the flow should be reduced. If signs of subsurface combustion are observed carbon monoxide concentration should be monitored. If subsurface combustion is suspected, the well should be shut off and a subsurface fire mitigation plan should be implemented.

More sophisticated methods of wellfield adjustments are based on more extensive data interpretation, which is ultimately a function of budget. At a minimum, well flow and gas quality data should be considered over time to determine trends, and adjustments made accordingly.

Dealing with Elevated Liquid Levels

Historically, the goal of landfill operations is to maximize the amount of refuse that can be contained within a permitted volume. This is typically accomplished by compaction. Often, this results in isolated areas which do not facilitate leachate drainage due to a high concentration and tight packing of impermeable materials, such as plastic bags or clay. Methods for dealing with such areas of “perched leachate” are described below.

An elevated liquid level in LFG collection wells greatly diminishes collection efficiency. LFG extraction wells are typically designed with the bottom 2/3 consisting of perforated pipe, the top 1/3 being solid pipe. The solid portion is designed to prevent air infiltration into the portion of the well casing located nearest to the final or intermediate grade. Often the LCRS is operating effectively, i.e. the pumps are operational, but areas of perched leachate exist due to the relative impermeability of some waste deposits. As the well screen begins to water in, wellhead vacuums will start to rise as the extractable volume becomes smaller. Liquid levels should be checked in the well casing immediately if this trend is determined. If liquid levels continue to rise above the well screen, the vacuum will quickly approach the system pressure and collection is approximately 100% inhibited. In this instance, it becomes necessary to pump out the liquid in the well.

It is suggested to run a pump test on the affected well(s). Care should be taken to pump the well at a relatively low rate (i.e. <1.0 gpm) to ensure integrity of the gravel pack in the well bore. Pneumatic pumps are preferred for this application as they tend to move a volume of liquid at some interval, creating natural infiltration to the well as opposed to a suction condition inside the well casing. This is preferred to ensure the integrity of the gravel pack of the well; aggressive pumping can lead to the gravel pack becoming inundated with silt, greatly affecting collection efficiency. After evacuating the well casing, depth to liquid measurements should be performed at a regular interval to determine the rate of recharge. Additionally, if a series of wells is affected in a particular area, it is suggested to monitor liquid levels in the vicinity of the pumping location to determine if any drawdown is occurring. The results of the pump test should be reviewed to determine the best pumping solution. The solutions can range from a non-dedicated, on demand pump and containment system, to a full scale comprehensive system of dedicated air lines, force mains, and dedicated down well pumps.

Training of Operators

LFG systems require a certain expertise for effective operations. As such, a LFG system operator must have adequate training before he or she can properly operate and maintain a LFG system. As a BMP, enhanced training of LFG system operators is recommended. This should include, at a minimum, an initial LFG course of four days, including two days of classroom training and two days of field training. This should be supplemented by one day of annual refresher training and specialty training classes offered by equipment vendors for typical LFG equipment, such as flares and blowers.

Relative Cost

The cost of this BMP is in increased costs for LFG system operations and maintenance (O&M). The relative cost is considered low compared to LFG systems where this BMP is not implemented. It is expected that O&M costs would increased by 15 to 25% with this BMP; however, some of this can be offsets by the avoided major repair costs from good maintenance practices.

Relative GHG Emissions Reduction Potential

It is difficult to estimate the amount of additional methane capture can be achieve with this BMP since many of the benefits of enhanced operations and maintenance are indirect. As such, it is expected that the GHG emissions reduction potential for this BMP will be low compared to other LFG BMPs, but could increase to medium at sites where the LFG system is experiencing excessive amounts of downtime due to poor O&M and repair requirements.

General LFG BMPs

Early Installation of LFG Systems---

The objective of early system installation is to capture emissions that would otherwise vent to the atmosphere.

Background – Regulatory Drivers

Early installation of a LFG system would be defined by regulatory timelines. System installation is considered early if it precedes the schedule mandated by regulation. For landfills, the primary regulations that dictate the timing of LFG system installation are the New Source Performance Standards (NSPS) and Emission Guidelines (EG) for Municipal Solid Waste Landfills (40 CFR 60 Subpart WWW and Cc) and the landfill maximum achievable control technology (MACT) rule (40 CFR 63 Subpart AAAA). In California, various air districts have LFG rules that are more stringent than the NSPS and mandate LFG system installation earlier.

The MACT rule primarily applies to landfills operated as bioreactors. Those facilities that meet the definition of a bioreactor must install a LFG system prior to initiating liquids injection and begin operating the system within 180 days after liquid injection commences or after the waste moisture content reaches 40 percent. The stringency of the schedule required by this regulation is such that early installation is not applicable. Accordingly, this BMP will not address early installation relative to the MACT rule. However, bioreactor landfills that are not subject to the MACT rule because they do not achieve 40 percent moisture should be highly considered under this BMP.

The NSPS stipulates that a LFG system must be installed when the landfill has a design capacity greater than 2.5 million metric tons (or megagram – Mg) and a projected non-methane organic compound NMOC emission rate greater than 50 Mg per year. The extent of the LFG system coverage depends on the age of waste in different areas of the landfill. NSPS requires LFG collection from landfill areas where waste has been in place for five years if active (i.e., interim grade) or two years if closed or at final grade. This requirement is typically referred to as the "2-year/5-year" rule.

Description

Early system installation or expansion generally requires LFG collection from active landfilling areas or installation of LFG systems at landfills not yet required to do so. Strategies for collecting gas in active areas include the use of horizontal collectors, extraction wells with remote wellheads to accommodate the well being buried under future waste, and extraction wells that are protected and raised with waste filling.

Feasibility and Rationale for Early Installation

The NSPS allows landfills to conduct site-specific testing to assess NMOC emissions, and thereby defer the requirement to install a LFG system. The 2-year/5-year rule can result in deposited waste being in place up to five years before LFG is collected from it. At large sites with high disposal rates, active cells may have sufficient waste for gas collection shortly after filling commences (less than 2 years); however, delays of two or three years before LFG system expansion can occur while still complying with the system expansion timeline stipulated by NSPS. Such delays or deferrals may cause significant amounts of uncaptured methane emissions.

Implementation

Implementation of early LFG system installation would generally apply to landfills without existing gas systems (or ones with only partial systems) and landfills with existing LFG system, which require expansion due to increased refuse filling as follows:

- No or Partial LFG System – enhanced emission reductions could be accomplished by early system installation ahead of triggering the NSPS 2.5 million Mg design capacity or the 50 Mg/yr NMOC emissions limit. In California, CARB is considering requiring control of methane at sites with 500,000 tons of waste in place. The proposed BMP would require comprehensive control at all active landfills with more than 500,000 tons in place as well as for closed landfills with more than 500,000 tons in place, which have been closed for less than 10 years. This BMP would only apply to non-desert landfills.

- Existing LFG System – early system installation ahead of NSPS 2-year/5-year rule. This BMP recommends expansion of an existing LFG system into a new disposal area once the refuse in that area is two years old regardless of the state of refuse filling.

Constraints on Early Installation

Although emission reduction benefits can clearly be accomplished by early LFG system installation in some situations, a number of practical constraints exist for landfill operators. Such constraints include the following:

- **Budgeting and budget cycles.** Major capital expenditures for landfills, including cell construction, landfill capping, leachate treatment works, gas system expansion, etc. These are normally addressed in a 5-year capital plan or even longer forward look at planned expenditures. Early installation of LFG collection system expansions typically involve more frequent expansions and represent a change to the budget plan. Such changes to the budget plan (at both municipal and private facilities) usually involve a significant approval process.

- **Mobilization costs, economy of scale.** Small system expansions may not be cost effective due to relatively high costs to mobilize a drill rig and the economies of scale for piping installation.

- **Landfill operations interference.** A potentially major impediment to early installation is the interference of landfill operations in active areas. GCCS damage from refuse compactors, truck traffic, and other landfill activities can be common and costly. This BMP includes suggestions for LFG system components intended for active areas.

- **Waste decomposition/filling rates.** At medium to small landfills or landfills in arid climates, early installation into a new cell may have limited emissions reduction value because LFG generation may be insignificant for the first couple years.

Relative Cost

The cost of this BMP is in increased capital and operations costs for new or expanded LFG systems at sites where they would not have been required otherwise. For completely new system installation, the relative cost would be high. For expansion of existing systems, the cost would be low since the cost would have been ultimately incurred at a later date.

Relative GHG Emissions Reduction Potential

For new LFG systems at sites without them, the relative GHG emissions reduction potential would be considered high. For early expansion of an existing system, the potential is low to medium depending on site conditions, but generally higher in cases where a landfill has been waiting the full 5 years to expand the LFG system in a new area.

LFG Master Planning---

Description

This BMP recommends the development and implementation of a LFG Master Plan for every site that has an existing LFG system or is planning the installation of a new one. The LFG Master Plan must be technically sound from an engineering standpoint, satisfy all regulatory requirements, and ensure that public health and safety are not compromised. Most importantly, the plan must minimize long-term risks and optimize LFG system design in the most cost-effective manner. LFG master planning efforts should focus on both short-term issues associated with enhancing the existing system to meet regulatory requirements as well as long-term issues associated with future system expansions as the landfill grows. The LFG Master Plan should cover the following points, at a minimum.

- **LFG recovery or generation modeling or empirical data** from an existing LFG collection system at a site as the basis for design.

- **Optimal collection system layout**. LFG systems installed in landfills typically utilize vertical extraction wells, horizontal collection trenches, or a combination of both. The LFG Master Plan must consider the most appropriate system layout, particularly for the active landfill areas, including type of extraction component, header and lateral layout and sizing, etc. Key considerations include the timing for gas collection system installation and proposed fill sequencing/closure schedule for various cells.

- **Future landfill expansion**. The gas system layout should minimize impacts with day-to-day disposal activities and consider future cell expansion.

- **Compatibility with closure activities and post-closure land use.** The master plan must consider the most effective means of gas control for active cells, interim closure of fill modules, and be flexible to accommodate upgrades at final closure and for the proposed post-closure land use.

- **Regulatory and permit requirements.** The overall objective of the LFG Master Plan must be to reduce LFG surface emissions, minimize migration, protect groundwater, and minimize long-term environmental risks. It must meet all applicable regulatory requirements and BMPs.

- **Liquids management.** LFG extraction systems generate liquid condensate. The plan must evaluate options for condensate management in terms of technical, cost, and regulatory considerations. Options to be considered include collection in above ground tanks with manual removal, automated pumping systems, below grade condensate sumps, integration with leachate system, etc. The key consideration must be to ensure that liquids do not adversely affect LFG collection.

- **Integration of LFG system and LCRS.** The plan should consider tie-ins between the leachate collection and removal system (LCRS) and the LFG collection system, in effect making the LCRS an initial horizontal collector, and other possible operational advantages to integration of the systems.

- **Energy recovery.** The LFG Master Plan should address the potential for energy recovery from the LFG and impacts an energy recovery system can have on LFG collection and control. The design of the LFG system should include consideration of the goals of the LFG system, which is often either to control emissions and odors or for beneficial LFG recovery or both. Many systems are required to both control emissions/odors and provide a high BTU value gas to an energy conversion device. This can be achieved through segmenting the LFG system. Typically, perimeter wells and wells/collectors designed for surface collection are segregated from interior wells. The perimeter/surface tend to be more challenging from a control standpoint, and often times perimeter wells/surface collectors should be operated more aggressively than interior wells. This typically results in LFG with a lower BTU value, which can be segregated and flared. If segmentation cannot occur, then the energy system must be able to accommodate the lower BTU gas so that gas control is not compromised.

- **Adequacy of existing LFG extraction and monitoring system**. The LFG Master Plan should review the adequacy of the existing LFG collection system to control surface emissions, limit lateral migration, and protect groundwater from LFG impacts. It should also assess the need to upgrade the extraction and monitoring systems in light of current site conditions, regulatory concerns, and future fill expansion plans. Where deficiencies are noted, the plan should propose corrective action or upgrade.

- **Overall system costs.** LFG systems typically operate for many years. It is possible that O&M costs will ultimately outweigh capital expenditures. The LFG Master Plan should assess short- and long-term costs for various collection and control strategies and recommend the most cost-effective strategies for both time horizons.

The LFG Master Plan will provide an overall "roadmap" for LFG management and guidance on when gas controls will be needed, order of magnitude costs, and a concept plan and schedule for the optimal system build out. This information can be used to plan and budget for future improvements.

<u>Relative Cost</u>

The cost of this BMP is in the cost to develop and update the LFG Master Plan. This cost is considered low relative to other LFG BMPs. For those landfills falling under NSPS/EG, the cost of a LFG Master Plan would be incremental to the cost of the GCCS Design Plan. The expected 2008 costs for LFG Master Plan could range from $20,000 to $35,000, depending on the size of the site and the level of detail for the plan.

<u>Relative GHG Emissions Reduction Potential</u>

It is difficult to estimate the GHG emissions reduction potential from the LFG Master Plan; however, if a plan is developed and implemented, it will allow a site to maximize LFG control and be proactive regarding LFG system expansion. As such, it is expected to have a low to medium effect on GHG emissions reductions, generally higher for sites expected to require long-term and continual upgrade and expansion of the LFG system.

Energy Recovery from LFG---

<u>Description</u>

The recovery of renewable energy from LFG can create additional GHG benefit through the displacement of fossil-fueled derived sources of electricity, natural gas, or vehicle fuel. The methane in the LFG can be combusted in a reciprocating engine, gas turbine, steam turbine, boiler, microturbine, and various other technologies to produce electricity for on-site use and/or sale. In the same manner, the LFG can be piped offsite, with our without pretreatment, and used as a replacement or supplement to natural gas or propane. Further, LFG can be converted into liquefied natural gas (LNG) or compressed natural gas (CNG) and used as a vehicle fuel. In each of these cases, the energy value of the methane can be utilized as an offset for the equivalent amount of energy produced from fossil fuel or other sources with the corresponding benefit in GHG reduction. As such, the recovery of energy from LFG is considered as a BMP for landfills. California has more LFG-to-energy (LFGTE) project than any other state (e.g., Otay Landfill, Puente Hills Landfill, El Sobrante Landfill, Sonoma Central Landfill, Kiefer Landfill, Altamont Landfill, Newby Island Landfill, etc.)

Feasibility

The feasibility of an energy recovery project at a landfill is dependent on its cost-effectiveness. Generally speaking, there are economies of scale for these projects, so large landfills with more available LFG have a greater chance of being viable. The price that the utility will pay for the power or methane or the comparative price for retail power, natural gas propane, and/or CNG/LNG has a very direct impact on the viability of an energy project.

Implementation

LFGTE projects are recommended for implementation at any landfill where the project can be shown to be economically viable.

Relative Cost

The cost of this BMP is in increased capital and operations costs for the LFG-to-energy (LFGTE) system beyond the costs for a standard LFG collection and control system. In general, the costs would be considered high. The capital cost for electricity generation projects can range from $1000 per installed KW for reciprocating engines and gas turbines to $3500 per installed KW for microturbines. The installed capital cost for a medium-BTU gas treatment facility can range from $600,000 to $900,000/mmscfd, increasing to $1.25 to $1.5 million per mmscfd installed for a high-BTU (including pipeline quality natural gas, LNG, or CNG) project. Capital costs for off-site gas pipeline can range from $30 to $50/foot

Relative GHG Emissions Reduction Potential

The GHG reduction potential is considered high for this BMP. The actual GHG reduction amount can be calculated uses emission factors for power production or natural gas, propane, LNG, or CNG combustion from the current version of the California Climate Action Registry's *General Reporting Protocol* (CCAR, March 2007). These factors represent the amount of GHG emissions that could be offset through the use of renewable energy.

Enhanced Monitoring, Modeling, and Testing BMPs

Enhanced Surface Emissions Monitoring----

Description

At the present time, surface emissions monitoring (SEM) remains the primary standard through which the effectiveness and efficiency of a LFG system is measured. Under the NSPS rule, monitoring is typically conducted quarterly with emission levels compared against a standard of 500 parts per million by volume (ppmv) above background of total organic compounds (TOC) measured as methane at two to three inches above the surface of the landfill. SEM is conducted using instantaneous testing by walking a serpentine pathway across the surface of the landfill while maintaining a pattern of less than 30 meters or about 100 feet apart for each successive pass along the surface. Exceedances detected during the SEM are subsequently mitigated and remonitored to demonstrate compliance.

This BMP proposes to utilize enhanced SEM (California is currently considering early implementation of SEM for specified landfills under Assembly Bill 32, beyond those required to do so under NSPS/EG or air district regulations) in order to identify and correct more instances of surface emissions and maintain a more stringent standard for allowable emissions:

- SEM should be conducted monthly rather than quarterly with a provision to reduce the monitoring back to quarterly after one year's worth of monitoring events without exceedances.
- The serpentine pathway should include a monitoring route with successive passes that are no less than 100 feet apart. The SEM path should be varied each quarter so that a larger percentage of the landfill surface is tested annually.
- SEM should include monitoring of cover penetrations at least quarterly such that every penetration is monitored at least once per year where it is not already required.
- SEM should include LFG system component leak testing at least once per month using SEM techniques with the same provision to reduce to quarterly when appropriate.
- The instantaneous SEM threshold should be 100 ppmv of TOC above background as methane with a provision to reduce the threshold back to 500 ppmv after one year's worth of monitoring events without exceedances. Measurements should be standardized to two inches above the surface of the landfill or above the landfill component.
- SEM should be conducted for all landfill areas not simply those required by regulations to have LFG collection with the exception areas that are considered dangerous such as steep slopes or the active face.
- Exceedances of these more stringent standards would not be considered regulatory non-compliance but would trigger additional corrective action to resolve the surface emission problem.

Figure 13 depicts a typical SEM pathway across the surface of the landfill.

<u>Feasibility</u>

This BMP is feasible for any landfill.

<u>Implementation Recommendations</u>

This BMP merely increases the stringency of existing landfill monitoring programs and requires no special changes in implementation. It is recommended for landfills where excess surface emissions have been an ongoing problem or sites with newly installed LFG systems.

<u>Relative Cost</u>

The cost of this BMP is in the additional cost for SEM and the likelihood of additional mitigation and remonitoring for exceedances. The cost is site dependent. This cost is considered medium relative the LFG BMPs, generally higher for sites that currently do not conduct SEM. Overall, the BMP is expected to increase the standard SEM costs by 100% to 200% due to the increased frequency in monitoring and other features of the BMP.

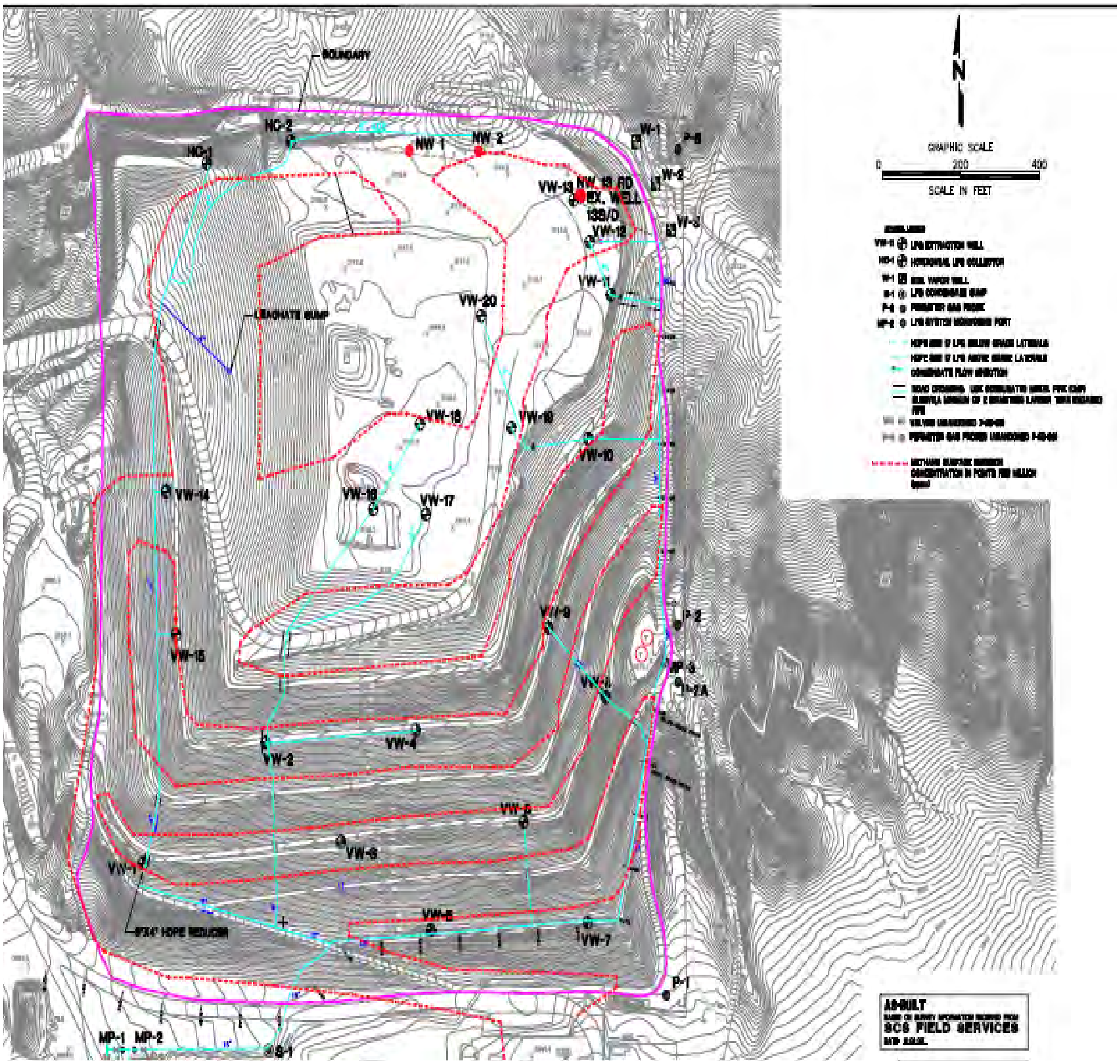


Figure 13. Typical SEM Pathway on Landfill Surface

<u>Relative GHG Emissions Reduction Potential</u>

It is difficult to estimate the GHG emissions reduction potential from enhanced monitoring since the positive effects will be indirect. However, enhanced monitoring will ultimately reduce surface emissions of methane by maintaining a more stringent emission standard and allowing for the detection and correction of exceedances. As such, it is expected to have a low to medium effect on GHG emissions reductions, generally higher for sites that currently do not conduct SEM.

Enhanced Gas Migration Monitoring---

Description

LFG migration monitoring is also used as a gauge of the effectiveness of a LFG system. Typically, under California regulations, this is conducted quarterly by monitoring probes installed on minimum 1000-foot spacing around the perimeter of the landfill, where the point of compliance is the permitted facility boundary. The standard established by the Resource Conservation Recovery Act (RCRA), and incorporated into California Code of Regulation Title 27, is 5% methane in the probe, and is based primarily on the lowest concentration of methane that is potentially explosive.

Under this BMP, gas migration monitoring would be enhanced through the following:

- Migration monitoring should be conducted monthly rather than quarterly with a provision to reduce the monitoring back to quarterly after one year's worth of monitoring events without exceedances.

- The probe spacing should be a minimum of 1000 feet at the facility boundary. If exceedances are detected at one or more of the boundary probes for more than 6 consecutive months, even after multiple corrective action measures have been implemented, then the perimeter probe spacing should be decreased to 500 feet in the problem areas and additional "sentry" probes should be installed directly adjacent to the refuse in that area. The sentry probes would be monitored at the same time as the boundary probes as an immediate gauge as to whether LFG is escaping the refuse prism.

- For the purposes of utilizing gas migration data to assist in assessing LFG system effectiveness, the threshold for excessive gas migration should be 1.25% at the facility boundary and 5% in the sentry probes. The 1.25% standard is equivalent the standard in California Code of Regulations, Title 27 for structures on a landfill.

- Exceedances of these more stringent standards would not be considered regulatory non-compliance but would trigger additional corrective action to resolve the migration problem.

Feasibility

This BMP is feasible for any landfill.

Implementation Recommendations

This BMP merely increases the stringency of existing LFG migration monitoring programs and requires no special changes in implementation. The siting and construction of the additional LFG probes should follow standards and guidance from the CIWMB under 27 California Code of Regulations.

Relative Cost

The cost of this BMP is in the cost for additional monitoring, installation of wells, and the likelihood of additional mitigation and remonitoring for exceedances. This cost is considered medium relative the LFG BMPs, generally higher for sites that currently do not conduct gas migration monitoring or have partial monitoring systems. Overall, the BMP is expected to increase the standard probe monitoring costs by 100% to 200% due to the increased frequency in monitoring and other features of the BMP. If additional LFG probes are installed as a result of the BMP, the 2008 unit cost is expected to range from $35 to $50 per foot for the capital cost for probe drilling and installation using the hollow-stem auger drilling technique.

Relative GHG Emissions Reduction Potential

It is difficult to estimate the GHG emissions reduction potential from enhanced monitoring since the positive effects will be indirect. However, enhanced monitoring will ultimately reduce gas migration by maintaining a more stringent standard and allowing for the detection and correction of exceedances. Reduced gas migration is expected to have an associated effect on increased gas system effectiveness. As such, it is expected to have a low effect on GHG emissions reductions, generally higher for sites that currently do not conduct gas migration monitoring.

Improved Modeling and Testing for LFG Design---

Description

LFG systems are commonly designed based on past experiences of the designer and accepted industry practices. However, the designs could be further enhanced by using various testing and modeling techniques to enhance the design. As part of this BMP, the following testing and modeling tools are recommended to develop a more site-specific LFG system design:

- LFG generation modeling can be used to predict the amount of the gas that is expected from a landfill or portion of a landfill; however, these models, such the U.S. EPA LFG generation model (LANDGEM), must be calibrated with site-specific data on rainfall and actual LFG recovery to improve their accuracy for LFG design purposes. There are numerous LFG generation models, and care must be exercised in model selection and use, including values for the various input parameters.

- Computer programs involving finite element analysis can be used to optimize LFG design for recovery. These include reservoir fluid flow models, as adapted to gas flow in a landfill.

- To supplement models, pneumatic methods for assessing gas generation rates can be applied to assess gas recoverability and reduce uncertainties at candidate sites.

- Pore-pressure penetrometer (PPT) testing can be used to identify areas in the refuse where there are high pressures (excess gas buildup), vacuum (already under the influence of existing LFG wells), and presence of liquids (areas to avoid when installing wells or collectors).

- LFG pumps tests can be used to assess the expected gas production from a landfill or portion of a landfill or can be used to determine site-specific values for the decay rate (“k” value) used in the LANDGEM or other first-order decay LFG generation model.

- Site-specific waste characterization testing and/or analysis of past waste stream data can be used to develop site-specific values for the ultimate methane generation rate (“Lo” value) used in the LANDGEM or other first-order decay LFG generation model.

An example output form a PPT testing program is depicted in Figure 14.

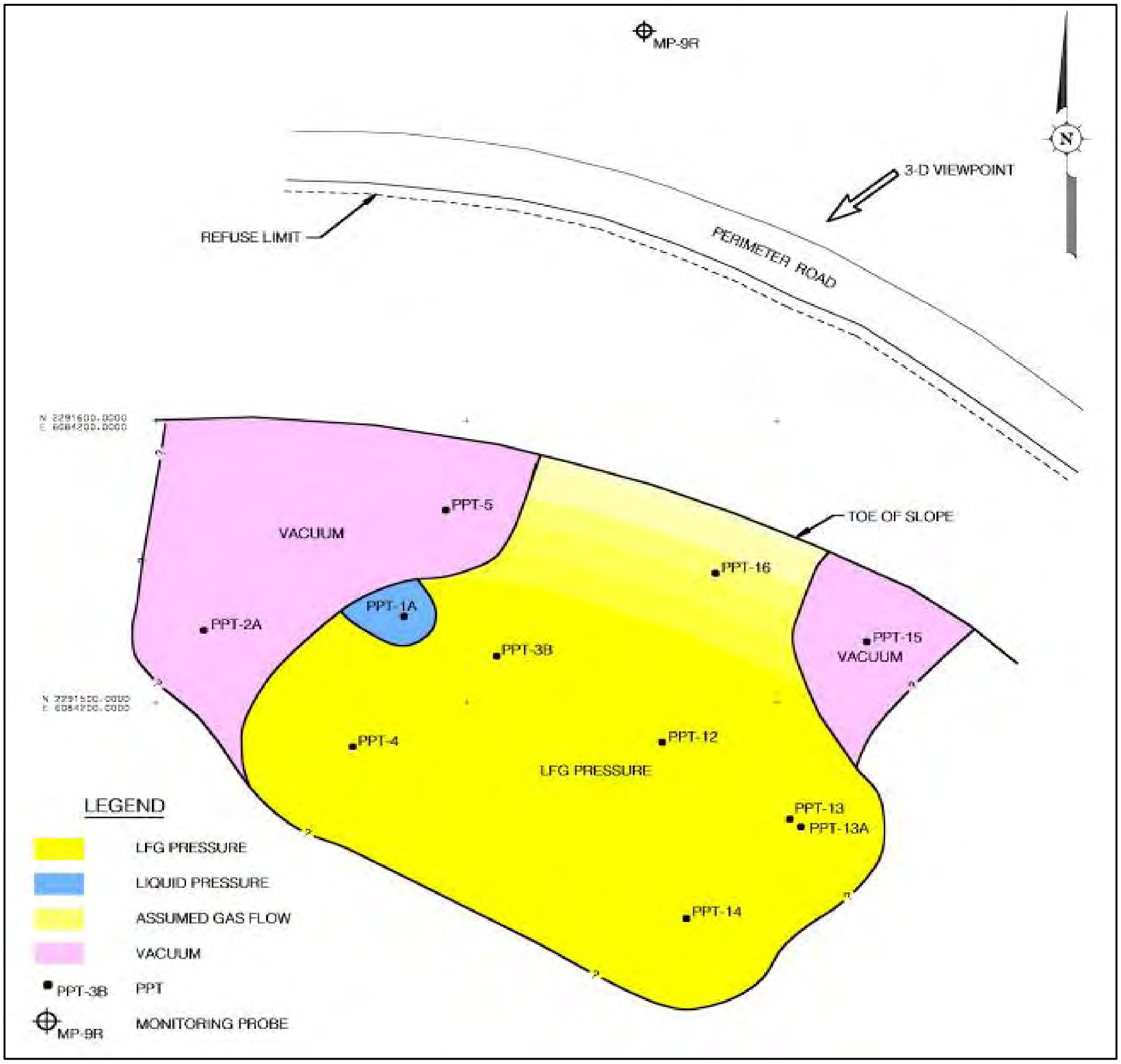


Figure 14. Results of PPT Test on Landfill

Feasibility

The various modeling or testing tools under this BMP are feasible for any landfill. They may have the most feasibility for sites where there are problems optimizing an existing LFG system or when designing a new gas system for a landfill or expansion area.

Implementation Recommendations

This BMP provides investigative tools that can assist in the development of improved LFG designs. Not all of these elements of the BMP are necessary for each site, and the decision to implement them should be made by a qualified individual based on site-specific conditions.

Relative Cost

The cost of this BMP is in the cost to for additional modeling and testing. This cost is considered low to medium relative the LFG BMPs, generally higher for the actual field testing elements. For example, a LFG generation modeling effort could cost $3,000 to $5,000 while a pump test program could cost over $100,000.

Relative GHG Emissions Reduction Potential

It is difficult to estimate the GHG emissions reduction potential from enhanced modeling and testing since the positive effects will be indirect. However, enhanced modeling and testing strategies will ultimate increase LFG recovery by improving LFG system design. As such, it is expected to have a low to medium effect on GHG emissions reductions, generally higher for sites where the additional modeling/testing can be used to solve an existing problem that was hindering gas recovery.

General Landfill

Design-Related BMPs for Landfill Systems

Cover LCRS Layer---

Description

Covering the liner and Leachate Collection and Recovery System (LCRS) layer with waste as timely as possible is a good solution to reduce GHG impacts for new cells constructed adjacent to an existing cell that is filled or partially filled with refuse and where LFG is being generated and with a common LCRS. The liner system contains the LCRS layer, which is a permeable layer above the liner system that carries leachate to a collection sump. It can also allow the migration of LFG to the edge of waste where it can be released to the atmosphere. Covering the liner system and LCRS would require waste fill sequencing to create a uniform 20-foot lift of waste over the LCRS to help contain gases as they are generated.

Feasibility

Covering the LCRS layer is a high priority for landfill drainage and LFG control operations. It is feasible unless waste is not available or timing is a problem.

Recommendations

Place a 20-foot thick layer of waste over the LCRS system. Thicker layers are better; however, it is better to cover the whole LCRS with a thin layer than part with a thick layer.

Relative Cost

There may be minor added cost to operations for the thin layer as opposed to placement of waste elsewhere. The relative cost is expected to be low.

Relative GHG Emissions Reduction Potential

This produces a low potential reduction of GHG since it possible for the GHG to escape from the LCRS layer despite the BMP. The BMP should be used in combination with connecting the LCRS to the LFG collection system.

Blockage of Permeable Layer within Landfill Footprint---

Description

To stop the migration of LFG up slopes and into the anchor trenches, several precautions and approaches have been proposed. Landfills that do not have a LCRS on slopes would not be applicable. Many landfills are designed with either a gravel layer or geocomposite layer extending across the bottom of the cell and up the side slopes. The geocomposite is extended into the same anchor trench used to hold the geomembrane liner from sliding. Creating a blockage in the geocomposite or gravel layer near the top of slope would limit or prevent the passage of LFG beyond the blockage. One possible solution involves the injection of closed-cell sealing foam along a narrow band around the top of the LCRS inside the landfill footprint. This blocks the free passage of LFG beyond the seal. It is also possible to weld a piece of membrane to the bottom liner that covers the geocomposite or gravel layer inside the anchor trench. Care must be exercised in design to ensure the integrity of the anchor trench is not compromised, and it can achieve its purpose of securing the liner and preventing geocomposite slippage along the side slopes. Figure 15 provides a schematic detail of a sealing of the liner to prevent escape of LFG over the anchor trench.

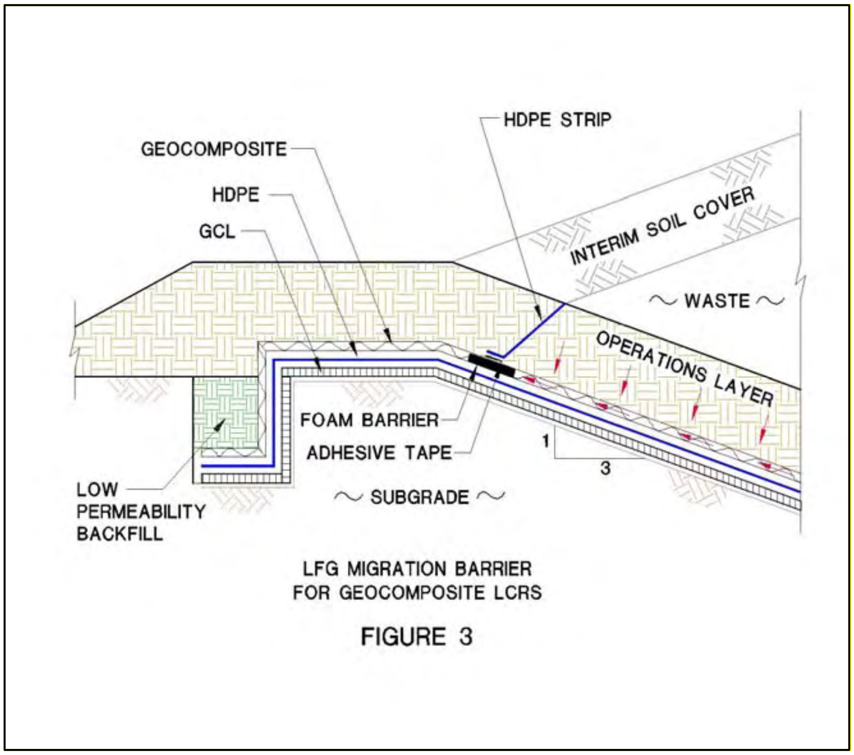


Figure 15. Design for Sealing the Liner at the Anchor Trench

Feasibility

The feasibility of installing sealing foam or a membrane seal in the geocomposite layers is feasible for new cell installations but more difficult for cell retrofits.

Recommendation

This BMP is recommended for all new liner system installations that have a geocomposite LCRS layer on the slopes which extends into the perimeter anchor trench. It should be considered for retrofit installations where there is a known problem of gas escaping through the anchor trench.

Relative Cost

This is a low cost modification that can be incorporated during the liner system installation; however, the cost of material and welding the strip is considerably more expensive than the sealing foam. The 2008 unit cost for installation of an HDPE strip as detailed above is $1 to $1.75 per foot. For the sealing foam, the installed cost is estimated to be $0.40 to $0.60 per foot. The cost will also increase for retrofit installations versus inclusion in the initial installation.

Relative GHG Emissions Reduction Potential

Blockage of the geocomposite layer around the perimeter of a landfill cell has a low GHG effect since it prevents only the GHG that migrates up the slope and is released to the atmosphere.

Designing for Closure and Post Closure---

Description

Proper closure and post-closure evaluation and design will keep a LFG collection system operating effectively and efficiently. Closure is a time when LFG systems usually get enhancements and new components, which are intended to last into the long-term post-closure maintenance period. Since the landfill is no longer active, consideration should be given to installation of the final set of vertical wells to address any gaps in LFG system coverage and to replace any aging or damaged vertical wells or horizontal collectors. Wherever possible, wellheads and piping should be installed or upgraded to above grade to allow future access for operations, maintenance, repair, and monitoring.

LFG system designs must also be considered in designing and installing the final cover layer. Penetrations and seals are particularly important since LFG can leak through any penetrations through the cover. Seals should be installed for all penetrations as discussed above. Protective cover thickness is important to assure that installation and maintenance activities for the LFG system do not damage a cover barrier layer. A thicker vegetative layer is recommended to prevent this from occurring.

Proper operation and maintenance in post closure is critical to the life of an LFG system; therefore, LFG systems in post-closure should receive adequate attention even though the landfill is no longer staffed on a full time basis. Consideration should be given to more automation and remote monitoring and emergency call-out capabilities to respond to system problems and downtime.

Feasibility

Providing LFG system enhancements at closure and properly operating and maintaining the system are typical activities that are well known and documented.

Implementation Recommendations

To implement this BMP, the landfill operator should develop a comprehensive operation and maintenance plan for the LFG system when closing a landfill. The plan should describe closure as well as post closure activities.

Relative Cost

The cost for closure enhancements and post closure maintenance are low since they can be coordinated with LFG and closure activities.

Relative GHG Emissions Reduction Potential

A properly operated and maintained LFG system will be effective in capturing and managing GHG at closed landfill sites if properly designed. This BMP has a low potential to reduce GHG emissions since it involves minor enhancements to a LFG system to accommodate closure and post-closure activities.

Promote Deeper Landfills---

Description

Landfill emissions are regulated based on measured surface concentrations from field monitoring from a given landfill area. To reduce emissions, either the emission rate and resulting concentration or the landfill surface area can be reduced.

Landfill geometries typically have a broad footprint with controlled height. As the height of a landfill increases, the ratio of the landfill surface area to the refuse volume changes. An objective would be to reduce the landfill surface area to the extent possible for any given volume of refuse. This can be accomplished by changing landfill geometry or using canyon landfills where the side slopes are blinded by the liners constructed up canyon walls thus restricting emissions.

Feasibility

Landfill geometry changes may be feasible based on site limitations. The most objectionable reason to restrict geometry changes would be caused by waste fill stability and secondly by increased landfill visibility. On a more practical note, as landfills get taller, the top desk size is reduced and at some point the deck size would not be sufficiently large to accommodate filling operations.

Implementation Recommendations

Landfills could be evaluated to determine the optimum geometry based on physical constraints of the landfill and surrounding area and slope stability analyses. Landfill owners and regulatory agencies would need to thoroughly evaluate the effect of adding height based on good engineering practice.

Relative Costs

The costs would be minor, and in fact could be positive (i.e., lower per unit volume of refuse) because more refuse may be deposited on a given landfill footprint. The costs would be related to permit modifications, studies, and engineering.

Relative GHG Emissions Reduction Potential

The potential for GHG emissions reductions could be medium to high if landfills emitted GHG at their maximum allowable level on all areas of the landfill. If it is assumed that the unit GHG emission rate is the same for the taller landfill as it was for a shorter landfill, then the GHG emissions reduction would be high.

BMPs for Landfill Cover Systems

Designing Covers for LFG Collection---

Description

Daily, alternate daily cover (ADC), interim or intermediate covers, and final covers are associated with landfill operation and ultimate closure. Daily covers and ADC are used to isolate waste as it is being placed so vectors do not become a problem, to control litter blowing, to help control odors, to promote runoff from the refuse and reduce infiltration of rainfall. Typical daily cover consists of onsite soil that has been excavated specifically for use as a 6-inch thick daily cover. ADC can include use of tarps, degrading foams, or green waste and/or other materials that sometimes have the added advantage of being able to attenuate (e.g., adsorb, oxidize, etc.) LFG constituents and prevent their release to the atmosphere (see section on Biocovers below). Interim or intermediate covers most often consist of a thicker layer (12-inches) of soil. They are intended to protect areas for extended periods of time when the landfill area reaches an interim grade. Biocovers are also considered as a replacement for typical soil interim covers, as detailed below.

Daily and interim covers are associated with ongoing landfill operations. LFG collection systems are not a problem for the temporary covers mentioned above; however, these systems provide little in the way of BMPs for methane reduction except as detailed below.

When a landfill closes, a final cover is placed that typically consists of a low permeability layer (e.g., clayey soils) that minimizes infiltration. The use of a synthetic cover (e.g., geomembrane) is considered a BMP for final cover systems since it provides the greatest degree of protection against surface emissions of methane. Synthetic covers also prevent air intrusion into LFG systems and allow system vacuums to be optimized. For the use of all types of final cover systems, seals around vertical LFG wells are necessary to stop the release of GHG and prevent oxygen intrusion.

Feasibility

LFG collection systems are present at many landfills with daily, interim, and final covers. The methods and procedures for extending wells, relocating piping, and sealing final covers are known and proven. The design and use of synthetic final covers are also well proven.

Implementation Recommendations

The cover system design should accommodate the installation, relocation, and operation of LFG collection system components. These issues should be thought out and incorporated into the initial design to avoid expensive changes that may be required later.

Relative Cost

The cost for incorporating an LFG system into landfill design is low for the elements related to installation, relocation, and operation of LFG collection system components and high for a synthetic final cover system versus other types of covers. When LFG systems are not included in a design, the result may be far more expensive. The 2008 unit costs for a synthetic geomembrane cover are expected to range from $40,0000 to $50,000 per acre of landfill surface.

Relative GHG Emissions Reduction Potential

Incorporating LFG systems into cover designs allow landfills to efficiently collect and manage GHG. Incorporating LFG issues into cover system design is expected to have a low potential for GHG emissions reduction. The use of a synthetic final cover is expected to have a high potential for GHG emissions reduction compared to soil covers.

Limit Delays on Final Covers Systems---

Description

The ability to apply vacuum to a LFG extraction well is dependent on how thoroughly it is sealed from the atmosphere. An important aspect of the seal is the landfill cover applied over the refuse. A tight (low permeability) cover can allow increased vacuum to be applied to a well.

The sooner the final cover can be applied to a landfill the better LFG extraction wells will perform. To encourage operators to close sections of a landfill as they are completed, regulatory agencies may want to allow sites to be filled some percentage above the permitted elevation with expectation that settlement will eventually cause the landfill to reach the final permitted elevation.

Feasibility

Early application of final closure cover is feasible for sites that do not expect additional refuse to be added following landfill settlement. This approach is also feasible where sources of closure soil and clay are available as well as funding for the closure. This response is conditioned that closure will not interfere with ongoing landfill operations.

Implementation Recommendation

The concept of placing final cover on landfills has a lot of merit and should be strongly considered once a landfill area of sufficient size is at final elevation to justify the cost of contractor mobilization is reached.

Relative Cost

This BMP could have a medium to high additional cost because the economies of scale are not present when constructing on smaller areas. Closing smaller areas will require more engineering, planning, and bidders will have to mobilize for each subsequent landfill phase that is closed.

Relative GHG Emissions Reduction Potential

It is expected that this BMP would have a medium GHG emissions reduction because it is expected that LFG wells will perform better with less air infiltration following construction of final cover. The emissions from a landfill with final cover should be measurably less than a landfill without final cover. However, it is assumed that closed and unclosed sites would be in compliance with all regulations.

Limit or Remove Intermediate Cover Systems---

Description

Landfills traditionally have variable permeability through the refuse. Part of the reason for the variable permeability is the moisture in the landfill; part of it may have to do with the type of refuse placed (i.e., paper vs. wood vs. plastic), and part of it could be caused by intermediate cover on a landfill creating preferential pathways and or barriers for LFG movement. If the LFG barriers are removed from the refuse (i.e., daily cover is replaced with tarps or degrading foam and/or intermediate soil cover is removed), then gas flow through the landfill could be more uniform, thus allowing a more uniform and predictable performance of the LFG extraction wells. Alternatively, alternative daily cover may be used to promote greater vertical permeability in a landfill.

Feasibility

This approach is technically feasible and should be moderately easy to implement. It would require tarps or degrading foams be substituted for daily soil cover and intermediate cover. Alternately, green waste or other organic ADCs and intermediate cover system could also be used. The cover systems would either need to be removed prior to continuing refuse filling (e.g., tarps) or allowed to incorporate into the refuse mass (e.g., green waste).

An advantage of replacing daily soil cover with tarps or degrading foam and removing intermediate soil cover is increased waste capacity in the landfill. This slight increase in waste capacity may justify part of the cost for removing the cover soil. A negative aspect of removing intermediate cover soil will be the additional odors that will be released when refuse is exposed and the additional operational burden of removing the cover. The area of removal of intermediate cover soil on a given day should be limited to help reduce the odors and other related issues. Also, complete removal of cover soil will be impractical because the bottom layer will be mixed with refuse.

Implementation Recommendation

Implementation would be by removal of cover to the extent possible using bulldozers, scrapers and other similar equipment or use of tarps or degrading foam. Cover would be stockpiled for use in the evening.

Relative Cost

The costs for implementation of this BMP include additional operator and equipment time or the cost of tarps or foam application. This cost is offset by requiring none or less cover soil to cover refuse at night and an increase in refuse deposited in a landfill. Overall, the relative costs are expected to be low to medium.

Relative GHG Emissions Reduction Potential

It is anticipated that the GHG emissions reductions by this BMP would be low because it is unclear how much additional LFG recovery can be attained by removing the vacuum resistance of the cover layers. One benefit of this would be potentially a greater radius of influence of wells and thus allowing wells to be more redundant on a landfill. That is, fewer wells could be used to collect the LFG. Allowing the wells to remain at a constant spacing as before would allow wells to become redundant and thus should a well fail, the redundancy would allow additional gas to be collected without installing new wells.

BMPs for Landfill Operations

Impacts from Landfill Operations---

Description

To eliminate the impacts of an LFG system being in the way of fill placement, advance planning and thought are required. Relocation of piping and extension of wells will be necessary and must be coordinated with the overall fill sequencing plans. Operators must take every precaution to avoid damaging wells and piping and/or be proactive in moving the piping prior to initiating disposal operations in the area. There are limitations to the height that wells can be extended that must be taken into account in a LFG system design. Some landfills have had success using GPS locating systems for LFG wellheads to avoid coming in contact with them with the heavy equipment, which have limited operator visibility.

Feasibility

Relocation of piping and extension of wells is done on most existing landfills that have an LFG collection system. The materials and procedures are well known and proven.

Implementation Recommendations

Fill placement operations and LFG collection system installation and operation must be thought out and planned on all landfills

Relative Cost

Operating the landfill with regard for the LFG system integrity is expected to have a low relative cost and may actually avoid some costs associated with system repair.

Relative GHG Emissions Reduction Potential

Operating the landfill with regard for the LFG system integrity is expected to have a low relative potential for GHG emissions reduction because it involves avoiding or limiting impacts from landfill operations, which only periodically affect LFG system effectiveness.

BMPs for Enhanced Landfills

Designing LFG Systems for Leachate Recirculation---

Description

The LFG collection system can be an integral part of a leachate recirculation design. Horizontal wells consist of shallow trenches with permeable materials and collection and distribution piping. Some elements of an LFG collection system may double as the leachate distribution system and may be oversized for this purpose. The enhanced LFG system is able to capture and transport larger volumes of GHG that is generated by the accelerated degradation process.

Feasibility

LFG collection systems are commonly used in leachate recirculation operations. The materials and procedures are known and proven.

Implementation Recommendation

LFG systems for leachate recirculation are not used on all landfills. Only those landfills that are approved for leachate recirculation will use them.

Relative Cost

LFG systems that are enhanced for leachate recirculation are more expensive than typical LFG systems. They may also include distribution layers or horizontal wells that would typically not be part of an LFG system. Further, there are additional costs for leachate collection, storage, and pumping system to accommodate the recirculation process. The additional cost is expected to be medium to high when all of the landfill and LFG system enhancements are considered to allow leachate recirculation to occur.

Relative GHG Emissions Reduction Potential

This BMP has a medium ability to capture more GHG than typical LFG collection systems. This occurs because leachate recirculation causes the landfill to generate more methane in a manner that can result in enhanced methane recovery (see description of bioreactor landfills below). The ultimate benefit depends on the efficiency of the leachate recirculation system and the enhanced LFG system. The more efficient they are designed and operated, the more LFG recovery that will be achieved. Leachate recirculation without an enhanced LFG system could result in increased GHG emissions. There also maybe GHG reductions realized by returning the leachate to the landfill instead of transporting it off site.

Bioreactor Landfills---

Description

A bioreactor landfill, as the term is being used in the landfill industry and in this document, is an MSW landfill that utilizes enhanced microbial processes under controlled anaerobic conditions to accelerate the decomposition of refuse. In the solid waste industry, bioreactor landfills are considered an alternative to the “conventional” MSW landfill. A bioreactor landfill takes a different approach to liquids management. Instead of limiting liquids addition into the refuse mass, a bioreactor landfill requires the addition of supplemental liquids to achieve optimum moisture content, e.g., greater than 40 percent moisture by weight.

In March 2004, the U.S. EPA revised the criteria for MSW landfills to allow states to issue research, development, and demonstration (RD&D) permits and assumed that the states would adopt the rule and receive approval of their respective rule changes from the U. S. EPA. The U.S. EPA proposed this alternative with the sole purpose of advancing innovative solid waste technologies. The RD&D permits allow variance from some parts of the criteria under RCRA Subtitle D (40 CFR Part 258). However, owners and operators must demonstrate that these operations will not result in an increased risk to human health and the environment. Examples of variance granted by the RD&D permit are exemptions from precipitation run-on, liquids restrictions, and final cover criteria set forth in §258.26(a)(1), §258.28(a), and Subpart F, respectively. This allows individual states the right to grant permits to test and employ bioreactor landfills and related technologies. The permit is issued initially for three-years, with up to three three-year renewals.

The organic fraction of MSW placed into a landfill begins to degrade and produce LFG through biochemical reactions. These organic compounds are initially oxidized. However, as the oxygen levels decrease, the principal bioreactions become anaerobic. Anaerobic decomposition takes place in three stages; the last of which is where methane is produced by methanogenic bacteria.

These methanogenic microbes thrive in a high moisture, low oxygen environment. The resulting gas is commonly referred to as LFG and typically is comprised of:

- Methane : CH_4 (45 - 60 % by volume);
- Carbon Dioxide: CO_2 (40 - 60 % by volume); and
- NMOCs (100-3000 parts per million by volume (ppmv) as hexane)

For a given amount of waste disposed of at a landfill, decomposition peaks quickly (as soon as oxygen is depleted and methanogens mature), possibly in weeks, but then begins a steady decline. This decline is proportional to the amount of waste left (referred to as “first order kinetics”). Complete decomposition may require decades, depending on conditions in the site.

The decline, however, is relatively slow compared to the increase in gas production because of more and more waste being received at the site. For a conventional landfill, the LFG generation rate increases steadily but slowly during the active life of the landfill (i.e., as refuse continues to be received). LFG generation reaches its peak approximately a year after closure based on LFG generation model results, after which the generation rate declines, first more rapidly and later more slowly over an extended period of time. This long “tail” of LFG production is particularly symptomatic of the “dry tomb” landfill where MSW degradation has been impeded through lack of moisture, resulting in a large percentage of LFG generation occurring many years after closure. This prolongs the post-closure care period for landfills and reduces the viability of energy recovery. For a bioreactor landfill, conditions more favorable for sustained anaerobic decomposition are maintained from the beginning (via liquid recirculation and addition).

The concept of a bioreactor landfill is gaining increasing prominence in the landfill industry in the US. The waste industry is considering the potential benefits that are offered by a bioreactor landfill through various research and full-scale demonstration projects. Potential benefits of a bioreactor landfill include increased disposal capacity (i.e., more waste can be placed within a fixed volume of landfill air space), shorter post-closure maintenance periods for LFG and leachate management, and better profiles for energy recovery from LFG. If all of these benefits were to come to fruition, the bioreactor landfill could transform the landfill industry by significantly reducing the long-term costs to operate a landfill site and increase the financial viability of both public and private landfill operations.

With the enhanced microbial activity in a bioreactor landfill, LFG generation and recovery rates have been demonstrated to increase substantially over the short-term because of the accelerated and more complete degradation of the biodegradable components of the refuse mass. As described below, the gas collection and control system can be enhanced and gas utilization technologies employed to effectively manage the potential challenges of accelerated and increased LFG production. LFG generation (and subsequent recovery) at a bioreactor landfill is anticipated to be limited to a shorter time horizon after landfill closure, thereby significantly limiting the post-closure period for LFG control.

Also, the methane recovery potential at a bioreactor landfill creates a more financially viable situation because LFG generation occurs at higher levels over a shorter time period, thus allowing for more methane recovery with less operational cost (i.e., fewer years of operation) for an LFG-to-energy facility. These shorter time periods of LFG generation are also more consistent with the typical life spans of energy-generating equipment, thereby reducing capital and replacement costs. Figure 16 provides a schematic of an anaerobic bioreactor landfill.

Feasibility

Bioreactor landfills are still in the RD&D phase; however, enough of these facilities have been developed such that the technologies are available. There are certain permitting hurdles that still must be overcome, and the technology requires additional capital expenditures on the front end before any of the benefits can be realized. A bioreactor is likely feasible at any active landfill; however, it is probably most feasible at larger sites where certain economies of scale can be realized. The commitment to a bioreactor landfill cannot be taken lightly since it will involve increased obligations for landfill and LFG management. Permitting of bioreactor landfills in California will likely be onerous, but the CIWMB has been supportive of their development.

Figure 16. Anaerobic Bioreactor Landfill Schematic

Implementation Recommendation

Bioreactor landfills require the installation of a LFG collection system sooner than conventional landfills for two reasons: 1) odor control resulting from increased LFG generation rates and 2) compliance with MACT rule requirements. The MACT rule requires that a LFG system be installed before initiating liquids addition and start up 180 days after initiation or within 180 days after reaching 40 percent moisture. The LFG system must be sized to accommodate the increased LFG generation and peak LFG flows, and likely will include a combination of horizontal and vertical LFG collectors installed in conjunction with liquids delivery systems. This improved design of the wellfield has allowed the site to achieve environmental compliance while at the same time collecting a significant amount of gas beyond what would normally be expected from a conventional landfill. Under this BMP, it is recommended that LFG systems at bioreactor landfills be installed and be in operation within 180 days of liquids addition regardless whether 40 percent moisture is reached.

Relative Cost

The development of bioreactor landfills, including LFG systems that are enhanced for increased gas production, are expected to have a high relative cost when the additional design, permitting, construction, and operational costs are considered. However, some or even all of this additional cost could be offset if the benefits of bioreactor landfills are realized. As such, bioreactor landfills may ultimately be implementable at low or no increased costs.

Relative GHG Emissions Reduction Potential

Whether more GHG would be captured has not been shown. The rate of GHG capture may be more because of increased LFG generation. However, there has been no case presented that the total GHG captured would be more. This BMP has a medium to high ability to capture more GHG earlier than typical LFG collection systems at conventional landfills. This GHG benefit is a combination of additional methane recovery along with the creation of more renewable energy. The ultimate success of the BMP depends on the efficiency of the enhanced LFG system to control the additional gas produced. Bioreactor landfills without an enhanced LFG system will result in increased GHG emissions.

Biocovers

Description

It has been well established that landfill cover soils provide some measure of oxidation of fugitive methane as it travels through the landfill surface. Methanotrophic microorganisms (the bacteria responsible for oxidizing methane) are present in most soils. The U.S. EPA estimates that landfill cover soils can oxidize from 10 to 25 percent of fugitive methane. Recent work has sought to increase the oxidation of fugitive methane by placing a “biocover” either over the entire surface of a landfill (see Figure 17), over select landfill cells (in which case it is called a “biocell”) (see Figure 19), or at passive methane vents. Typically a biocover consists of a coarse gas distribution layer followed by a layer of organic material of varying type, engineered properties, and depth. Materials used range from sand, to wood chips to highly engineered, mature compost. Various designs have been developed for smaller biocovers used at passive LFG vents, often called a “biofilter” (see Figure 18).

Figure 17. Conceptual Compost Biocover

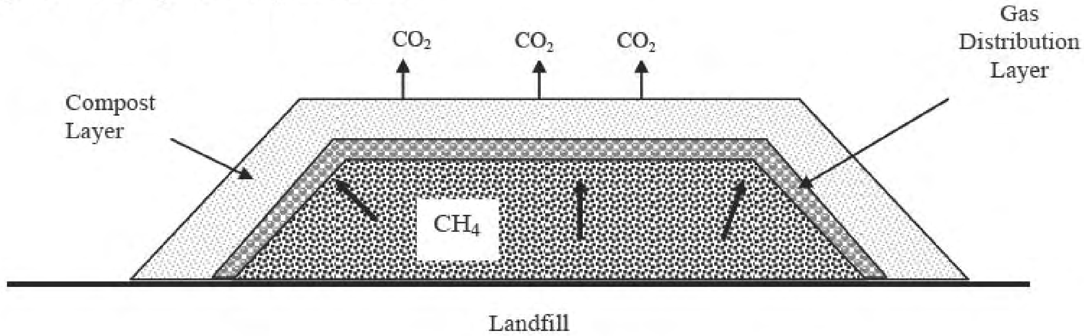


Figure 18. Conceptual Compost Biofilter (After Abichou, 2006)

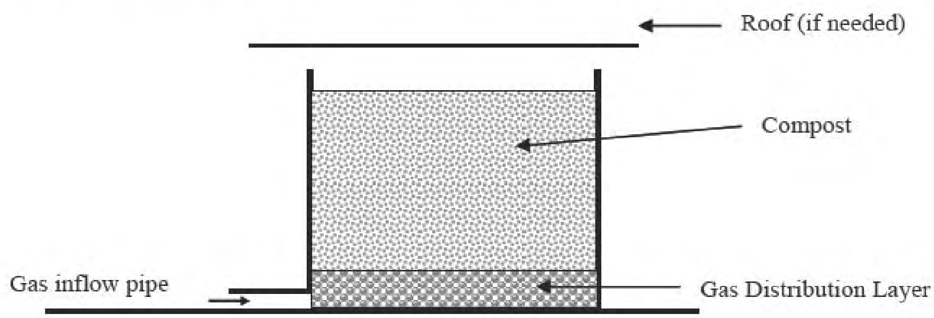
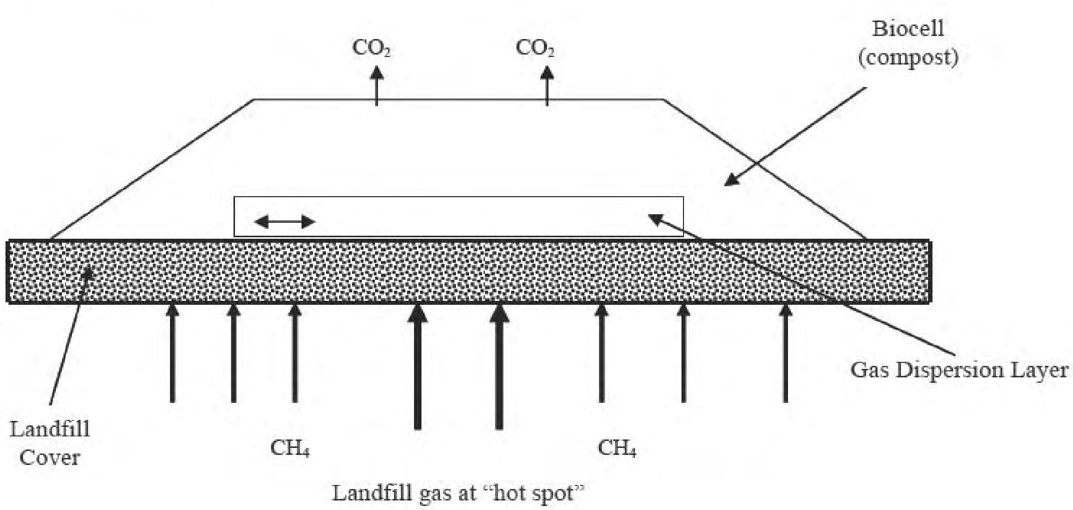


Figure 19. Conceptual Compost Biocell (After Abichou, 2006)



These typically consist of an inlet tube from a passive LFG vent leading to a vessel or chamber filled with a distribution layer and a "filtering" layer of organic material.

Field studies have indicated that well-engineered biocovers using large amounts of very mature compost can produce oxidation rates greater than 200 $g/m^2/d$

Feasibility

As is true with landfill cover soils, the effectiveness of a biocover/biocell/biofilter will be affected by its thickness, physical properties, moisture content, and temperature (Bogner, IPCC 2007). The oxidation rate also relates to the amount of methane being released to the landfill surface.

No research exists on the long-term performance, long term effectiveness or maintenance requirements of biocells, biocovers, or biofilters (Abichou, 2006). Wilshusen (2004) conducted relatively long-term laboratory tests (220 days and 600 days) for four compost biofilters.

While the technical feasibility is not really subject to discussion, there is a small enough body of work to suggest that any biocover/biofilter/biocell project be approached as a pilot study and be carefully monitored for effectiveness.

Implementation Recommendations

The scientific community has clearly demonstrated that fugitive methane from landfill covers can and is oxidized to a greater or lesser extent based on the substrate of the cover (for example some oxidation is expected under most cover scenarios). The amount of methane oxidized appears to be able to be increased based on using a gas distribution layer followed by an appropriate organic feedstock (i.e., yard trimmings compost, biosolids compost, etc). However, very few "whole-landfill" biocovers have really been demonstrated. There are a number of variables that would need to be considered in designing a compost biocover. First and foremost would be the flux of methane currently leaving the landfill. CIWMB and Federal regulations govern landfill cover practices, especially when it comes to final cover. In California the implementation of a biocover would need to be demonstrated as a pilot project.

The "prototype" biocover (Humer) involved minimal compaction and covering of the final lift of the landfill; a gas distribution layer (consisting of gravel, broken glass or other similar substrate that would allow equal and uninterrupted distribution of LFG), followed by a layer of very stabilized, mature compost (Bogner, 2007). Other mediums have been used for "biocells" (a partial biofilter for a portion of a landfill), including freshly ground yard trimmings mulch, leaf compost, sewage sludge compost, mixed solid waste compost and sand.

A process for measuring the effectiveness of methane oxidation has been developed (Chanton & Liptay, 2000) which uses the relationship of two stable carbon isotopes (^{13}C and ^{12}C). To simplify, methanotrophic microorganisms preferentially consume CH_4 containing the lighter isotope (^{12}C,) leaving residual CH_4 enriched ^{13}C. This relationship can be expressed as an equation and the ratios of one isotope to another analyzed after methane oxidation.

Although a biocover would work for any landfill, they seem to be particularly appropriate for smaller, landfills, probably after closure. A biocover is designed to work in concert with a well-engineered gas collection system (Bogner, 2007); but would also have application for those landfills, perhaps smaller landfills for which implementing extensive gas collection systems is not economically feasible or for closed landfills, continuing to expel LFG. California has many small, closed landfills which might benefit from installing a biocover to mitigate fugitive methane which may not be available in sufficient quantities to capitalize a gas collection system, but should be captured or treated prior to it entering the atmosphere. A layer of mature compost would also serve to help establish vegetative cover.

Where possible, compost should be locally made to reduce costs and minimize transportation emissions (another source of GHG). Most landfills in California, even with many communities implementing separate collection of organics for composting, still receive a significant amount of organic materials suitable for composting. Many landfills operate composting facilities on or adjacent to the operating landfill, these facilities could be used to generate the material necessary for a biocover.

Compost/Substrate Conditions---

In order to achieve high oxidation rates, the oxidation layer must ensure optimal ambient conditions for methanotrophic bacteria (Humer, 2001). Very mature compost is a suitable substrate for biocovers (Humer, 2001). The organic matter of the compost must be stable (respiratory activity in 7 days at least <8 mg o2/g DM) (Humer, 2001). Someone looking to source compost for a biocover project could use either the Test Methods for Evaluating Compost and Composting Specific Oxygen Uptake test or the Compost Maturity Index developed by the California Compost Quality Council to select compost.

In laboratory experiments (Humer 1999) the “age” of the compost ranged from 11 weeks to 60 weeks. In the subsequent field experiments (Humer 2001) the age of the compost ranged from 20 weeks (140 days) to 60 weeks (420 days). Most compost in California is not this old. In addition, the bulk density of the composts also ranged from 0.83 kg/l (1,399 pounds per cubic yard) to 1.06 kg/l (1786.7 pounds per cubic yard). This reflects the feedstocks used in those experiments (mixed solid waste compost and sewage sludge compost). Most California green material composts would not be this dense. Two predominantly green material composts reported bulk density (on an as received basis) of 783 pounds per cubic yard (at 31 percent moisture) and 1134 pounds per cubic yard (at 35 percent moisture) respectively. Both of these are much lighter than the compost used in Humer’s experiments.

Technical Considerations---

- Gas distribution layer is crucial (Humer 2001)--0.5 meters (1’7.5”) gas distribution layer greater than or equal to 1.2 meters (approximately 4 feet) of compost (Humer 2001)

- Oxygen penetration depth; settling behavior; dependence of the temperature on the inside of the landfill with ambient temperature.

- Compost should be put in place without compaction to maintain porosity in the compost and gas permeability (Humer 2001).

- Might be necessary to irrigate compost in dry climates.

Relative Cost

Humer (2001) discusses a 1-foot, 7-inch layer of coarse gravel for a gas distribution layer and approximately 4 feet of compost for the biocover. There are a number of possible substrates that could be used for the gas distribution layer which could be obtained at low or no cost at most California landfills (crushed concrete, crushed glass cullet, etc.).

The cost of obtaining and placing 4 feet of compost on the landfill might be prohibitive unless the compost was made on or adjacent to the landfill. Four feet over one acre would require approximately 6,500 cubic yards of compost. Extrapolating this, a 10-acre landfill would need approximately 65,000 cubic yards of compost; a 100-acre site would need 650,000 cubic yards. Many landfills in California operate composting operations on landfills presently (e.g., Western Regional, Newby Island Landfill, Redwood Landfill, etc.). Many California landfills import hundreds of thousands of tons of processed green material for use as ADC annually. The biggest issue would likely be storage space. Not all landfills would be able to store large amounts of compost; however since landfills are built in sequence, the biocover material could be added to closed cells sequentially, avoiding large stockpiles of compost. If the compost were purchased off-site, the cost might be prohibitive. Some commercial composting facilities might offer a discount for bulk sales and for unscreened compost (it is assumed the biocover compost would not need to be screened as the porosity of unscreened compost is more conducive to biocover operations).

For example, the Sonoma Compost Company (located on the now closed Sonoma County Central Landfill) offers retail compost in volumes greater than 500 cubic yards for $9.00/cubic yard. This cost would undoubtedly be cheaper for unscreened compost. The cost of the compost at $9 per cubic yard would be $58,500 per acre. It is extremely likely that the cost for a very large volume of unscreened compost would be lower. But again, this argues for making wholesale compost at the landfill to reduce costs and eliminate transport costs.

If the cost of manufacturing the compost could be minimized by manufacturing on-site (with operating costs offset by avoided cost of landfill disposal) the major cost in implementing a compost biofilter would be placement of the material on the landfill surface. The cost of this should be equivalent to placing the traditional soil cover.

Relative GHG Emissions Reduction Potentials

Humer (2001) reports a compost biocover could oxidize 0.1 – 0.5 m^3/m^2 d. The GHG emissions reductions from a biocover will vary considerably based on landfill variables and ultimately the flow of fugitive methane through the cover system. In addition the types and extent of the biocover will influence the effectiveness of oxidation.

Field studies have indicated that well-engineered biocovers using large amounts of very mature compost can produce oxidation rates greater than 200 $g/m^{-2}/d$. Thus, the reduction in GHG emissions would be considered moderate.

Other Solid Waste Management Strategies

Composting

Controlled composting has been practiced commercially around the world since the early 1900's if not before. The composting process is a naturally occurring biological process that has been refined and adapted as a means of decomposing various organic materials to create a stable substrate, most often used as a soil amendment. There are approximately 4,000 composting facilities in the US. California has over 200 permitted composting facilities, and undoubtedly almost as many on-farm composting operations (which are not required to be permitted). Anything that was once alive (organic) can be composted. Leaves, grass, and brush are the materials most commonly composted in California, though sewage sludge, animal manures, food wastes, liquid wastes, animal mortalities, and mixed solid waste all have and are being composted currently in California.

Description

Composting is the controlled biological decomposition of organic materials. Composting is fundamentally a biologically mediated process that relies on the balancing of feedstock properties, oxygen, moisture, and temperature. If the biological conditions are met, the process of commercial composting is largely a matter of material handling (Moon, 2006). The biological parameters are the same regardless of the scale of the operation. From a practical standpoint, most landfill-based composting operations consist of 5 basic processing steps: Feedstock receiving, material processing, composting, screening, and load out.

- **Feedstock Receiving.** A composting facility located at a landfill is at an advantage because it can utilize existing infrastructure (like the scale house, load checking functions, contaminant disposal, existing access roads, etc.) In many cases, landfills charge a differential tipping fee for source separated organic materials. In some cases hard-to-dispose of organic materials (like liquid wastes) are charged a premium. Feedstock receiving also includes load checking to ensure that the material is free from contaminants that could damage expensive grinding equipment or contaminate the compost.

- **Processing.** In California, most typical "green material" or "yard trimmings" are largely brushy materials in addition to leaves and grass. These materials generally require pre-processing prior to composting. This typically includes size reduction using mechanical shredders and/or grinders.

- **Composting.** The vast majority of composting facilities in the US and in California use a turned windrow method of composting. Processed organic materials are formed into elongated trapezoidal piles called windrows. Windrow dimensions largely depend on the turning mechanism and the porosity of the materials being composted. Front-end loaders are commonly used to form and turn windrows, though larger facilities typically invest in specialized windrow turners to increase efficiency. The length of the compost process depends on the feedstock materials, the optimization of the fundamental parameters (particle size, porosity, balanced carbon to nitrogen ratio, moisture content, etc.), and the intensity of the management. Some compost facilities in California report producing mature compost in as little as eight weeks, though most facilities take longer. Moisture is a major limiting factor in most parts of California and water addition can be a major challenge to California composters. Turning frequencies vary by facility, though all are required to perform and document a 5 turns in 15-day pathogen reduction process.

- **Screening.** Most (but not all) markets require that the finished compost be screened. Each market segment will have its own preferences as to screen size. Some markets may require a mix of coarse and fine particles. Compost used as a biocover, may be usable without screening (the larger particle fraction being critical in providing porosity to the biocover).

- **Load out.** Typically finished, screened compost is stockpiled on-site prior to being loaded out in trucks for delivery to off-site markets.

A composting facility may have any number of intermediate steps and in general the process requires a fair amount of monitoring (temperature, moisture, etc.) in order to optimize the key process variables. Most literature on biocovers (at least those that are sophisticated enough to describe the compost at all) indicate that the compost should be very mature. This is typically defined through laboratory testing, not necessarily the age of the material.

A simplified composting flow chart is provided in Figure 20.

Feasibility

Commercial composting is well demonstrated and technically feasible at landfills in California. It is unknown when exactly the first composting operation commenced in California but it is likely to have been the 1950's. A critical requirement is available flat land. Landfills often have this in buffer zones, adjacent properties, future expansion areas, and on top of decks in the process of being "filled". Composting can typically be conducted on compacted native soil and is often accomplished on landfill surfaces with intermediate cover in place. The surface should be relatively flat with a slight grade for drainage. More than a slight grade is permissible, but will impede operations in excess of 5 percent. An all weather surface is necessary unless the operation is going to be seasonal. Access to water is probably the next most important item.

Implementation Recommendations

A landfill owner should conduct an analysis of the feasibility of developing a composting site on or adjacent to their landfill. The analysis could include the amount and types of feedstock accepted, the composting technology, the required permit amendments or new permits and to what existing equipment might be used for the composting program. The vast majority of landfill-based composting sites use a windrow technology. This technology should be implemented unless site conditions, proximity to sensitive receptors or regulations require additional process control. An exemption exists for permitted solid waste facilities that handle Compostable Organic Materials at permitted landfills, if they use all of the material on-site (as one might if producing compost for a biocover). Title 14, Chapter 3.1, §17855(5)(A):

"The handling of compostable materials is an excluded activity if the activity is located at a facility (i.e., landfill or transfer/processing facility) that has a tiered or full permit as defined in section 18101, has a Report of Facility Information which is completed and submitted to the EA that identifies and describes the activity and meets the requirements of Titles 14 or 27; and, will only use the material on the facility site."

Numerous training programs and classes exist to gain operational knowledge in composting.

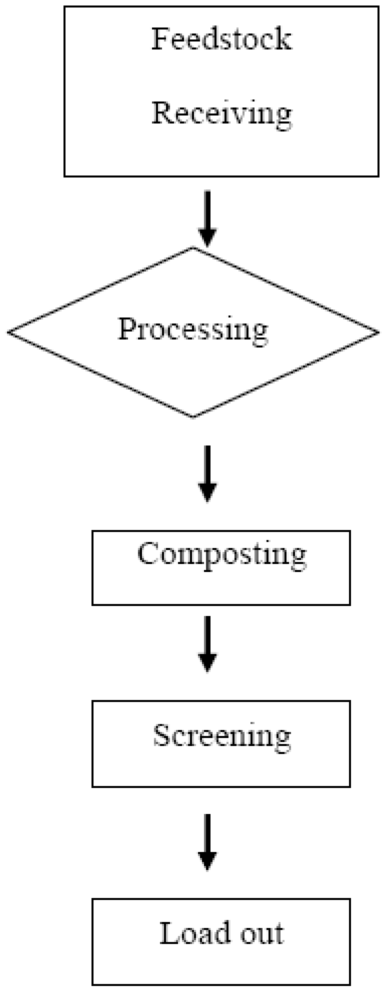


Figure 20. Simplified Composting Flow Chart

<u>Relative Cost</u>

Costs for implementation vary with the type of infrastructure required for the composting operation. In general, economies of scale exist in composting such that costs per ton go down as incoming tonnage increases. It is difficult to provide any meaningful cost data given the number of variables involved.

Relative GHG Emissions Reduction Potential

The most recent IPCC report (Bogner, 2007) contains a simplified mass balance for landfill methane: Methane (CH_4) produced (mass/time) = (CH_4 recovered + CH_4 emitted + CH_4 oxidized). The United Nations Framework Convention on Climate Change (UNFCCC) Clean Development Mechanism (CDM) has developed a methodological tool for determining the amount of methane avoided (i.e., not produced), based on the total amount of degradable organic carbon in various waste types. While a review of that model is beyond the scope of this report, it can be assumed that one could calculate the amount of methane avoided (not created) as a factor of the total amount of degradable organic carbon not disposed in the landfill. This is a similar approach that is being taken at the California Air Resources Board (ARB). The ARB has created a spreadsheet of degradable carbon by material type. Using these assumptions an estimate could be made of specific methane avoided by composting rather than landfilling organics.

This calculation obviously would vary depending on the composition of the feedstock. For example, food scraps might have more readily degradable carbon than brush. The amount of reduction would also depend on the expected GHG emissions that would occur at the landfill where the organic material would be otherwise disposed if not composted. Compost operations can also create additional GHG emissions, such as direct methane emissions when not properly operated and additional GHG emissions from transportation and processing, may offset some of the methane that is avoided if landfilled. Also, consideration has to be given whether the organic material would have otherwise been disposed in a well-controlled landfill with minimal methane emissions and/or one that recoveries energy form the methane, which composting does not do.

Since under anaerobic conditions, organic materials will generate methane, it is important for composting to be managed aerobically. Even if managed aerobically, depending on the feedstock, other GHGs, like N_2O, can be released, especially if significant amounts of grass are composted. In general, less harmful gasses will be released if composting parameters (like oxygen) are optimized. There are numerous published guidance documents that should be consulted to guide composting BMPs; however, these are beyond the scope of this Report, which simply presents composting as an option to reduce landfill methane through diversion of organic material.

Anaerobic Digesters

Description

Digesters can be established at several California landfills to compost organic waste. The decomposition of organic waste in a landfill is a large contributor to GHG emissions, specifically methane. Digesting the waste, rather than letting it decompose in landfills, will reduce methane emissions because the resulting gas can be captured completely and used beneficially as fuel. The byproduct can be used as soil conditioner. A schematic for an anaerobic digester is provided in Figure 21.

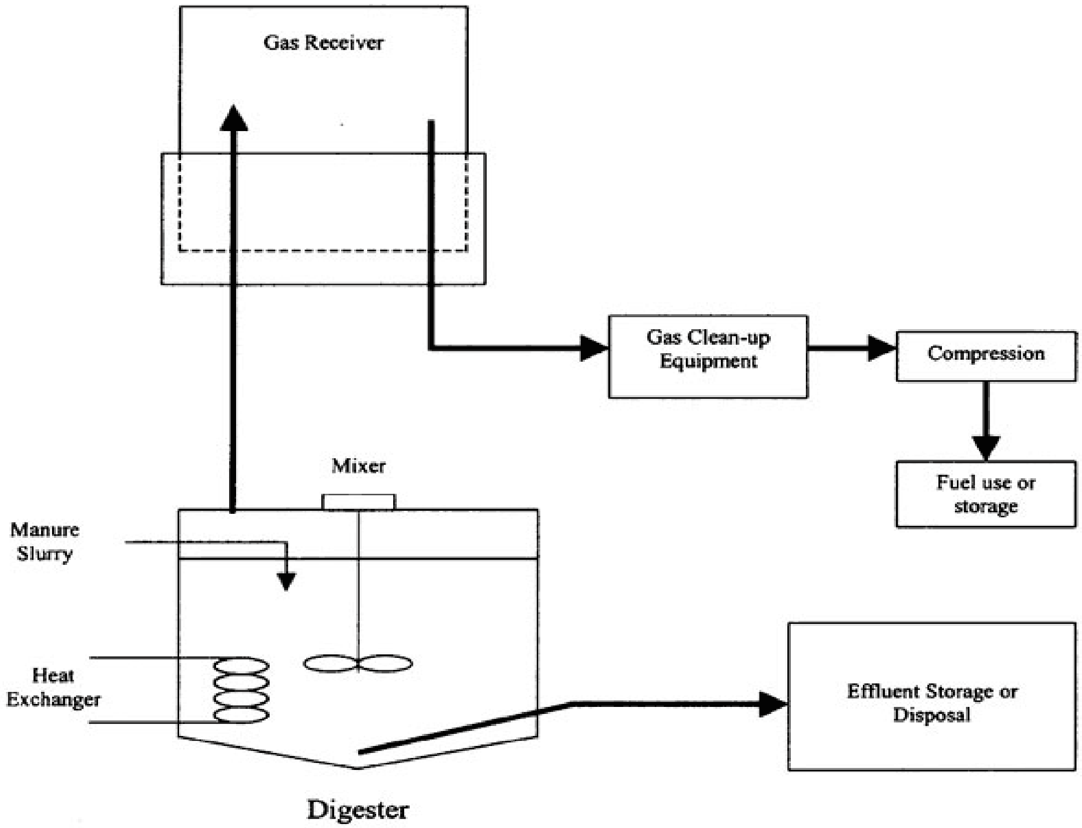


Figure 21. Schematic for Anaerobic Digester

Feasibility

The number of composting facilities is increasing rapidly. Each facility is well planned and documented so others can learn from implementation successes and downfalls. According to the U.S. EPA, there are hundreds of organic digestion facilities at landfills in other countries that mitigate the release of GHG emissions and produce electricity. The quality of the incoming organic waste is dependent on collection and processing, therefore composition can vary. The end use of the byproduct is also dependent on the composition of the organic waste digested.

Some composition may not support the movement of the byproduct in the market. Organic waste will need to be source separated and implementation of the program will depend on a food waste collection program. Some air district rules are moving towards enclosed composting operations, which may be an additional driver to consider these types of anaerobic digester technologies.

Implementation Recommendations

It is recommended to accept material from organic waste collection programs in the commercial sector that include restaurants, grocers, gardeners, cafeterias, food processing plants, and scraps from canneries as well as similar wastes from the residential sector if it can be cleanly segregated. Many wet/dry collection programs already exist in this sector and will provide less contaminated material.

Managing the process for the digester and production of methane can be a complicated process and vary significantly at each landfill. It is recommended that each landfill further research their options for implementing an organic waste digestion program.

Relative Cost for Implementation

The cost of establishing digesters at landfill facilities can initially be expensive and would be initially high compared to current landfill disposal costs. The cost can be reduced to the degree value can be obtained from the sale of energy and/or from the by-product.

Relative GHG Emissions Reduction Potentials

Organic waste has the greatest impact on GHG emissions at the landfill. The U.S. EPA Office of Solid Waste and Emergency Response (OSWER) program indicates that 350,000 ft^3 of methane can be reduced by diverting 182 tons of organic waste. In-vessel anaerobic digestion has the greatest potential for methane reductions from landfills by recovering all of the methane form the diverted organic waste and maximizing renewable energy.

Bale Waste Prior to Disposal

Description

Waste can be mechanically compacted into bales, wrapped with low density polyethylene (LDPE) and placed in the landfill. Among other reported environmental benefits, it can reduce GHG emissions from the landfill because it reduces the decomposition rate of the waste by preventing air and water from entering. According to studies, the acidic concentration becomes very high and does not allow micro-organisms to develop, forcing the material to stabilize without producing methane. This method is recognized as producing short term GHG emission reductions. The long term GHG emission impacts of baling waste are unknown. Several schematics for baled waste are provided in Figure 22.

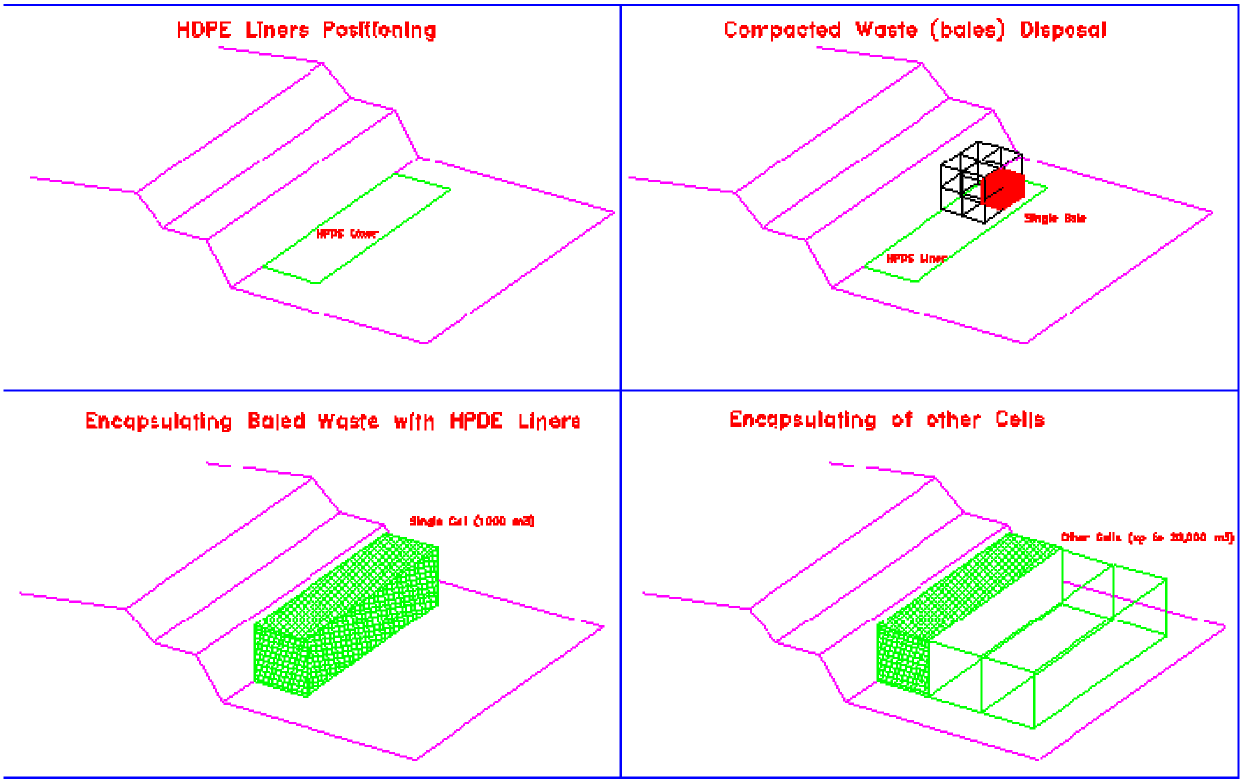


Figure 22. Schematics for Baled Waste

Technical Feasibility

Many landfills already bale waste. The machinery needed to compact the MSW into a bale and wrap it with LDPE is readily available through companies that offer balers for other material types. Establishing the operation will require minimal equipment purchase and space to house the baling and wrapping machine. This can be feasible for large and small landfills as the space requirements needed to house the baling and wrapping machine are generally not demanding. The baler systems have to have the capability of handling the liquids that are drawn from the waste during baling and compaction.

Implementation Recommendations

There are two methods for baling waste. One produces rectangular bales and the other produces cylindrical bales. It is recommended to use rectangular bales as studies show they result in more GHG emission reductions than cylindrical bales. There are fewer studies that report on rectangular bales. However those studies observe rectangular bales performing better due to their higher density, more efficient use of space, and higher processing capacity of machinery. Bales can have waste densities that exceed 2000 pounds per cubic yard.

Relative Cost

The initial investment is higher compared to conventional landfill operation (loose compaction of the waste). However, the difference can be offset by the increased capacity that will result from placing baled-wrapped waste. An analysis comparing the cost of conventional landfill operation and a baling-wrapping operation indicated that the cost per ton for placing baled-wrapped waste was approximately the same cost as conventional landfill operation over an operation span of 15 years.

Relative GHG Emissions Reduction Potentials

Short term GHG emission reductions can be expected from this practice. According to experiments carried out on bales of MSW wrapped in LDPE, approximately 96 percent of tests performed over 300 days showed insignificant values of GHGs from the bales and organic compounds were not detected. Specific reductions in GHGs were not reported and will vary depending on the seal produced by the LDPE film wrapping.

Segregate Organic Wastes in Dedicated Cells

Description

Source separated organic waste can be placed in a designated cell. Gas production in these cells will accelerate because of the high density of organic material and enhanced gas collection techniques would be necessary. The span of time that gas will be collected in those cells can dramatically decrease.

Technical Feasibility

This type of source separation and storage would require a large enough cell to manage the organic waste separately and maintain multiple active cells. The program will need to be paired with enhanced organic and food waste collection programs independent of the landfill.

Implementation Recommendations

It is recommended that this program be implemented at landfills where wet/dry collection programs are already established so acceptance policies will not need to be revised to accommodate the program.

Relative Cost

The increased cost for this program would include expanded organic waste collection, construction and management of a separate organic waste cell, and enhanced gas collection in the segregated cell. There may be some reduction in costs due to reduce LFG construction obligations for the remainder of the landfill due to reduced gas production. Ultimately, the relative cost is expected to be high compared to other BMPs despite some economies in LFG management.

Relative GHG Emissions Reduction Potential

The GHG emission reductions would depend on the quantity placed in the single cells, the composition, and the current proportion of those materials in the disposed waste stream at each landfill. However, low to medium reductions are possible by consolidating and enhancing gas control in the specialized organic cell.

Screening Process For Site-Specific BMPs

Applicability

Each of the BMPs described above should be initially screened for general applicability for the site or project in question. Initial screening can be accomplished by reviewing the summary descriptions and feasibility components of the BMPs and assessing whether the site/project conditions meet the minimum criteria for possible use. For example, BMPs that pertain to active landfills need not be further considered for any sites that are closed or have reached final grade. This step should include a fatal flaw analysis to eliminate any BMPs that are simply not workable because of site conditions. After completion of an initial screening, a reduced list of potential BMPs should be created for further evaluation.

Assessing Technical Feasibility

Technical feasibility must be assessed on a site-specific and even project-specific basis at a landfill for each of the BMPs that passed initial screening. Just because a BMP has been carried through the initial screening for applicability does not mean that is has sufficient technical feasibility for ultimate use. The objective of this review is to identify a limited number of BMPs that appear to meet all or most of the prerequisites for technical feasibility and create the highest potential for GHG emissions reductions.

The analysis for technical feasibility should be a more detailed assessment of the same criteria used above for the initial screening. This task may be best conducted by a person knowledgeable landfill engineering principals; however, there may be one or more BMPs that have high technical feasibility and can be identified without any special expertise.

When evaluating technical feasibility, more is not necessarily better as simultaneous implementation of multiple BMPs may create a situation of diminishing return. In fact, some BMPs are directly or indirectly conflicting with others. The combination of BMPs chosen for each site as being technically feasible should be complimentary to each other or at least additive in their ability to achieve additional LFG control or methane reductions. The outcome of this step in the process is a short-list of BMPs that have the highest degree of feasibility for the site or project in question and will be further assessed as detailed below.

Evaluating Implementability

The evaluation of implementability essentially includes a thorough assessment of the implementation recommendations for each BMPs as detailed above. The goal is to develop a preliminary plan for implementation of each BMP deemed technically feasible. The expected pros and cons related to actual field implementation should be evaluated and weighed against each other. Only BMPs that show a clear path and strategy for implementation should be identified for continued consideration. Again, this task may be best conducted by a person knowledgeable landfill engineering principals; however, there may be one or more BMPs that are clearly implementable for a particular site or project.

Estimating Cost to Implement the BMP

The cost of implementing a particular BMP can only be assessed on a site- or project-specific basis. The relative costs of the various BMPs are ranked as low, medium, and high in the descriptions above. In addition, specific unit costs or cost ranges have been provided where available or applicable. These costs or rankings may not hold true for every site or situation. However, these rankings and cost values can be utilized to conduct an initial screening of BMPs on a cost basis. It is critical to complete at least a preliminary estimate of the costs for implementation for each BMPs that have passed the various evaluation steps detailed above. The costs should include both capital and annual operating costs of the BMPs. Engineering costs should be assumed to be approximately 10% of the capital costs for large projects (i.e., $500,000) and up to 20% for smaller projects. Annual operating costs are expected to range from 5% to 10% of the capital costs for a BMP. It will be difficult to obtain the necessary accuracy in costs without involving someone knowledgeable in the actual real world costs for the BMPs in question. These cost comparisons should only be used for screening of BMPs and should not be considered to represent the actual costs for BMP implementation. Economies of scale or indirect costs associated with other BMPs as well as existing site conditions must also be considered.

Estimating GHG Emissions Reduction Benefit

The estimation of GHG benefit is extremely difficult to complete with any degree of accuracy since actual reductions that can be achieved is very site-specific and because many of the BMPs provide only indirect benefit in terms of actual reductions. To assess relative GHG emissions reduction potential of the BMPs for screening purposes, it is recommended to use the high, medium, and low rankings detailed in the BMPs listing above and make adjustment to those based on site- or project-specific conditions, considering both synergistic and antagonistic effects of the BMPs being considered in concert.

Prioritization and Ranking

Once the above steps have been accomplished, the final list of BMPs should be ranked according to the main criteria of feasibility, implementability, cost, and GHG emissions reduction potential. This is best accomplished by charting the BMPs and ranking them in each of the categories for comparison against each other. Ranking could be numeric in nature or the categories of low, medium, and high could be used, as long as the ranking procedure is consistently applied. BMPs should also be grouped based on which measures would likely be implemented together and ranking should also occur on each grouping. After ranking, the various BMPs and/or groups of BMPs should be prioritized for immediate, short-term (within 6 months to a year), or long-term (more than a year) implementation.

Final Selection

After the BMPs have been prioritized in the previous step, a final decision as to which BMPs will be selected for implementation must be made, including timing for implementation. At a minimum, it is recommended that BMPs or groups of BMPs with the highest cumulative ranking scores be selected for implementation within each of the immediate, short-term, or long-term categories. This would provide a good starting point for use of BMPs. Additional BMPs should be considered as well in the order of their rankings while ensuring that subsequent BMPs will be additive in terms of GHG emissions reduction.

Action Plan

At this juncture, the final BMPs that will be implemented have been selected. It is critical that the BMPs be further detailed in an Action Plan that is both site- and project-specific. The Action Plan will essentially be a conceptual design for full-scale engineering and installation of the selected BMPs. The Action Plan need not contain actual designs plans and specifications for new construction, but the conceptual design must be of sufficient detail for scheduling and cost estimating. The specifics of the conceptual design will depend on the nature of the BMP, such as whether it is a LFG design BMP or one related to other solid waste management alternatives, like composting. The Action Plan should also include a listing of required permitting or approvals, schedule, phasing plan, performance criteria, measurement techniques, and engineering cost estimate. The Action Plan is clearly best conducted by a person knowledgeable landfill engineering principals or other expert, and involvement of such a person is strongly recommended.

Metrics For Assessment Of GHG Emissions Reductions

Performance Criteria

The Action Plan described above should also contain the project- or site-specific performance criteria against which success will be measured. Success under this program is based on methane reductions. Performance criteria can be direct reductions in methane emissions or measurement of surrogate parameters that can be used to relate to methane reductions. The type of BMP will again dictate how the performance criteria should be structured i.e., performance criteria LFG BMPs may be very different from a BMP for increased composting and diversion of organic waste from landfills); however, the criteria would fall into the following general categories:

- Performance criteria that account for the increased collection of LFG through improvements to LFG or landfill design, construction, operations, and/or monitoring. A typical criterion would be standard cubic feet per minute (scfm) of methane recovered.

- Performance criteria that account for the decreased surface emissions of LFG through improvements to LFG or landfill design, construction, operations, and/or monitoring and improvements in landfill covers or cover practices. A typical criterion would be surface emissions of total organic compounds (TOCs) in parts per million by volume (ppmv) as methane.

- Performance criteria that account for the diversion of organic waste from landfills resulting in reduced methane generation. A typical criterion would be tons of waste diverted.

Measurement Techniques

The measurement techniques pertain to the various monitoring, testing, or assessment techniques that will be used to quantify the success of the BMP or group of BMPs in terms of actual GHG emissions reduction. The measurement techniques will allow comparison against the identified performance criteria for each BMP. The Action Plan should include a summary of the measurement techniques to be used to quantify GHG emissions reductions under each set of performance criteria. For every situation, the baseline conditions (i.e., before the BMP or group of BMPs were implemented) must be measured first using the same technique to establish a comparative basis for quantification of real reductions.

Example measurement techniques for the performance criteria identified above include the following:

- For the criterion of scfm of methane recovered, measurement would include in-line flow meters for LFG systems in conjunction with LFG testing (either periodic or continuous) of the methane content of the LFG. The intent would be to measure the increase in methane collection and ultimate destruction beyond the baseline conditions. For new LFG systems, the baseline would essentially be a prediction of LFG recovery potential without use of the BMP.

- For the criterion of ppmv of methane from surface emissions, measurement would include a comprehensive program of SEM to assess the reduction in surface concentrations of methane after implementation of the BMP using a field testing device such as a flame ionization detector (FID) calibrated to methane. The intent would be to measure the decrease in measured surface emissions over baseline conditions. With these measurements, the actual mass of methane reduction could not be directly measured and would have to be estimated. For new LFG systems, the baseline would essentially be a prediction of expected LFG surface emissions without use of the BMP. There are other measurement techniques, which could be used to attempt to measure actual methane fluxes (such, as flux chambers, remote sensing, etc.), however, these remain somewhat speculative in their ability to accurately measure actual flux. As these techniques become more accurate and accepted, they would present an improvement over concentration measurements and could be used to directly estimate mass reductions in methane.

For the criterion of tons of organic waste diverted, the measurement technique would include scale house records of diverted organic waste as well as records of the amount of waste that was processed through the alternative management strategy (e.g., composting, anaerobic digestion, etc.). With these measurements, the actual mass of methane reduction could not be directly measured and would have to be estimated by calculating the displaced methane emissions from the landfills where the material would have been disposed and the life cycle GHG emissions reductions from the act of recycling itself minus any increases in GHG emissions from the transportation and processing of the diverted material. There are a variety of tools and emission factors for the GHG benefit from recycling, which could be used to complete this estimate.

For displacement of fossil fuel derived energy production, the most current CCAR General Reporting Protocols can be used for GHG emission factors for electricity production, combustion of natural gas propane, as well as transportation emissions from diesel, gasoline, biodiesel, LNG, or CNG. For GHG factors for recycling or alternative solid waste management strategies, the U.S. EPA's Waste Reduction Model (WARM), which was developed to help solid waste managers evaluate management options with respect to their GHG emissions impact, can be used. WARM calculates the emissions impacts of several waste management options (i.e., landfill, recycling, composting, and combustion with energy recovery) for 34 separate categories of waste material. The WARM emission factors are based on an U.S. EPA study entitled S*olid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks* originally published in 2002 and now in its 3rd edition (September 2006). However, the field of GHG and climate change is rapidly developing and improved techniques may become available to complete these estimates and should be used.

The above items only represent examples of measurement techniques that can be used. Any comparable techniques could be feasible as long as they can achieve the objective of measuring or assisting in the estimation of methane reductions. The proposed methods should be clearly spelled out in the Action Plan.

Tracking of Progress

The progress and success of the BMPs should be continually tracked so that adjustments can be made, if necessary, or the BMPs could be discontinued if no success is being achieved. Quarterly progress reports are recommended for at least the first year with annual reports thereafter. Tracking would include rolling averages and cumulative totals of GHG emissions reductions and costs for continued implementation. The values should be compared back against the ranking matrix to assess which BMPs have met expectations and which have not. Successful BMPs should be made permanent while marginal or unsuccessful BMPs should be discontinued with consideration given for implementation of additional replacement BMPs.

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