California Integrated Waste Management Board

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Contractor's Report

To The Board

Technologies and Management Options for Reducing Greenhouse Gas Emissions From Landfills

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Executive Summary

A major concern of California and the California Integrated Waste Management Board (CIWMB) is reducing greenhouse gases (GHG). One major source of GHG is landfill gases (LFG), especially methane.

CIWMB's Project Team, under the management of SCS Engineers, environmental consultants and contractors, researched and developed this report. The report is designed primarily as a guidance document for landfill operators and regulators and provides recommended technologies and management practices for reducing LFG emissions through improved landfill design, construction, operation, and closure. It is also designed to help evaluate whether potential landfill changes will lead to reduced LFG emissions.

CIWMB also assembled a separate Technical Advisory Group (TAG). The TAG reviewed and provided feedback on all aspects of this report to ensure that:

- This report has the approval of the overall solid waste industry
- The strategies and technologies presented in this report are state-of-the-practice

As a first step, the Project Team compiled and reviewed all available literature on the technologies and practices for reducing GHG emissions from landfills. Though the literature collection is extensive, a large percentage of the information used in developing the best management practices (BMP) detailed in this report did not come from published literature, but instead from the experience and expertise of the Project Team members.

BMPs, in this context, are defined to mean technologies and management practices that are best-suited for implementation at a particular landfill site. For most sites, only a limited number of the BMPs will be feasible and implementable.

Technologies and Management Options

The Project Team evaluated technologies and management options for applicability, cost, and overall effectiveness in reducing GHG emissions. This evaluation included, but was not limited to, the design, construction, and operational practices for:

- LFG collection and control systems.
- Landfill waste management unit design and construction practices.
- Landfill operational practices including:
    1. Daily cell development and construction
    2. Waste acceptance and placement
    3. Leachate recirculation and bioreactor landfill operation
    4. Daily, intermediate, and final cover materials and practices
- Use of compost and other recycled materials as landfill biocovers to reduce GHG emissions.
- Landfill closure and post-closure maintenance practices, including partial closure.

Utilizing its experts in each topic area, the Project Team developed an initial list of strategies for reducing GHG emissions under each area of landfill or LFG practice area. The strategies were based on information developed from the literature review as well as the personal expertise and experience of the topic experts.

From this initial list, the Project Team selected those technologies or strategies that were fully developed and created the list of primary BMPs for reducing landfill GHG emissions.

Table 1 below provides a summary of these primary BMPs. For a complete discussion of each BMP in greater detail, refer to the applicable section in this report.

Screening Process

In addition to identifying and evaluating the primary BMPs, the Project Team recognized that not every BMP is applicable to every site and that many are site- and even project-specific. To help determine the best technologies and BMPs for a specific site, the team developed a recommended screening process which includes the following steps:

1. Initially, screen all BMPs for general applicability to the site or project.
2. Screen those selected in step one for technical feasibility based on the site or project specifics.
3. For those selected as technically feasible, review the BMP implementation recommendations and develop a preliminary implementation plan.
4. Estimate the costs to implement. Although each BMP is given a low, medium, or high ranking for cost, these are estimates only. A preliminary estimate for each BMP should be made based on specific site requirements and conditions. Where available, more detailed cost values to be used for screening purposes are provided in the report.
5. Estimate the GHG emission reduction benefit. As with the costs, the provided rankings of potential GHG emission reductions are just general estimates. A more detailed estimate should be made, again based on the specific site requirements and conditions.
6. Based on the results of steps 1-5, rank the final list of BMPs for feasibility, implementability, cost, and potential GHG emission reductions. After ranking, the BMPs can be prioritized and a schedule created, showing immediate, short-term, and long-term implementation plans.
7. Make the final selection of BMPs, including their implementation timing.
8. Develop a site-specific action plan. The action plan is a conceptual, though not necessarily detailed, design for full scale engineering and installation of the selected BMPs.

Evaluating GHG Emission Reduction Effectiveness

After incorporating one or more BMPs at a landfill, it is very important to assess their effectiveness in reducing GHG emissions. This is best accomplished by including site- and/or project-specific performance criteria in the action plan (see step 8 of the screening process).

Because the various BMPs have diverse application, construction requirements, and results, developing a set of detailed performance criteria is almost impossible. However, general requirements for all performance criteria include:

- Accounting for the increased collection of LFG. A typical criterion would be additional standard cubic feet per minute (scfm) of methane recovered.
- Accounting for the decreased surface emissions of LFG. A typical criterion would be surface emissions of total organic compounds (TOCs) in parts per million by volume (ppmv) as methane.
- Accounting for the diversion of organic waste from landfills resulting in reduced methane generation. A typical criterion would be tons of waste diverted, which can be converted into GHG benefit using available reduction factors.

Table 1. Summary of Best Management Practices (1)

No.	BMP	Description	Feasibility	Implementation Recommendations	Relative Cost	Relative GHG Emissions Reduction Potential	Page No.
Design-Related BMPs for LFG Collection Components							
A-1	Horizontal Collectors or Surface Collectors	Horizontal collectors collect LFG before vertical wells are installed. This BMP included surface collectors. Surface collectors collect gas from a landfill where traditional wells fail due to water infiltration	Can provide appreciable gas collection before vertical wells become feasible, but they may not be feasible in wet conditions. Surface collectors are feasible where traditional horizontal and vertical collectors fail	Horizontal collectors can be installed during the filling process but vacuum should not be applied until they will be effective. Installation must be coordinated with fill planning to avoid damage. Collectors are installed after filling is complete and are most effective with synthetic or low permeability cover	Low for horizontals Low where synthetic cover already exists, high elsewhere for surface collectors	Medium for horizontals Low for surface collectors	20
A-2	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 show 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	24
A-3	Mixed horizontal and 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.	Feasible for most landfills but may be costly for some and requires coordination with landfill operations.	Recommended for deep landfills that take years to fill each section.	High	Medium	28
A-4	Connection of LCRS layer to GCCS	LCRS is connected to the GCCS to collect LFG along the bottom of the landfill.	Feasible for most landfills with a LCRS and GCCS where the LCRS contains LFG.	High side of the LCRS is connected to the GCCS to prevent blockage. LCRS may be monitored for gas quality to determine when vacuum should be applied.	Low	Medium	30
A-5	Deep multi-depth vertical wells	Wells placed at multiple depths in the same boring at higher vacuum. Also, wells can alternate between shallow and deep.	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	32

Table 1. Summary of Best Management Practices (2)

No.	BMP	Description	Feasibility	Implementation Recommendations	Relative Cost	Relative GHG Emissions Reduction Potential	Page No.
A-6	Maximize borehole and well diameters	Pipe diameters of 4” or 6” are used for wells, with larger diameters if high LFG production is expected.	Feasible for the construction of all vertical well systems.	Err conservatively and select the largest diameter.	Medium	Low	34
A-7	Enhance seals on LFG wells and 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	35
A-8	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, 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	38
A-9	BMP for LFG System Piping	System piping is designed so it does not limit LFG flow.	Feasible for all LFG systems, but specific elements must be chosen on a site-specific basis.	Should be implemented after an engineering review and should use conservative assumptions.	Low to medium	Low to medium	39
BMPs for LFG Systems and Operations and Maintenance							
BMPs for Gas Mover Equipment and Vacuum Control							
B-1	Barometric control of LFG system	Vacuum applied to wells is changed based on the change in barometric pressure.	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	43
B-2	Redundant flare station equipment	Spare equipment is available for less downtime.	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	44

Table 1. Summary of Best Management Practices (3)

No.	BMP	Description	Feasibility	Implementation Recommendations	Relative Cost	Relative GHG Emissions Reduction Potential	Page No.
B-3	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	47
BMPs for LFG Control Systems							
B-4	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	48
BMPs for LFG Enhanced LFG Operations and Maintenance							
B-5	Enhanced O&M	Training of operators, maintenance, and monitoring are increased.	Feasible for all LFG systems, but specific elements must be chosen on a site-specific basis.	Should be implemented after site specific conditions are available.	Low	Unknown, expected low	49
Other LFG BMPs							
BMPs for LFG Management Strategies							
C-1	Early installation of LFG systems	LFG systems are installed earlier than currently required by regulation.	Expands the number of landfills required to install LFG systems and requires earlier expansion of LFG systems at landfills with existing systems.	Constraints are budget, mobilization costs and economy of scale, landfill operations, and filling rates.	High for new systems, low for expansions	High for new systems, low to medium for expansion of existing systems	54
C-2	LFG Master Planning	Implementation of a LFG Master Plan for long term gas management planning.	Feasible for all landfills.	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	56
C-3	Energy Recovery from LFG	LFG is combusted for energy, displacing fossil-fuel use	Feasible for large projects where and when fuel and energy costs are high.	Recommended for implementation at landfill where project can be shown to be economically viable.	Low, over the project lifetime	High	58

Table 1. Summary of Best Management Practices (4)

No.	BMP	Description	Feasibility	Implementation Recommendations	Relative Cost	Relative GHG Emissions Reduction Potential	Page No.
Enhanced Monitoring, Modeling, and Testing BMPs							
C-4	Enhanced surface emissions monitoring	SEM is conducted more frequently and under more stringent limits to detect and control lower level emissions.	Feasible for any landfill.	Increases the stringency of existing landfill practices.	Medium	Low to medium	59
C-5	Enhanced gas migration monitoring	LFG migration monitoring is conducted more frequently and under more stringent limits to detect smaller emissions.	Feasible for any landfill.	Increases the stringency of existing landfill practices. Siting of additional LFG probes should follow CIWMB standards and guidance.	Medium	Low	62
C-6	Improved modeling and testing for gas design	LFG system design is enhanced by improved modeling and testing	Feasible for any landfill Most feasible at landfills with problems optimizing LFG recovery.	Includes elements that can be included on a site specific basis.	Low to medium	Low to medium	63
Other Landfill Design and Operations-Related BMPs							
BMPs for Landfill Systems							
D-1	Cover LCRS layer	The LCRS layer is covered with waste as timely as possible.	Feasible unless waste is not available.	Cover the LCRS with at least 20 feet of waste when possible.	Low	Low	66
D-2	Blockage of permeable layer within landfill	Blockage is created in the geocomposite near the top of the slope.	Feasible for new cell construction, but is difficult in existing cells.	Recommended for sites with a geocomposite LCRS layer which extends into the anchor trench.	Low	Low	66
D-3	Designing for closure and post-closure	Closure design operations take LFG 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	68
D-4	Promote deeper landfills	Deeper landfills are allowed without requiring a larger footprint.	Landfill heights are limited due to visibility; top deck size becomes a limiting factor.	Landfills could be evaluated to determine optimum geometry.	Low	Medium to high	69

Table 1. Summary of Best Management Practices (5)

No	BMP	Description	Feasibility	Implementation Recommendations	Relative Cost	Relative GHG Emissions Reduction Potential	Page No.
BMPs for Landfill Cover Systems							
D-5	Designing covers for LFG collection	The type of cover is chosen to control LFG. Synthetic final cover system.	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	70
D-6	Limit delays on final cover systems	Final cover is applied to landfills sooner.	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	71
D-7	Modify, limit or remove intermediate cover systems	Remove daily and intermediate cover to create more uniform gas flow through the landfill.	Technically feasible and can be done by removing daily 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	72
BMPs for Landfill Operations							
D-8	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	73
BMPs for Enhanced Landfills							
D-9	Designing LFG systems to recirculate leachate	Horizontal and vertical LFG collection wells are used to recirculate leachate.	LFG collection systems are commonly used in leachate recirculation systems.	Only landfills that are approved for leachate recirculation will use them.	Medium	Medium	74
D-10	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	75

Table 1. Summary of Best Management Practices (6)

No.	BMP	Description	Feasibility	Implementation Recommendations	Relative Cost	Relative GHG Emissions Reduction Potential	Page No.
D-11	Biocovers	Biocovers are installed to increase methane oxidation in the landfill cover.	Feasible at sites with available compost material and/or onsite compost.	Should first be demonstrated in a pilot project before being fully implemented.	Low	Medium	78
Other Solid Waste Management Strategies							
E-1	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	83
E-2	Anaerobic digesters	In-vessel digesters are for organic waste in-vessel with an extremely high % of methane control	The technology for digesters has been demonstrated.	Organic material collection programs can collect organic waste. This would likely be done in an energy system.	High	High	87
E-3	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	88
E-4	Segregate organic wastes in dedicated cells	Organic waste is stored separately from inorganic waste, which allows enhanced LFG collection in a limited area containing organic waste.	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	90

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

Introduction

Objectives

The objective of this project was to develop a guidance document (Report) for landfill operators and regulators. This Report is designed to help evaluate potential actions that, if implemented, could further reduce greenhouse gas (GHG) emissions from landfill gas (LFG) beyond what is currently achieved with existing landfill practices. 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 or recommend policy 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 reducing GHG emissions related to the methane contained in LFG.

BMPs, in this context, are defined to mean technologies and management practices that are best-suited for implementation at a particular landfill site. For most sites, only a limited number of the BMPs will be feasible and implementable.

Project Team

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

The CIWMB Project Team includes the following team members:

- CIWMB staff, including Stephanie Young and Scott Walker.
- 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.
- Industry experts on the Technical Advisory Group (TAG).

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 reducing near-term GHG emissions from specific sources (including landfills), and sets emission limits to cut the state's GHG emissions to 1990 levels by 2020. Both the legislation and 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 to reduce GHG emissions.

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). However, estimates of landfill GHG emissions are based on factors and assumptions that are poorly understood and highly debated. Many researchers and stakeholders conclude that although there are opportunities to further reduce GHG emissions from landfills, the baseline emissions are much lower than currently estimated because of advancements in solid waste management and LFG control efforts. Other stakeholders believe that landfill GHG emissions are higher than currently estimated and that reduction estimates are exaggerated.

In response to this debate, CEC is conducting a study on landfill methane emissions and capture efficiencies. When complete, it will provide a more accurate estimation of landfill GHG emissions and reductions. This Report is designed to complement the CEC study by providing guidance on ways to actually reduce landfill GHG emissions. These reductions could then be measured by the methodologies being evaluated in the CEC study.

The California Air Resources Board (CARB) recently updated the statewide GHG inventory, including the 1990 baseline and current years. Based on CARB's 2007 inventory, California landfills were estimated to emit 5.62 million metric tons of carbon dioxide equivalent (MMCO2E) emissions in 2004, the last year of the inventory, which comprises approximately 1.2% of the statewide inventory. For the baseline year of 1990, landfills were estimated to emit 6.26 million metric tons of MMCO2E emissions. As such, landfills are one of the only source categories that are already below their 1990 baseline. Despite this, landfills are identified under AB-32 as requiring additional reductions for methane emissions. CARB is also developing the various regulatory programs necessary to achieve AB 32 objectives. These include early action measures for reducing GHG emissions. Landfill emissions are a prime focus of these potential early action requirements, and this Report provides 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. This lack of guidance or roadmap is a significant barrier for the industry in achieving targeted GHG emissions reductions. This Report sets forth landfill technologies and practices that can be used to reduce GHG emissions and recommends practical and cost-effective site-specific measures to reduce GHGs from California landfills.

Workplan

The Project Team developed an initial detailed work plan and submitted it to the CIWMB contract manager for approval. As part of the work plan, the Project Team prepared a detailed outline of the final Report. This outline became the basis for the Report contained herein.

Technical Advisory Group

Background

CIWMB convened an advisory group to review the project deliverables in consultation with CIWMB staff. CIWMB believes 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 provided a list of proposed nominees to CIWMB for inclusion on the technical advisory group (TAG); CIWMB staff made the final selection of TAG members.

TAG Members

TAG members 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. TAG members are:

- 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

TAG member duties include:

1. Confirm and accept their TAG nomination, including agreement to complete the proposed TAG duties.
2. Serve as point of contact and coordinator for 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 workshop or conference call on the draft final report.
6. Provide an alternate TAG member to act in their absence and fulfill all responsibilities.

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 relevant information sources. This included, but was not limited to, the following topics:

- 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
- 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, individuals landfill companies, etc.), and any other available and relevant sources of information. Specific requests of recognized experts in this field, including the TAG members, were also made to obtain data sources from their collections, if available. In this way, the Project Team ensured that the majority of applicable and relevant information on the topics was available for review.

The Project Team then conducted a detailed review of the collected data. The review focused on making the most defensible and up-to-date conclusions about the potential for reducing GHG emissions from the 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.

Based on the literature review, the following general conclusions were made:

- Although there is substantial published literature on methane emissions from landfills, there was a clear deficiency in practical measures for reducing GHG emissions 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 technical papers from the landfill industry 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 useful information from regulatory agencies on the relevant topics.
- The areas where the most recent study has been conducted 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 experience and field testing.
- The majority of the BMPs developed for this Report are derived directly from the actual experience of 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.

BMP Selection Methodology

The Project Team evaluated technologies and management practices for applicability, cost, and overall effectiveness in reducing GHG emissions, 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 to reduce GHG emissions.
- Landfill closure and post-closure maintenance practices including partial closure.

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

- LFG design techniques for maximizing 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 impacts on LFG system and how to minimize.

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.

Based on published literature, the team developed a brief qualitative analysis of the potential for organic waste diversion to reduce GHG emissions.

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 BMP description explains what the BMP encompasses and how it serves 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 for determining when the BMP would be technically feasible (or not) without regard for cost or other factors.
- Recommendations for implementation provide specific instructions for BMP use in actual landfill situations.
- Relative cost is provided to help compare the various BMPs on a generalized cost basis. Because landfills come in varying sizes and degrees of complication, it is impossible to provide any meaningful absolute cost information for assessing a particular BMP's implementation cost for a specific site. Instead, costs are ranked as low, medium, or high relative to other BMPs. A detailed cost-effectiveness analysis, as detailed in "Screening Process for Site-Specific BMPs," must be conducted on a case-by-case basis before final selection of any BMP. To assist in this regard, specific cost information in 2008 dollars is provided where available for certain BMPs. This information is not a substitute for a site-specific cost analysis, but may be useful for screening purposes.
- The relative potential for GHG emissions reduction is also graded as low, medium, and high 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, driven by many different factors. As such, a qualitative assessment of the GHG emissions reduction potential is probably the only way to determine 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 explained in "Screening Process for Site-Specific BMPs."

The BMP listing was originally submitted to CIWMB and TAG for a pre-review prior to inclusion in this Report. Table 1 above provides summaries for all BMPs. It is recommended that this document be periodically updated to reflect changes and improvements to the BMPs or new technologies that are developed. This will ensure that it represents the state of the practice for reducing methane emissions from landfills.

Landfill Gas BMPs

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 despite 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 or Surface Collectors (A-1)---

Description

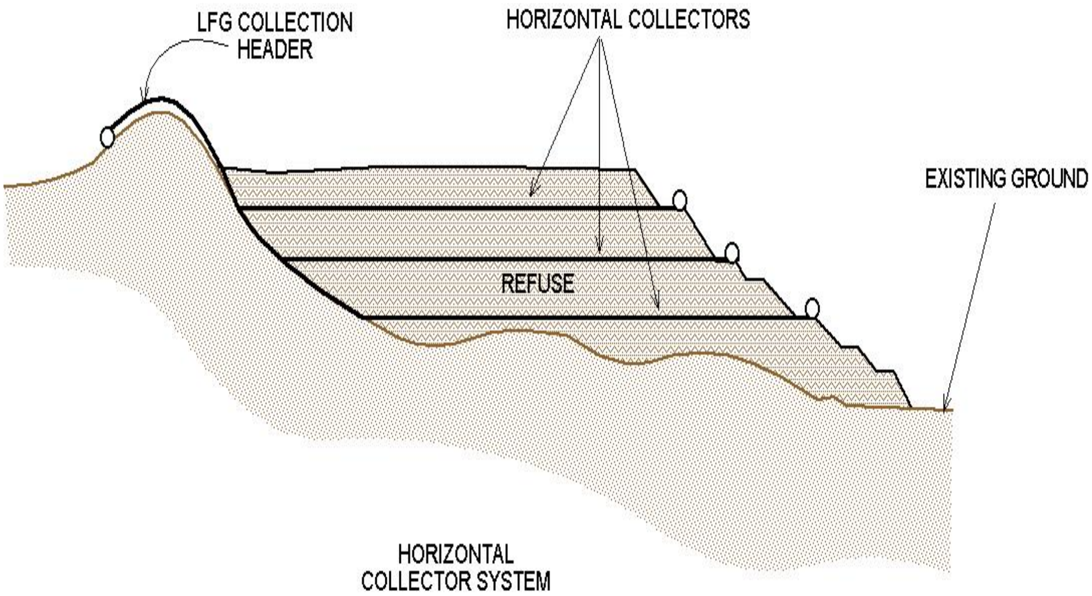
Horizontal collectors can be used in the early life of a cell or landfill to control surface emissions. The horizontal collectors are installed across the landfill surface in trenches within the refuse and connected to the piping system at the outside slope of the landfill.

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 gas collection while the cell or landfill is in active filling mode. However, to limit air infiltration into the landfill, the collectors are not brought online until adequate refuse has been placed above them, which may be up to 30 feet thick.

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 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 is accomplished by alternating the length of adjacent horizontal collectors between short and long. A long horizontal collector traverses 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 protrudes 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 due to the horizontal permeability of refuse being greater than the vertical), while reducing installation costs of using uniform spacing using longer pipe. . 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.



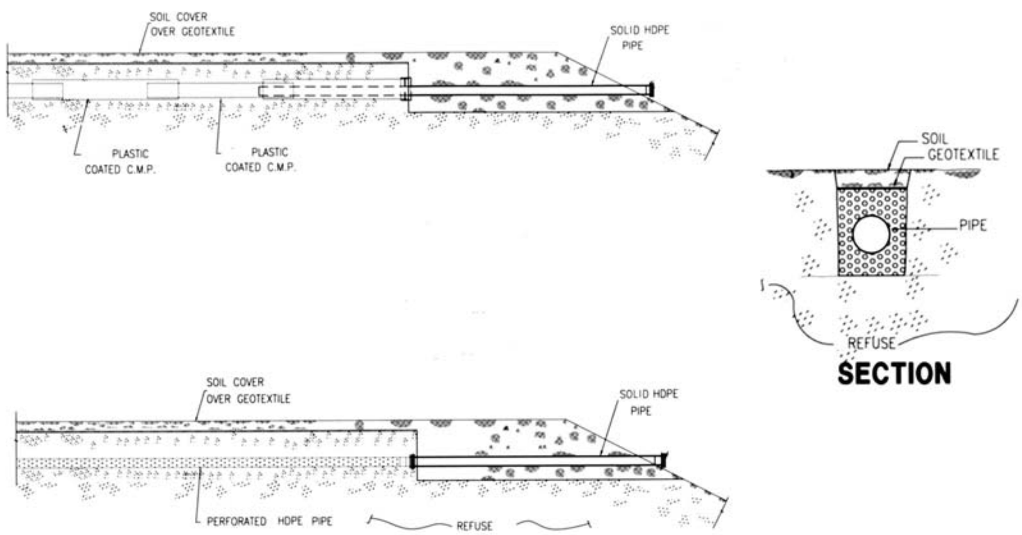


Figure 1. Typical Horizontal Collector Layout and Details

A continuous planar layer of permeable material ("surface collector") 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. .

Surface collectors can be used to collect gas from a wet landfill where traditional horizontal and vertical wells fail due to water infiltration or as an enhancement for surface emissions control. The 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 or by the landfill cover itself. Gas flow below the geomembrane is promoted by installing the permeable layer of the surface collector. The wellheads for the surface collectors are installed at the outside of the geomembrane to allow for monitoring. By burying these collectors, they are protected from the weather.

Feasibility

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).

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 collectable quantities of LFG will begin to produce. 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 limit the placement of horizontal collectors. Long, relatively consistent lifts are needed to effectively install the collectors.

Because it may have limited benefit for LFG control, 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. It 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 water inundation.

Surface collectors are feasible whenever more conventional vertical and horizontal LFG extraction wells are not. Surface collectors can provide gas collection when other well types fail due to flooding; however, their overall feasibility is limited to certain unique circumstances.

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, a vacuum is not applied to them immediately after installation. This is because at their shallowest point, the collectors are too close to the landfill surface 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, horizontal collectors are monitored for gas quality, quantity, and/or pressure build-up prior to applying a vacuum to confirm anaerobic conditions have been established before implementing gas collection.

Horizontal collectors should be activated when the following occur:

- The depth of waste above the collector is adequately thick to prevent excessive air intrusion
- After the cell begins to generate sustainable quantities of LFG
- 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 their construction has the potential to impact landfill operations, and poor coordination can result in damage or destruction of the collector.

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

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. This short-circuiting reduces collector effectiveness and radius of influence. Therefore, surface collectors use passive gas collection, that is, the gas vents to the collectors or operated under lesser vacuum. Surface collectors are at risk of failure due to air short-circuiting below the geomembrane.

Relative Cost

Using horizontal collectors increases 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 reduce 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, which can occur for vertical wells systems where above grade piping and wellheads are commonly damaged by landfill operations. Horizontal wells may also reduce the need for vertical wells offsetting some of the increased capital costs of the horizontal collectors. 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.

Using surface collectors increases the cost of the LFG system versus using vertical wells when final or interim grade is reached and/or when regulations mandate installation. Overall, the relative cost of implementing surface collectors is rated medium to high because of additional geomembrane material cost. . 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 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.

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.

(Return to Table 1)

Tighter Spacing of Vertical LFG Wells (A-2)---

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
- The vacuum available

LFG system designers use various tools, models and experience to estimate the expected radius of influence (ROI) for particular wells. This value is then used to determine the number and spacing of wells needed 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. 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. 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. Types of vertical wells include those installed directly in refuse, wells installed along the landfill perimeter, and vertical wells installed in the vadose zone adjacent to the landfill, which are used for migration control. 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.

Feasibility

The feasibility of using tighter spacing of vertical wells is best determined after initial well installation and LFG collection data can be analyzed. If the data suggests the LFG system is not collecting the amount 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. It 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 landfill areas. Extension of the wells is difficult and the survival rate of wells is not good. Dozers and compactors used for landfill operations tend to run over these wells.

Implementation Recommendations

To implement, 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 suggests complete LFG coverage does not exist.

Tighter spacing can first be employed on a limited basis. Tracking the increase in total and per well gas flows will help determine if larger scale employment will be successful. There is a point of diminishing return with this BMP, as additional collectors do not increase the amount of extracted methane because they are simply drawing gas from other wells rather than from an uncollected reservoir. . Competing vacuums between neighboring wells can also increase operation and maintenance costs.

Relative Cost

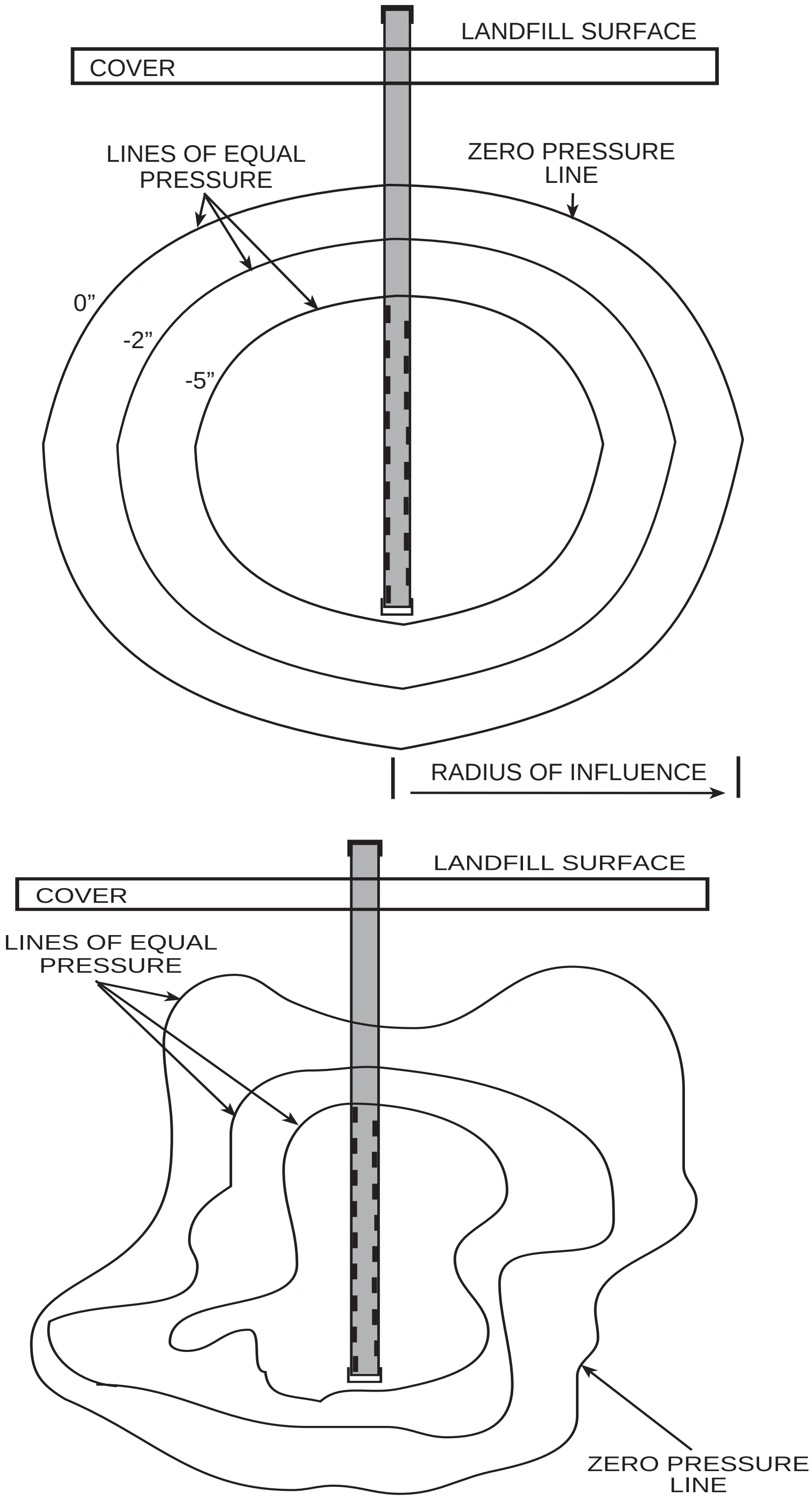
The use of tighter well spacing would increase the cost of the LFG system versus systems with less comprehensive landfill coverage. The cost-effectiveness of this BMP is ultimately dependent on the amount of LFG not collected under the existing or less conservative design. Many times this can only be 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. . 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.

(Return to Table 1)

Figure 2. Theoretical and Actual ROIs



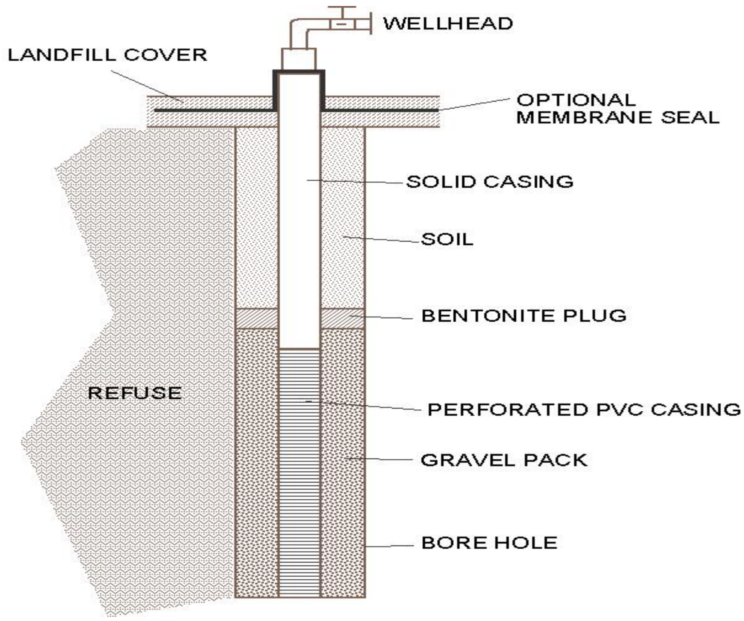


Figure 3. Typical Vertical Extraction Well

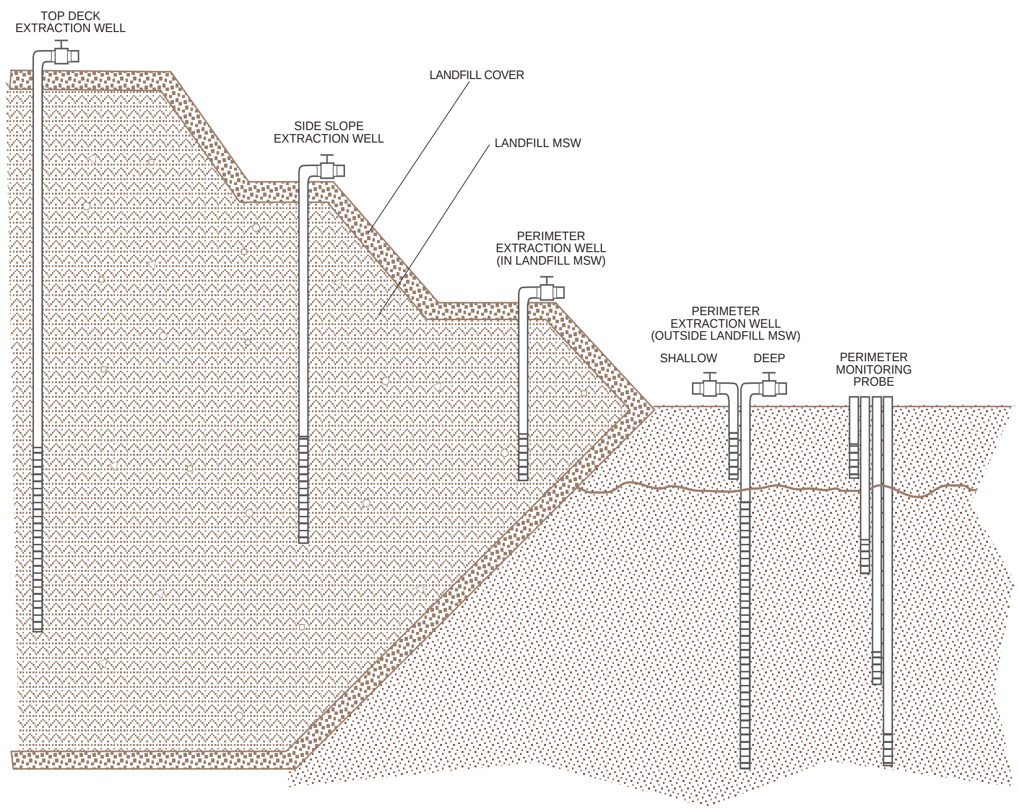


Figure 4. Network of Vertical Extraction Well Types

Mixed Horizontal/Vertical Well Systems (A-3)---

Description

Horizontal collectors offer the benefit of early gas collection, but they are not as efficient as vertical wells because refuse permeability is greater horizontally than vertically, and vertical wells apply vacuum in the horizontal plane. Therefore, horizontal collectors create a horizontal layer of efficient gas collection, but vertical vacuum distribution is not as good for these collectors. This requires tighter vertical spacing of horizontal wells to 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. 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 hybrid system consists 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 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 there is no damage risk from operations. Figure 5 depicts a general schematic a mixed horizontal and vertical well system at a landfill in California, showing the general arrangement of such wells. .

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 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 are more costly than single mobilizations for installation of a larger number of vertical wells. The horizontal collector installation 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. This approach provides 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.

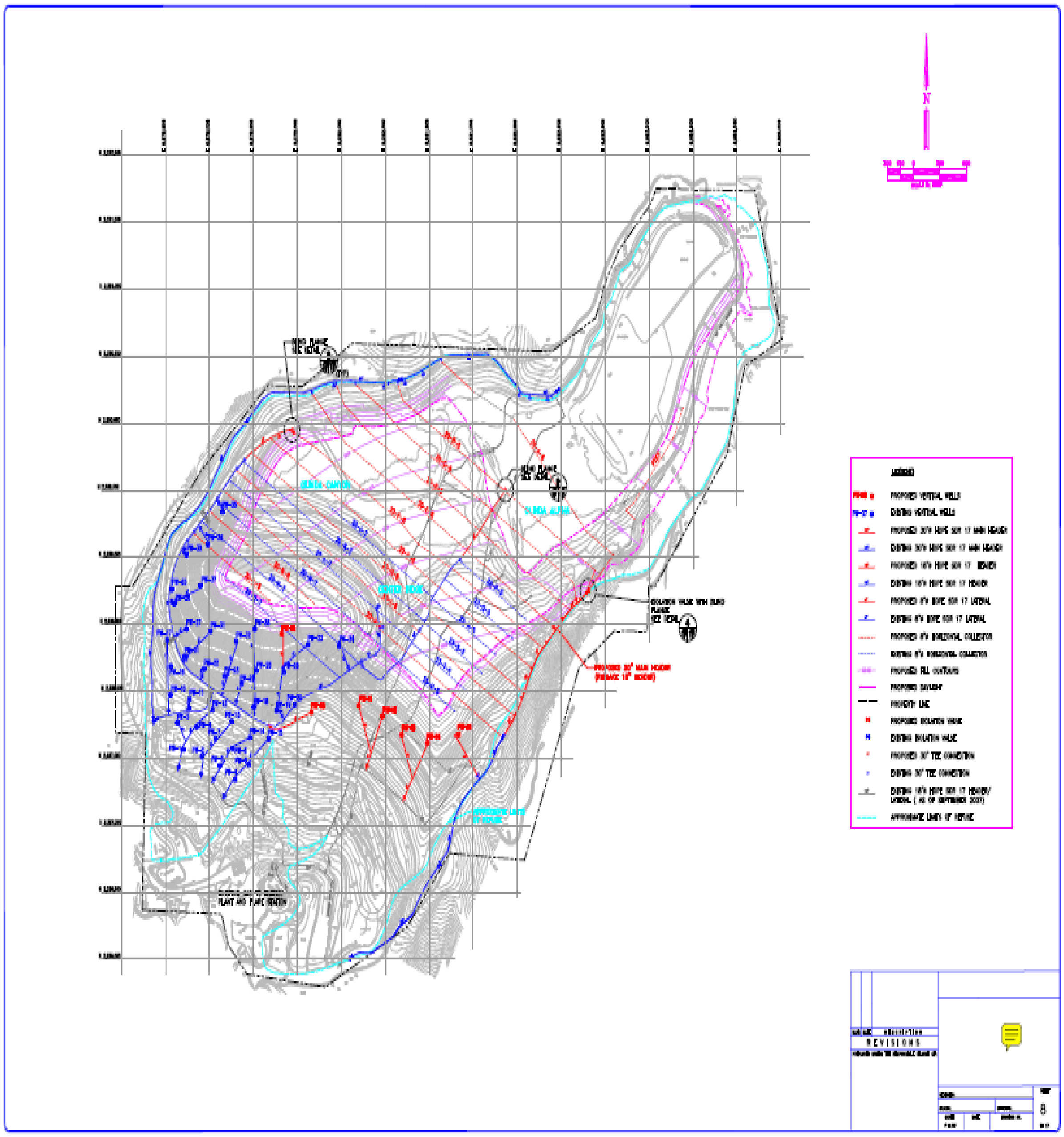


Figure 5. Example of Combination of Vertical Well and Horizontal Collector System in California

Relative Cost

This system is expected to be more expensive because of the higher horizontal collector costs and multiple drill rig mobilizations for vertical wells. 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 as they are crushed by 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.

(Return to Table 1)

Connection of LCRS Layer to LFG Collection System (A-4)---

Description

By connecting the leachate collection and removal system (LCRS) to the LFG collection system, LFG is collected 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. The connection of the LCRS to the LFG system is becoming more commonplace in California (e.g., Pacheco Pass Landfill, Ostrom Road Landfill, etc.). . Figure 6 provides photographs of an LCRS connection to the LFG system.

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 most effective when there are appreciable quantities of LFG in the LCRS. This can be determined through testing. .

This BMP should also be considered for newer lined landfill cells as a 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 (i.e., reduce the liquid pressure on the bottom liner system), it has proven feasible at most landfills in the state.

Implementation Recommendation

The Project Team recommends 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 there may be vacuum influence on the side slope drainage layer as well. This helps prevent LFG migration or gas escaping 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.

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.

Figure 6. Photos of LCRS Connections to LFG System

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.

(Return to Table 1)

Deep, Multi-Depth Vertical Wells (A-5)---

Description

The deeper a well is imbedded in refuse, the greater the vacuum that can be applied before the well will short-circuit with ambient air. With this BMP, 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 vs. horizontal permeability of refuse.

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 from 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.

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 is most feasible for:

- Deep unlined or clay-lined landfill cells with evidence of lateral gas migration
- LFG wells operating near a landfill slope where shallow wells are prone to short circuiting.

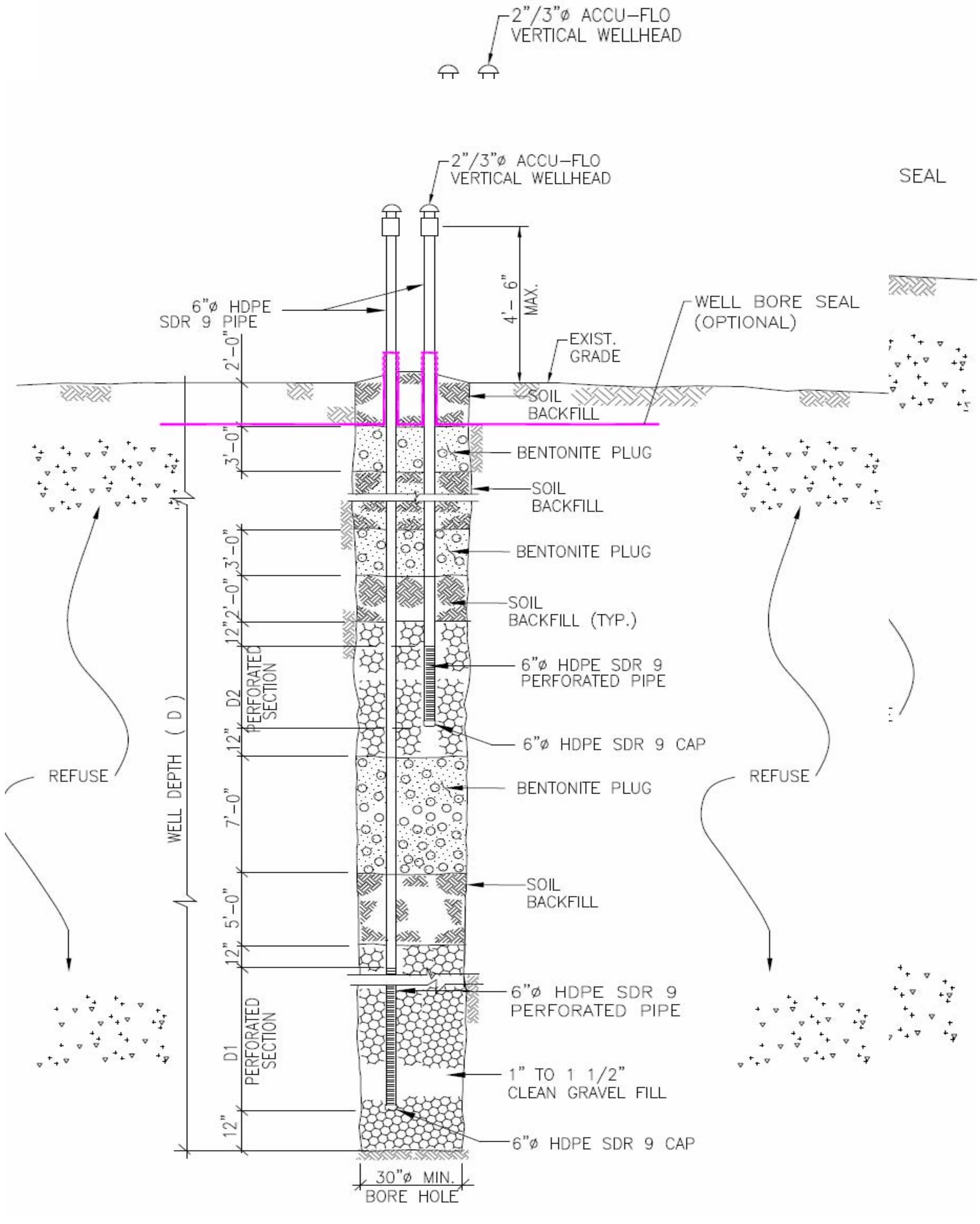


Figure 7. Typical Dual-Completion Vertical Extraction Well

In the 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 should first determine well spacing using conservative design assumptions for the spacing. Next an evaluation of the possible deep well zone vacuum should 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.

(Return to Table 1)

Maximize Borehole and Well Diameters (A-6)---

Description

One way to help maximum production and extend the 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, when designing vertical well systems, larger diameter pipe with a minimum of four inches is preferred, with 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. They help avoid the plugging of piping perforations due to fine material passing through a thin gravel pack layer. They also reduce 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 boreholes 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

Implement this BMP after an engineering review of the site conditions and selection of the appropriate pipe and borehole sizes. If there is uncertainty in the design, the Project Team recommends erring on the conservative side and selecting 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 drilling refusal (i.e., obstructions in the borehole that can limit drilling) 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.

(Return to Table 1)

Enhanced Seals on LFG Wells and Boreholes (A-7)---

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 for vertical wells is through the well borehole; for horizontal collectors it is through the well trench.

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.

A well's connecting pipes are typically sealed using three different techniques: 1) bentonite clay seal, 2) compacted clay seal, or 3) plastic well bore seal. Since a good seal is critical for proper well performance, multiple seals are often used. 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 the details of a typical well bore seal.

Feasibility

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

Table 2. Connecting Pipe Combination Seal Specifications

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 seals are critical, a minimum of two seals is recommended. Additional seals do not cost a lot and provide additional security against failure. In arid landfills, alternate seals may be preferable in addition to the bottom bentonite seal as the arid conditions may 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.

(Return to Table 1)

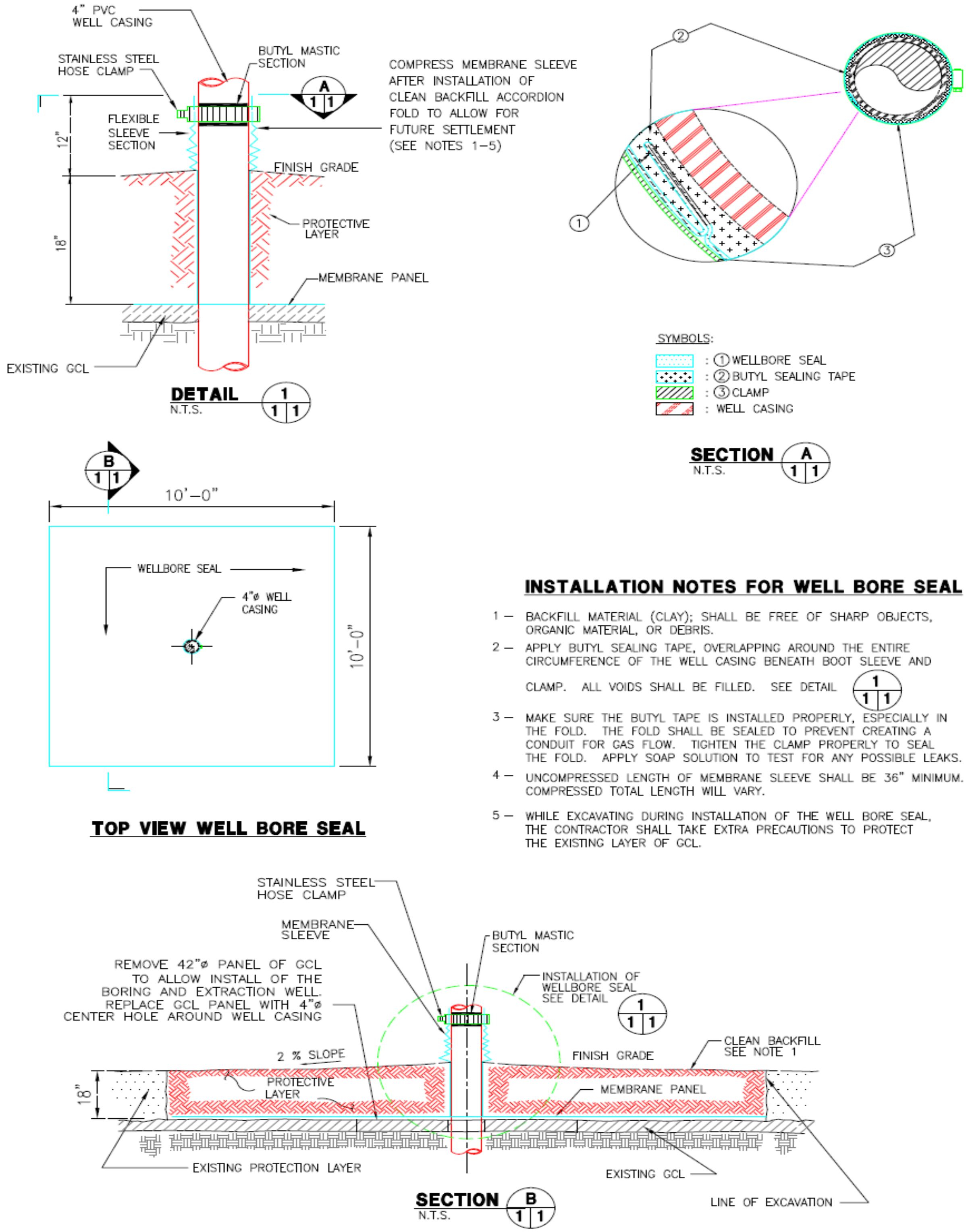


Figure 8. Typical Well Bore Seal

Dewatering of Gas Wells (A-8)---

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 used with some success is to place a bentonite seal opposite perched water in the refuse. Problems arise in identifying the perched liquid levels (this is best done using a down-hole camera) and the ability to accurately 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 the well screen or filter pack due to the liquids passing into the screen. Methods are also available for flushing 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 successfully remove liquids; 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 build a high point on the deck for the horizontal well installation. This requires significant planning and coordination with the designer of the landfill's storm water 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, the ends of the collector (i.e., the solid pipe portion near the edge of the landfill) should be designed with the 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 that is excavated 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 due to 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, infiltrating leachate can bring silt into a well and around the pump, which can cause pumps to fail. In addition to added pump maintenance, it may be necessary to remove silt from the well.

Implementation Recommendation

Implement by increasing the well pipe size, allowing installation of automatic pumps specifically designed for leachate removal, and by providing the required above ground utilities such as power and compressed air to facilitate pump operation. The cost and performance of installing pumps should be measured against those of installing a well with perforations above the leachate level.

Relative Cost

Long-term costs for pumping can be high. These costs include 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 flooded well cannot collect gas; hence, this BMP could salvage non-functioning wells. Where wells have become watered in, GHG emissions reduction would be high.

(Return to Table 1)

BMP for LFG System Piping (A-9)---

Description

The LFG piping should be designed to carry the necessary volume of LFG. This is critical to prevent it from becoming 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, the amount of gas that will be generated and recovered is always uncertain, 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 working life of the piping so that the pipe sizing is not based on future flows that the pipe would never see, as long as provisions are made to upgrade the piping when needed. Larger pipe sizes also help against condensate formation and pipe blockage by allowing gas flow to continue despite 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 where condensate can collect and block gas flow. Piping on native soil outside the refuse boundary avoids this problem and also allows the piping to be installed with less slope, making 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. When installed on native soil, the piping should have a minimum slope of 1% with a provision to increase 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% 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. They should also undergo a more rigorous and frequent pipe inspection program. Pipes can be run down or across landfill slopes to increase slope.

- **Above or below 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, promoting maximum effectiveness. However, to protect against weather effects, above grade piping systems must be staked to control movement from thermal expansion/contraction or landfill erosion, provide UV protection to protect plastic pipe against the sun's influence, etc. The only exceptions would be cold weather locations where frequent freezing temperatures 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 for buried pipe. Figure 9 is a photograph of an above grade header pipe that is staked to prevent down-slope movement.

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. Therefore, 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. A LFG system would have a primary piping loop around the entire refuse area. For large landfills, however, multiple interior loops, including temporary, movable ones, may be warranted. Looped piping systems equalize vacuum throughout the gas system and reduce downtime for those portions affected by non-functioning piping. With these looped systems, including isolation valves allows non-functioning pipe sections to 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.

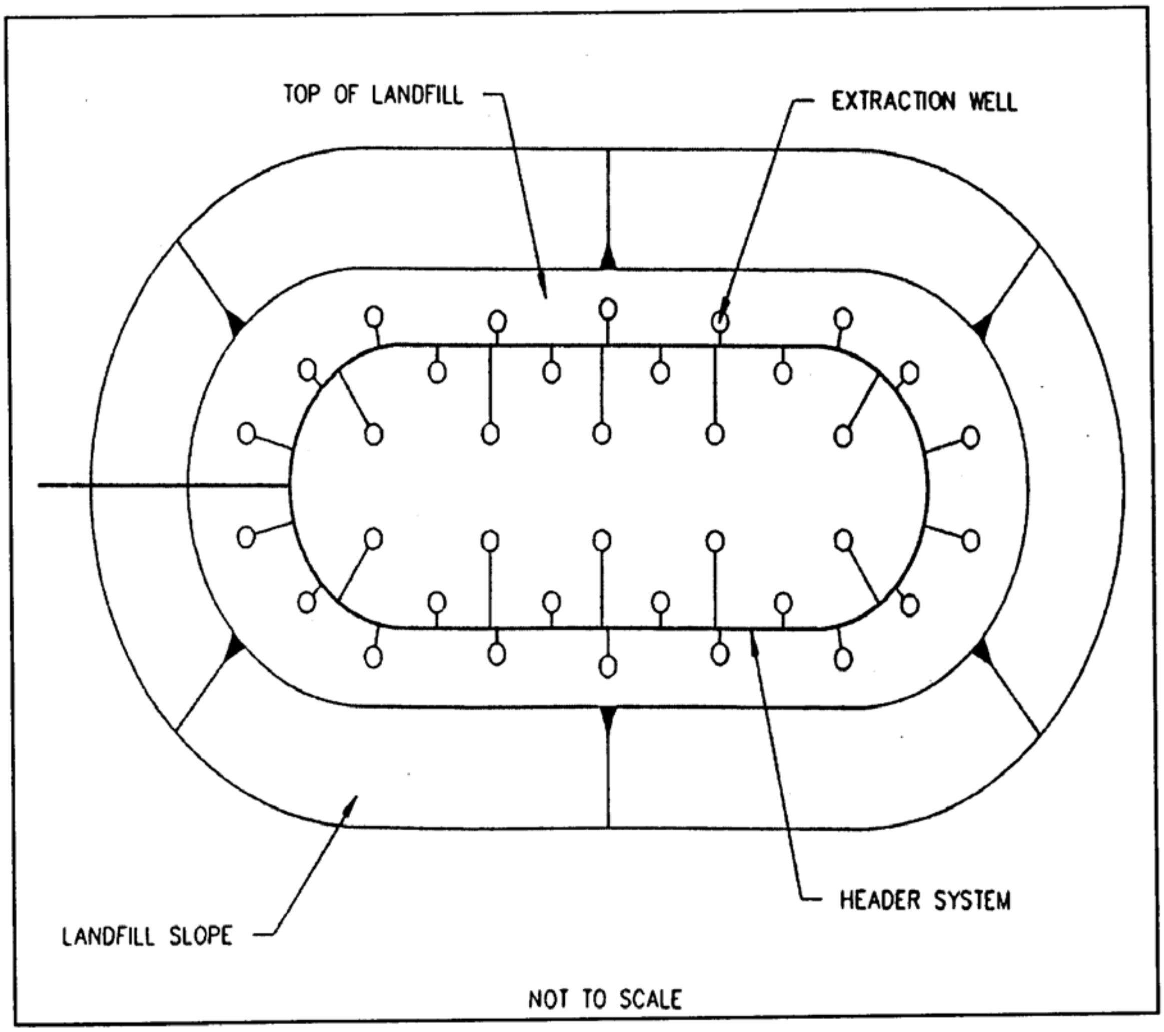


Figure 10. Schematic of Looped Header System

- **Pipe specifications.** Beyond the size and slope of the pipe, the type of pipe grade specified is important as well. Plastic piping systems are commonplace in the LFG industry and still considered BMPs. However, specifying high grade pipe is important for the effectiveness and longevity of the piping system. This includes using Schedule 80 PVC over Schedule 40 and using 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 due 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 while not affecting gas system operation.

  Automated condensate systems are preferred with either electric or pneumatic pumping systems. These systems 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.

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, the Project Team recommends erring on the conservative side and selecting 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.

(Return to Table 1)

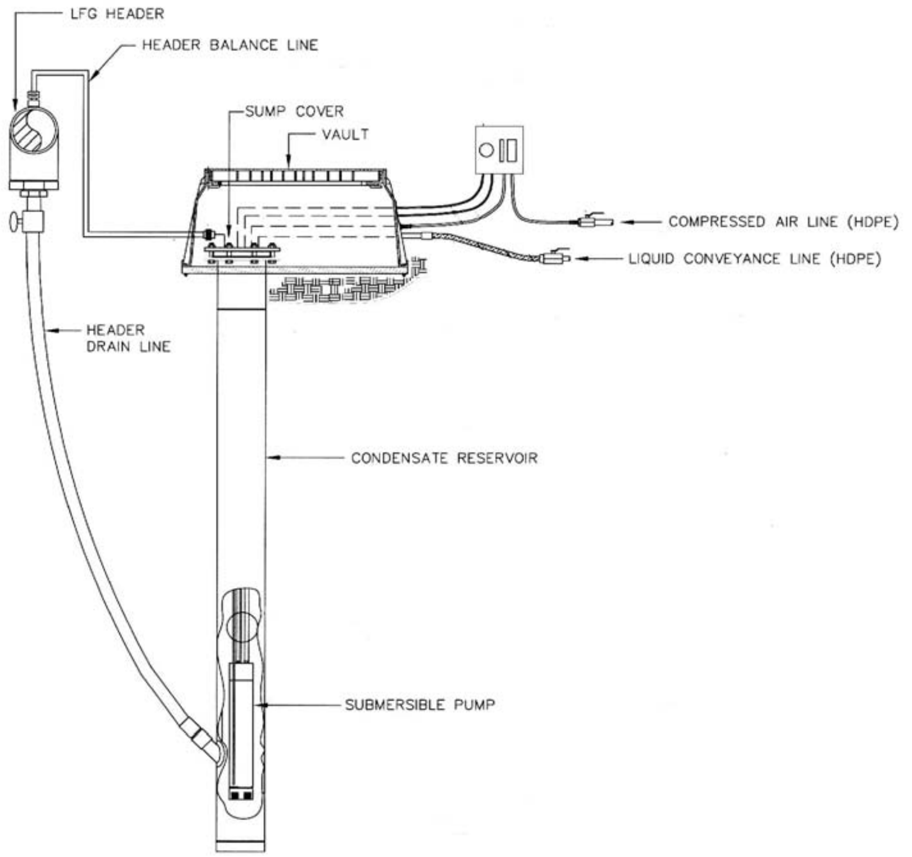


Figure 11. Schematic of Typical Automated Condensate Sump

BMPs for Gas Mover Equipment and Vacuum Control

Barometric Control of LFG System (B-1)---

Description

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 a weather event causes a drop in barometric pressure. 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 depends on the flow rate required to collect LFG and remain in compliance, and the ability to vary this flow rate. Additionally, the blowers and LFG combustion device need a wide operating range to accommodate flow changes. These flow changes could result from variations in barometric pressure, or varying LFG generation 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) causing the vacuum to vary according to the desired changes in LFG flow rate. Simultaneously, the flare or disposal device will also need to be able to accommodate the variation in LFG flow.

The recommended procedure is to use blowers and a flare with wide ranges 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 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.

(Return to Table 1)

Redundant Flare Station Equipment (B-2)---

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:

Table 3. Flare station shutdown examples

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 much can be done to reduce downtime. Notification of a shutdown is critical. This is normally accomplished using an automatic dialer. The simplest and least costly approach to controlling the repair time is to have a thorough spare parts inventory. 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 safety at a park is more critical than 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.

As an alternative to redundancy, increased operations, maintenance, monitoring, testing, and inspection can achieve the same objectives of minimizing system downtime and excess emissions that occur during downtime. See BMP below for "Enhanced LFG Operations and Maintenance" for additional details.

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. However, redundant control devices can provide an additional degree of safety in reducing downtime.

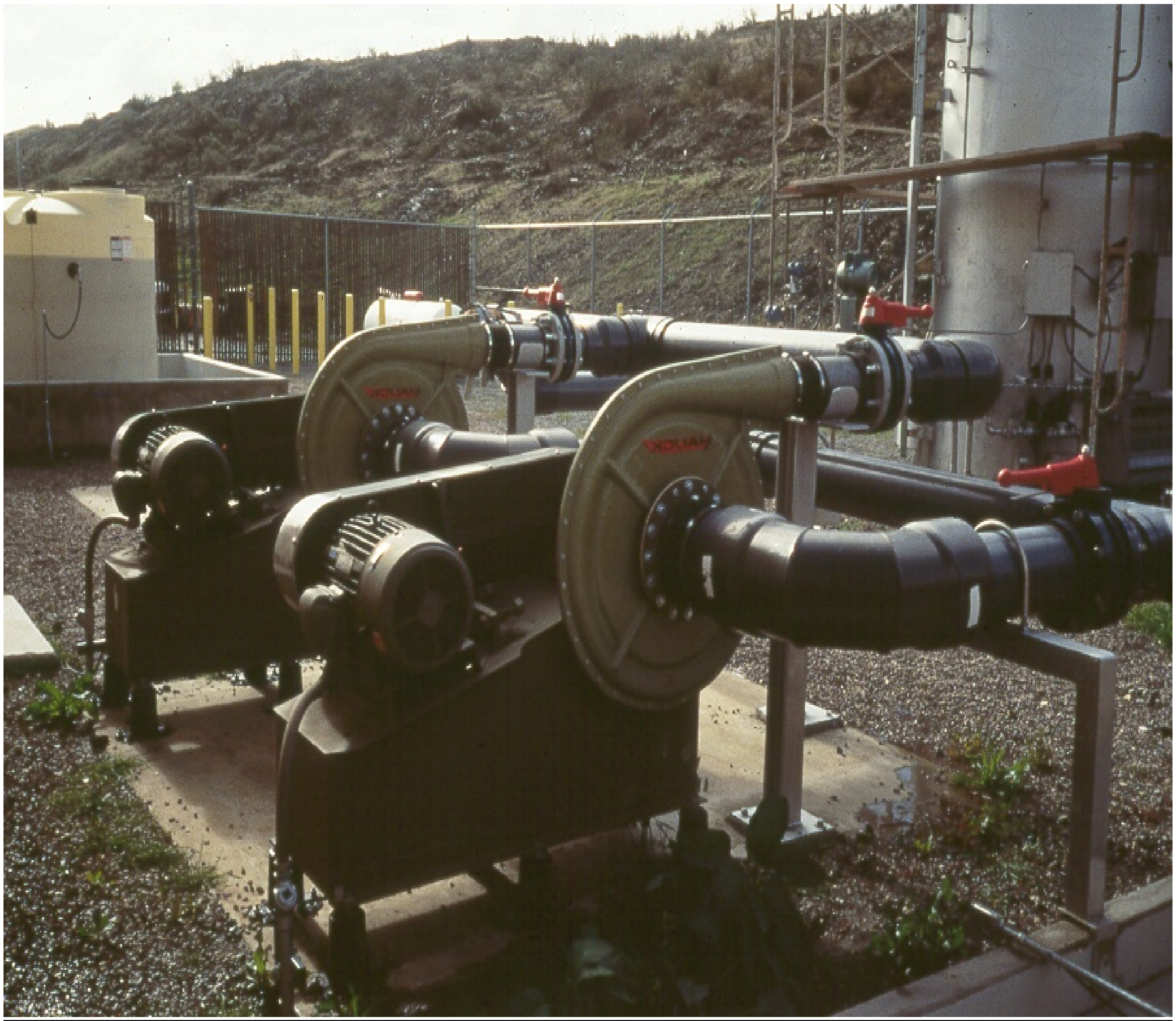


Figure 12. Photo of Redundant Blower Assembly

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.

(Return to Table 1)

Maximize Capacity of Gas Mover Equipment (B-3)---

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 ensure 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 estimate of the expected LFG collection rate. The more uncertain the collection rate, the more likely the blower will be sized for operation closer to its 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 to avoid the pipe becoming a flow bottleneck is to increase its size.

Implementation Recommendations

When selecting a blower, the designer should review the performance data for numerous units and consider their capacity for both current and future gas collection requirements. The blower manufacturers’ representative should be included in the selection process.

Relative Cost

Depending on the type of blower used, increasing the blower size can have two costs:

1. The cost for the blower, pipe, wire, and motor controls.
2. Higher operating costs from 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 for a larger blower in the future if determined to be more cost effective.

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.

This BMP could increase the costs of the blower by 25 to 40% over a smaller 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 up with the increased capacity. In these cases, the GHG reduction benefit is expected to be medium.

(Return to Table 1)

BMPs for LFG Control Systems

Redundancy on Gas Control Equipment (B-2)---

Included above under "Redundant Flare Station Equipment"

Maximize Capacity of Gas Control Equipment (B-4)---

Description

For this discussion assume 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. Also, candlestick or open flares are also not considered a BMP because they have lower combustion efficiency and likely do not destroy methane as well. These flares also will not meet best available control technology (BACT) requirements in most air districts.

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.

This BMP has two goals:

1. To increase the gas combustion capacity
2. 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 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 8:1 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 for 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. Either install the largest flare with the greatest practical turndown or 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.

(Return to Table 1)

BMPs for Enhanced LFG Operations and Maintenance (B-5)

The objective of these operational strategies is 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 apply:

Efficiency The ratio 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 The percentage of time the system is operational. For most systems, partial operation is possible, such 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. Sometimes, in order for a system to be effective, it may need to be somewhat inefficiently operated, such 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 system's operational goals. 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, with more frequent monitoring if the wells are 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 the blower curve and LFG system design report 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 (i.e., each subsequent round of monitoring results in minor modification to the individual wells (i.e. flow adjustments < 10%)), the monitoring frequency can be cut in half. 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 are 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 a one 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, creating a standard maintenance schedule is difficult for some LFG system components. Though a maintenance schedule is typically provided by a component's 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 by creating a preventative maintenance plan. As part of this plan, we suggest dividing the LFG system components into two classes, fixed and variable.

Perform the following actions at fixed intervals with a minimum frequency as defined by manufacturers' specifications:

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

The following components should be maintained on a variable schedule:

- 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, if a differential pressure does not increase over time, it may be an indication that the pad is not fouling and needs 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 maintenance downtime.

A spare parts inventory should be stored at the landfill to minimize downtime due to component failure from wear, settlement, etc.

The following is a list of recommended LFG system spare parts:

- 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
- Pipe and fittings with diameters representative of existing system sizes.

Methods for Wellfield Adjustments

There are many wellfield adjustment methods. A specific wellfield adjustment strategy is not as critical as 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 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 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, to test the short-term effectiveness of the adjustment ,a second round of monitoring data should be collected after any adjustments have been made,. It is good practice for the monitoring technician to carry the previous 6 months monitoring data with him to allow comparison with historical values.

Data Interpretation

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 indicates air infiltration, either from overly-aggressive 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. Aerobic activity 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 wellfield adjustment methods 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 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. If this trend is seen, check liquid levels in the well casing immediately. 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.

Running a pump test on the affected well(s) is recommended. Care should be taken to pump the well at a relatively low rate (i.e. <1.0 gpm) to ensure gravel pack integrity in the well bore. Pneumatic pumps are preferred 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 ensures 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 regular intervals to determine the rate of recharge. Additionally, if a series of wells is affected in a particular area, liquid levels in the vicinity of the pumping location should be monitored to determine if any drawdown is occurring. Review the results of the pump test 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.

Operator Training

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 one. 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.

(Return to Table 1)

Other LFG BMPs

Early Installation of LFG Systems (C-1)---

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

Background – Regulatory Drivers

Regulatory timelines define early installation of a LFG system. System installation is considered early if it precedes the schedule mandated by regulation. For landfills, the primary regulations that dictate LFG system installation timing 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. Due to this regulation's stringent schedule, early installation is not applicable. Accordingly, this BMP does not address early installation relative to the MACT rule. However, bioreactor landfills 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 landfill 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. This strategy is in use at landfills in the South Coast Air Quality Management District and other air districts, who apply most stringent requirements than the NSPS for installation of LFG systems.

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, LFG system expansion can be delayed two or three years 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 systems 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, the most stringent applicability threshold in local district rules is requiring LFG control at sites with 500,000 tons of waste in place. The proposed BMP recommends 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 may not be warranted for landfills in very dry climates (average less than 10 inches of rain annually).
- 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. This may not be warranted for landfills in very dry climates where gas production at the two-year mark may not be sufficient to warrant collection.

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; sometimes even farther forward in 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 is** potentially a major impediment to early installation. 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.

(Return to Table 1)

LFG Master Planning (C-2)---

Description

This BMP recommends developing and implementing a LFG Master Plan for every site with an existing LFG system or that 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 expansion as the landfill grows. At a minimum, the LFG Master Plan should cover the following points:.

- **LFG recovery or generation modeling, or empirical data** from an existing LFG collection system 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 from 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 to control emissions and odors, 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. This includes 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.

Relative Cost

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.

Relative GHG Emissions Reduction Potential

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.

(Return to Table 1)

Energy Recovery from LFG (C-3)---

Description

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) projects 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 mmscf per day 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 using 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.

(Return to Table 1)

Enhanced Monitoring, Modeling, and Testing BMPs

Enhanced Surface Emissions Monitoring (C-4)----

Description

At the present time, surface emissions monitoring (SEM) remains the primary standard for measuring the effectiveness and efficiency of a LFG system. Under the NSPS rule, monitoring is typically conducted quarterly. Emission levels are 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. Each successive pass is less than 30 meters or about 100 feet apart. Exceedances detected during the SEM are subsequently mitigated and remonitored to demonstrate compliance.

Utilizing enhanced SEM will identify and correct more instances of surface emissions and maintain a more stringent standard for allowable emissions (California is currently considering early implementation of SEM for specified landfills under AB 32, beyond those required to do so under NSPS/EG or air district regulations). Components of enhanced SEM include:

- 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 wider than 100 feet apart. The SEM path should be varied each monitoring period 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 500 ppmv of TOC above background as methane, which represents the most stringent standard in current federal, state, or local air quality requirements. 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.

Feasibility

This BMP is feasible for any landfill; however, it will be more costly and time consuming to implement these enhanced monitoring procedures. No regulatory changes are recommended to include this enhanced monitoring.

Implementation Recommendations

This BMP merely increases the stringency of existing landfill monitoring programs and requires no special changes in implementation.

Relative Cost

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 200% to 300% due to the increased frequency in monitoring and other features of the BMP.

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 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.

(Return to Table 1)

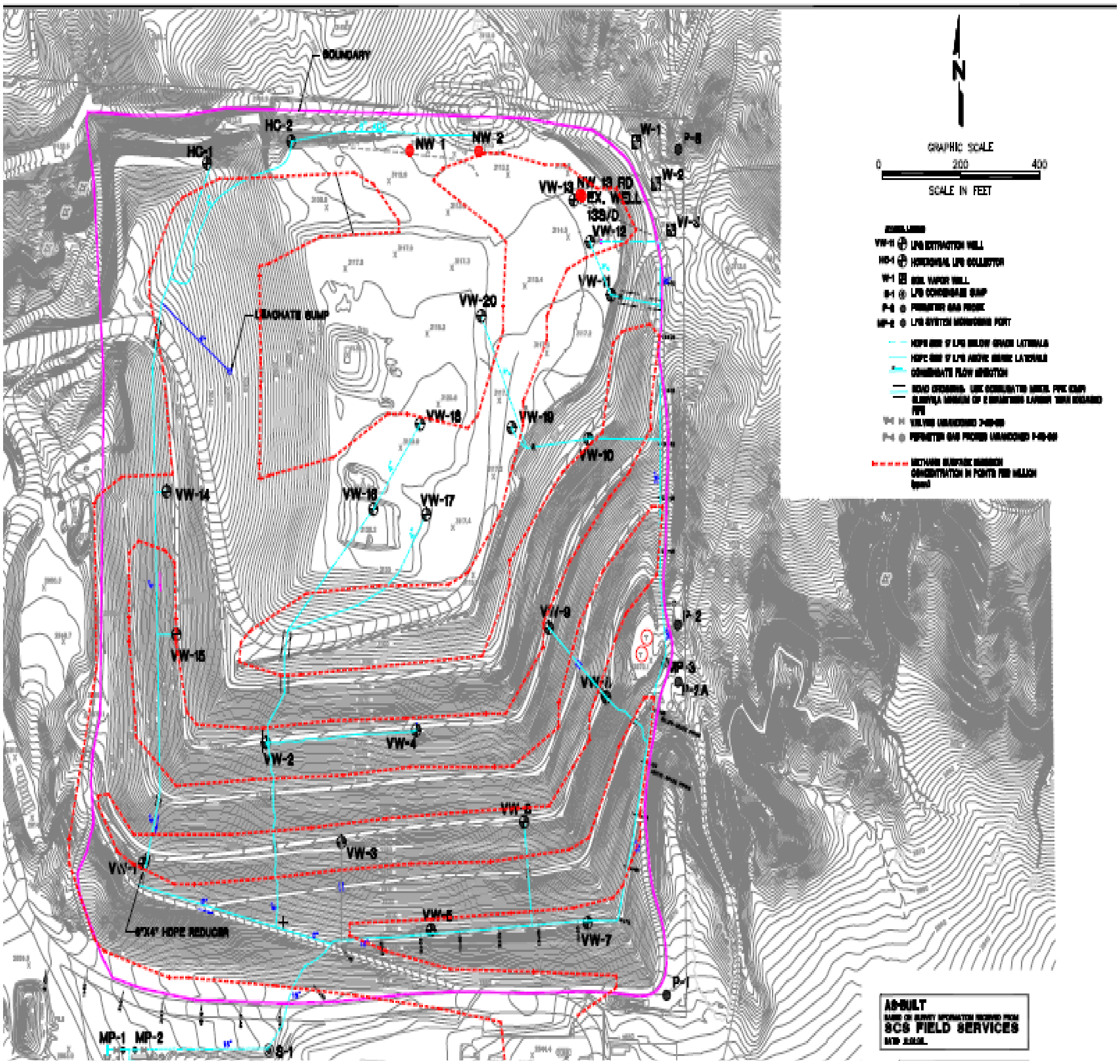


Figure 13. Typical SEM Pathway on Landfill Surface

Enhanced Gas Migration Monitoring (C-5)---

Description

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

Under this BMP, enhanced gas migration monitoring includes:

- 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 27 CCR 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; however, it will be more costly and time consuming to implement these enhanced monitoring procedures. No regulatory changes are recommended to include this enhanced monitoring.

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 CIWMB under 27 CCR.

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.

(Return to Table 1)

Improved Modeling and Testing for LFG Design (C-6)---

Description

The following are potential elements of an improved or enhanced modeling or testing program that could be used to assist in LFG design. 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 as follows:

- LFG generation modeling, such the U.S. EPA LFG generation model (LANDGEM), can be used to predict the amount of gas expected from a landfill or portion of a landfill. However, to improve their accuracy, these models must be calibrated with site-specific data for rainfall and actual LFG recovery. There are numerous LFG generation models, and care must be exercised in model selection and use, including values for the various input parameters to the models (e.g., decay rate, methane generation potential, refuse amounts, etc.).
- 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 from a PPT testing program is depicted in Figure 14.

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 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.

(Return to Table 1)

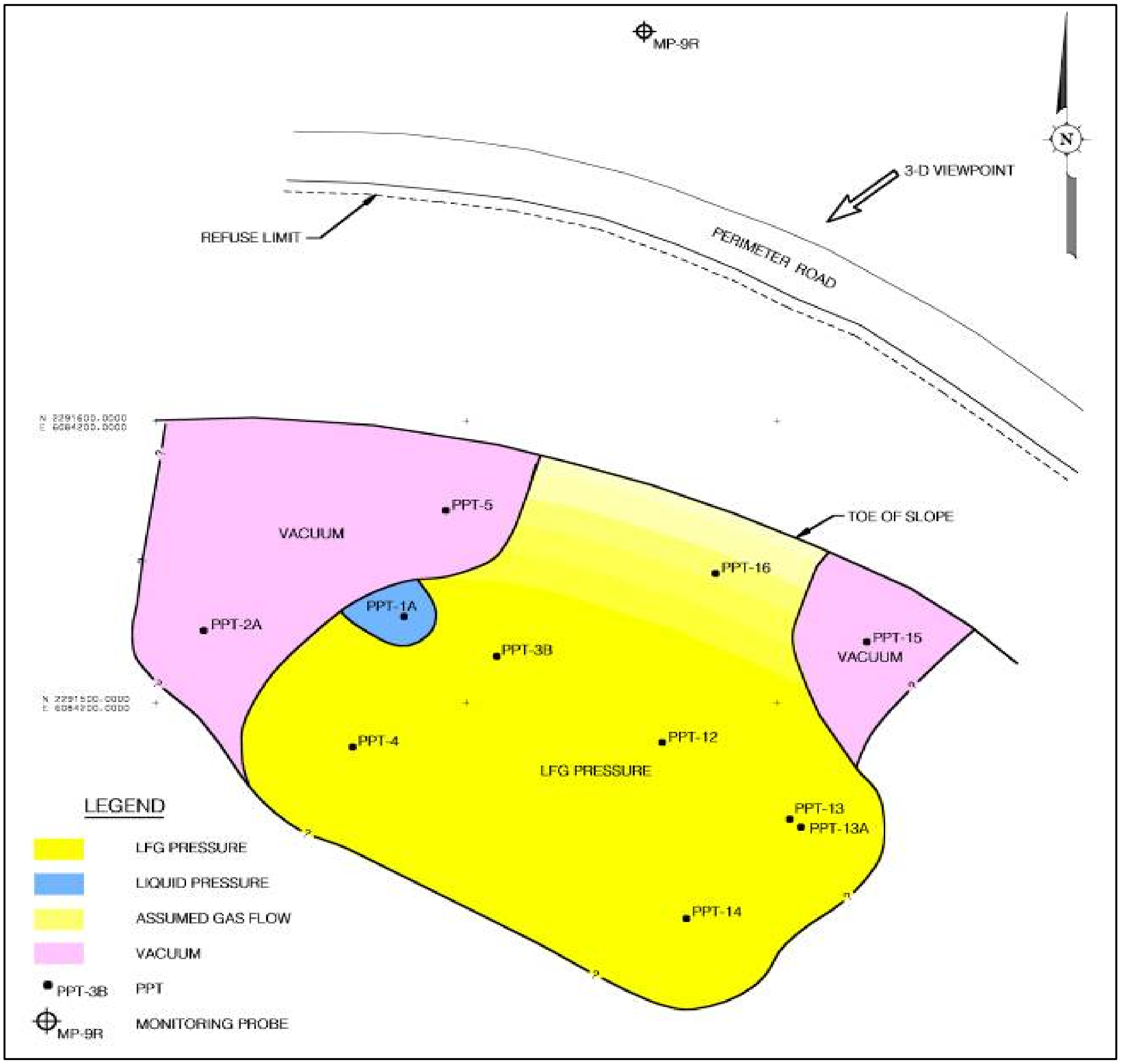


Figure 14. Results of PPT Test on Landfill

Other Landfill Design and Operations-Related BMPs

BMPs for Landfill Systems

Cover LCRS Layer (D-1)---

Description

Covering the liner and Leachate Collection and Recovery System (LCRS) layer with waste in as timely a manner 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.

(Return to Table 1)

Blockage of Permeable Layer within Landfill Footprint (D-2)---

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 prevent 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 injecting 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.

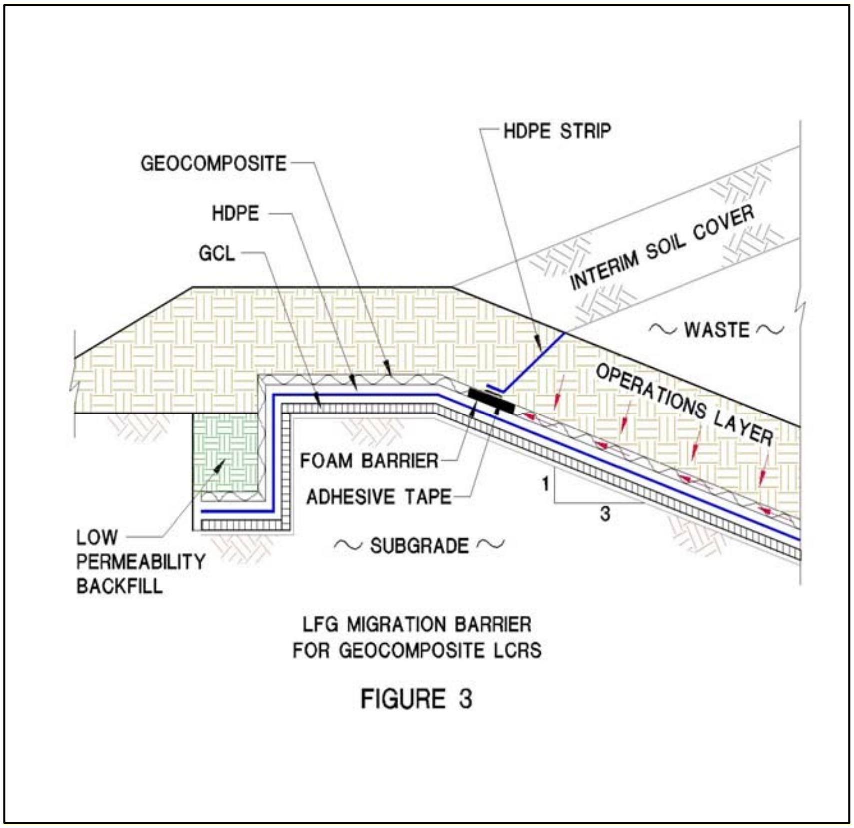


Figure 15. Design for Sealing the Liner at the Anchor Trench

Feasibility

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.

(Return to Table 1)

Designing for Closure and Post–Closure (D-3)---

Description

Proper closure and post-closure evaluation and design will keep an 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, operators should consider installing 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 in the cover. Seals should be installed for all penetrations as discussed above.

Protective cover thickness is important to ensure 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 cover maintenance is a critical part of the post-closure regime for landfills. Inspecting, repairing, and maintaining the integrity of the landfill cover will ensure that it retains its ability to reduce methane emissions, oxidize methane, and prevent air intrusion.

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. Operators should consider using 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 LFG and cover systems are typical activities for landfills 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 and cover 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

Properly operated and maintained LFG and cover systems 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.

(Return to Table 1)

Promote Deeper Landfills (D-4)---

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, depending on site limitations. The greatest objections to changing landfill geometry would be waste fill stability and increased landfill visibility. On a more practical note, as landfills get taller, the top deck 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.

(Return to Table 1)

BMPs for Landfill Cover Systems

Designing Covers for LFG Collection (D-5)---

Description

Daily, alternative 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, low permeability daily or interim covers can actually be a hindrance to gas collection by impeding gas movement at various points within the refuse (see section on modifying, limiting, or removing covers 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.

This BMP also includes cover inspection, maintenance, and repair on an ongoing basis to ensure the integrity of the cover remains intact and the cover is optimized for emission reductions.

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 $40,000 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.

(Return to Table 1)

Limit Delays on Final Covers Systems (D-6)---

Description

The ability to apply vacuum to an LFG extraction well depends 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.

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 and 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.

(Return to Table 1)

Modify, Limit or Remove Daily and Interim Cover Systems (D-7)---

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 the daily or interim cover used on a landfill creating preferential pathways and/or barriers for LFG movement. Because there are many layers of daily cover within a landfill, low permeability daily cover material can actually become a direct impediment to gas collection by preventing adequate vacuum distribution and coverage in the waste.

If the LFG barriers are removed from the refuse (i.e., daily cover is replaced with tarps or degrading foam, permeable daily cover is used, and/or interim 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. Alternately, ADCs, such as green waste or other higher permeability material, 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 interim cover where feasible. Alternately, green waste or other organic higher permeability ADCs could also be used. The cover systems would either need to be removed prior to continuing refuse filling (e.g., tarps) or be allowed to incorporate into the refuse mass (e.g., green waste). Interim covers could also be comprised of higher permeability material or removed prior to additional filling, such as biocovers.

An advantage of replacing daily soil cover with tarps or degrading foam and removing interim 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 interim 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 interim 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

Implement by removing cover to the extent possible using bulldozers, scrapers and other similar equipment or by using 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.

(Return to Table 1)

BMPs for Landfill Operations

Impacts from Landfill Operations (D-8)---

Description

To eliminate the impacts of an LFG system being in the way of fill placement, advance planning and thought are required. Relocating piping and extending 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 LFG system design. Some landfills have had success using GPS locating systems for LFG wellheads to avoid heavy equipment (machines with limited operator visibility) coming in contact with them.

Feasibility

Relocating piping and extending 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/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.

(Return to Table 1)

BMPs for Enhanced Landfills

Designing LFG Systems for Leachate Recirculation (D-9)---

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.

(Return to Table 1)

Bioreactor Landfills (D-10)---

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 US EPA revised the criteria for MSW landfills to allow states to issue research, development, and demonstration (RD&D) permits. The US EPA assumed that the states would adopt the rule and receive approval of their respective rule changes. The US 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)
- 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 bioreactor landfills 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 reducing 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.

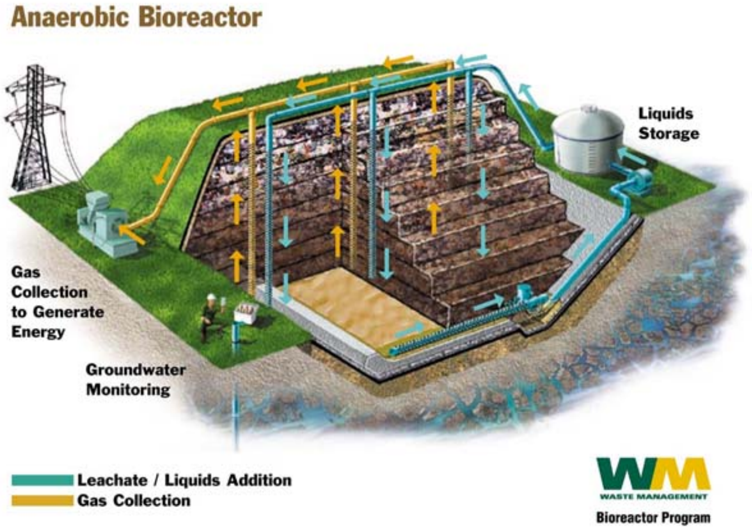


Figure 16. Anaerobic Bioreactor Landfill Schematic

Implementation Recommendation

Bioreactor landfills require the installation of an 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 an 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.

Also, the bioreactor landfill in California will be required to undergo extensive permitting for air, solid waste, and water quality permits. The time and expense for these permits must be factored into their consideration.

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.

(Return to Table 1)

Biocovers (D-11)

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 landfill surface (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. However, the biocover can function without the gas distribution layer and still retain much of its effectiveness because the waste itself is very permeable. 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). 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/m2/d and up to 35 to 40%.

Green waste ADC is a recognized form of biocover; however, its effectiveness is less than the engineered biocovers noted above, but may be comparable to daily soil covers. The use of a permeable ADC biocover has the additional advantages of not limiting gas movement in the refuse, helping to retain soil moisture, and reducing desiccation cracking, which provide for additional GHG reductions. This has been demonstrated by Yolo and Orange Counties.

Feasibility

As 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.

However, the research has indicated that the technology is clearly feasible. Specific details of the site-specific design would need to determined and 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, the biocover can be effective without a gas distribution layer. 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.

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 stabilized, mature compost (Bogner, 2007). Other media 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 (13C and 12C). To simplify, methanotrophic microorganisms preferentially consume CH_4 containing the lighter isotope (12C,) leaving residual CH_4 enriched 13C. 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 or smaller landfill cells and would be most effective for interim cover systems or as a component of a final cover system. As noted above, ADC as a biocover is also feasible but would have less methane oxidation potential, and the research is very limited in this area. 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 justify a gas collection system, but should be captured or treated prior to the methane 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, and these facilities could be used to generate the material necessary for a biocover.

Figure 17. Conceptual Compost Biocover

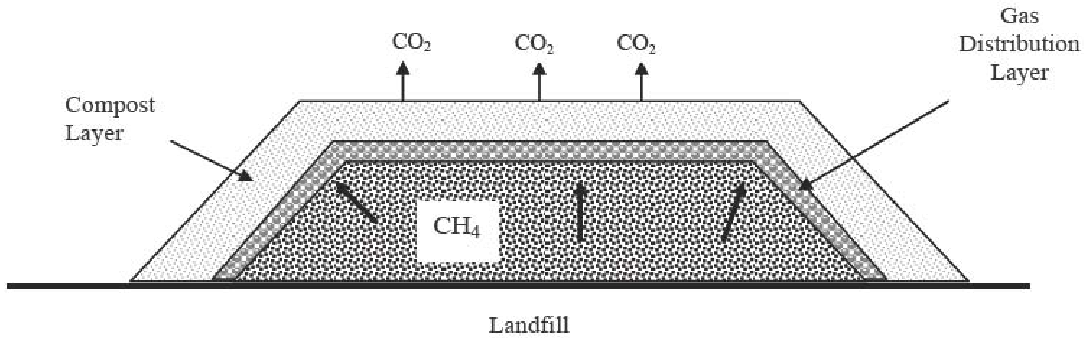


Figure 18. Conceptual Compost Biofilter (after Abichou, 2006)

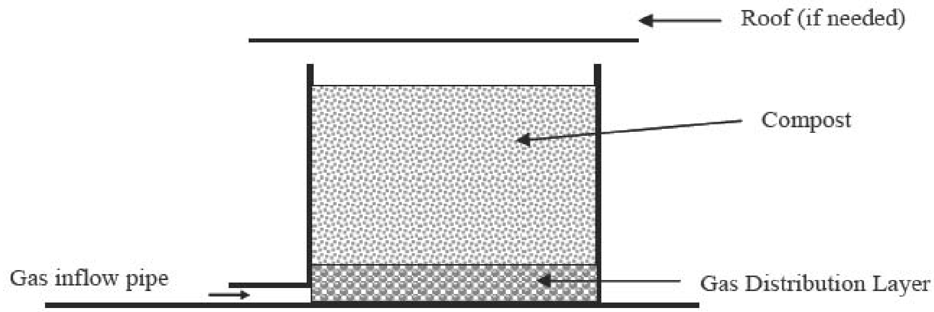
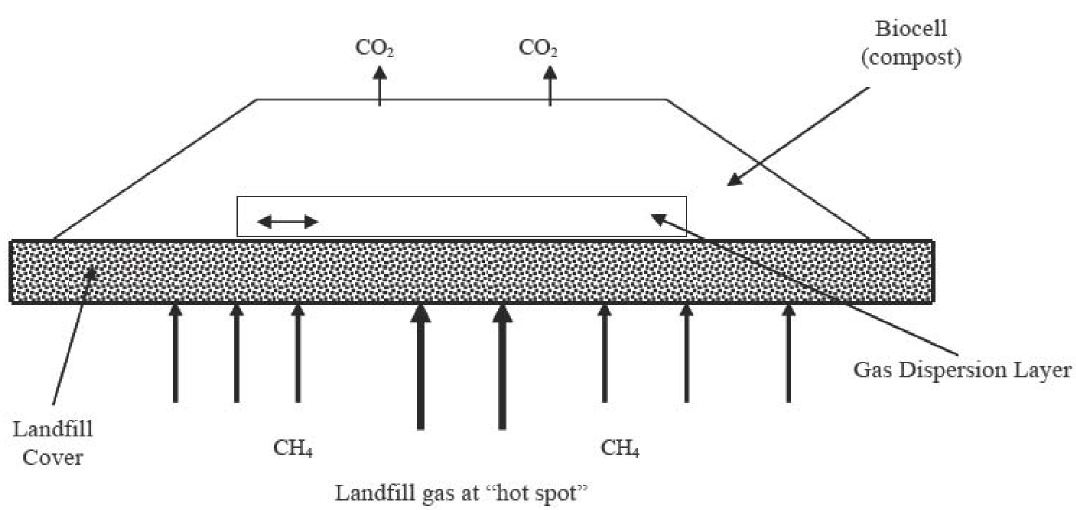


Figure 19. Conceptual Compost Biocell (after Abichou, 2006)



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 seven 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 improve performance (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.

<u>Relative Cost</u>

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 $9.00 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 m3/m2 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.

(Return to Table 1)

Other Solid Waste Management Strategies

The BMPs included under "Other Solid Waste Management Strategies" are offered as potential alternatives to traditional MSW disposal in landfills that could serve to create additional GHG reductions through diversion of organic wastes from landfills or through alternative landfill disposal. Each of these BMPs, along with the BMPs detailed above for landfills and LFG, should be considered components of a comprehensive strategy for management of degradable wastes. In evaluating and selecting any combination of these strategies, equitable consideration should be given to the life cycle impact and benefits relative to GHG emissions from the various strategies. All direct and indirect GHG emissions and reductions should be considered, including the displacement benefit of recycling or through the production of renewable power.

Composting (E-1)

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 do not require permits). 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. For this BMP, we are specifically recommending composting at or adjacent to the landfill site as a means to divert organic waste without additional transportation costs and to create a synergy with ongoing landfill operations. This will also allow the creation of compost material for use in biocovers that will be placed on the landfill surface.

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 has 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, including 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 has its own screen size preferences. 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. To optimize the key process variables, the process generally requires a fair amount of monitoring (temperature, moisture, etc.). 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. Although this BMP generally references the traditional and more proven aerobic composting technology, anaerobic composting has been researched by Yolo County and could provide an additional option for composting. Anaerobic composting has the additional value of recovering energy from the compost process in the form of methane.

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 during 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 analyze 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 extent 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.

Relative Cost

Implementation costs 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 Potentials

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 (CARB). CARB 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 varies depending on the composition of the feedstock. For example, food scraps might have more readily degradable carbon than brush. The amount of reduction also depends on the expected landfill GHG emissions that would occur if the material is not composted.

Compost operations can also create additional GHG emissions, such as direct methane emissions, when not properly operated and from transportation and processing. These may offset some of the methane that is avoided if landfilled. Also, consider whether the organic material would have otherwise been disposed in a well-controlled landfill with minimal methane emissions and/or one that recovers energy from the methane, which composting does not do.

Since organic materials will generate methane under anaerobic conditions, it is important to manage composting aerobically. Even if managed aerobically, depending on the feedstock, other GHGs, such as N_2O, can be released. This is especially true 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 for 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.

(Return to Table 1)

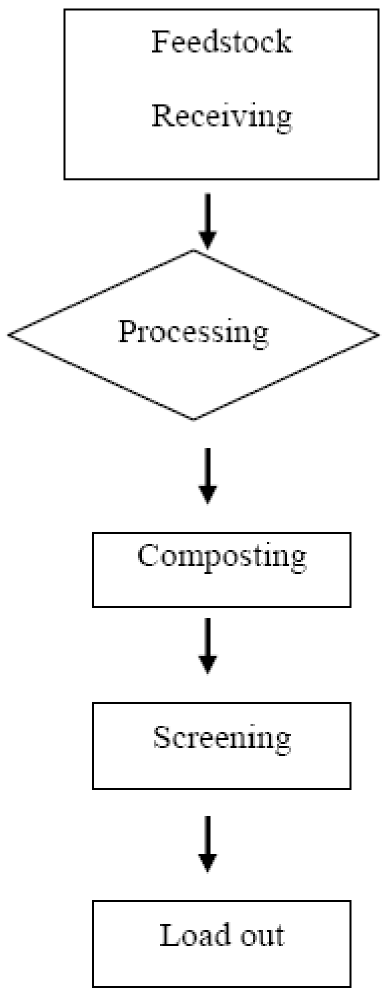


Figure 20. Simplified Composting Flow Chart

Anaerobic Digesters (E-2)

Description

Digesters can be established at California landfills to compost organic waste. Organic waste decomposition in a landfill is a large contributor to GHG emissions, specifically methane. Digesting the waste reduces methane emissions because the resulting gas is completely captured and used beneficially as fuel. The byproduct can be used as a soil conditioner. For this BMP, we are specifically recommending anaerobic digesters at the landfill site as a means to divert organic waste without additional transportation costs and to create synergies with landfill operations. This would also allow for the collective use of biogas for energy recovery gaining additional economies of scale. Figure 21 is a schematic for an anaerobic digester.

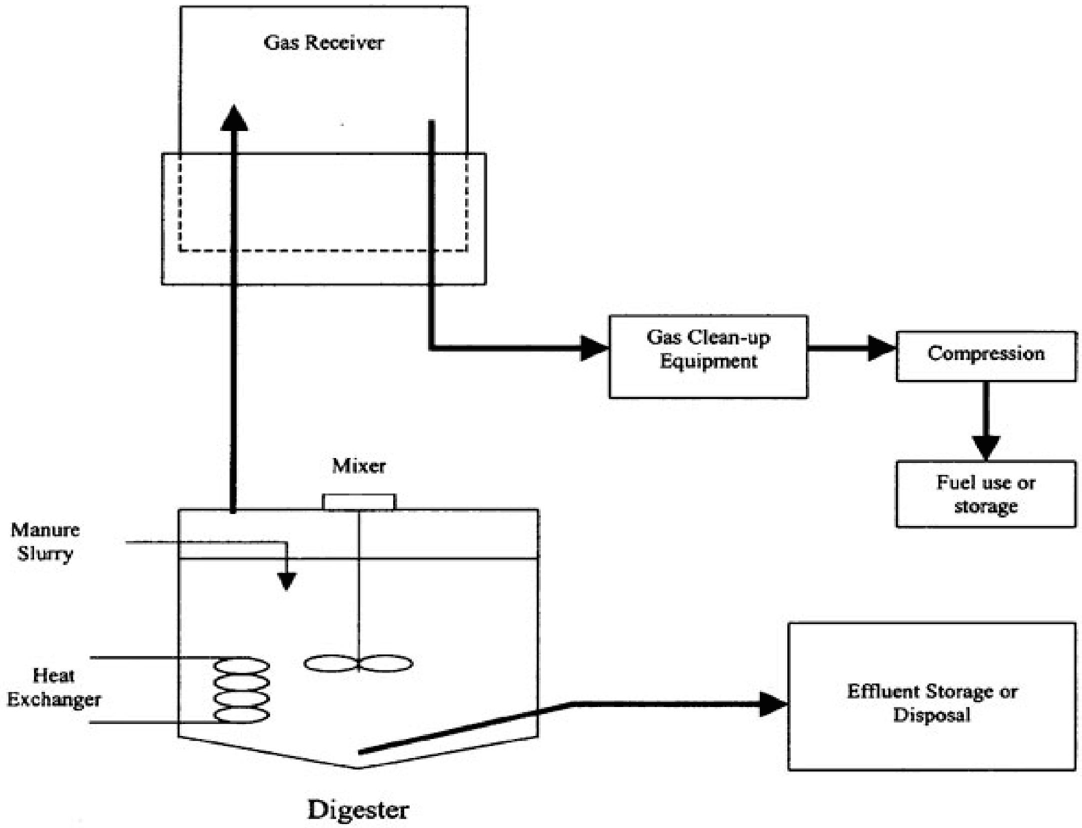


Figure 21. Schematic for Anaerobic Digester

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 byproduct's end use also depends on the composition of the organic waste digested. Some compositions of organic material (i.e., from municipal waste) may not support the movement of the by-product in the market (that is, it may not be usable for various types of agricultural operations).

Organic waste will need to be source separated and implementing this 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

The Project Team recommends accepting material from organic waste collection programs in the commercial sector including 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 providing less contaminated material.

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

Relative Cost

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 from the diverted organic waste and maximizing renewable energy.

(Return to Table 1)

Bale Waste Prior to Disposal (E-3)

Description

Waste can be mechanically compacted into bales, wrapped with low density polyethylene (LDPE) and placed in the landfill. By preventing air and water from entering, it reduces the waste decomposition rate and therefore, reduces landfill GHG emissions. According to studies, the acidic concentration becomes very high. This prevents micro-organisms from developing and forces the material to stabilize without producing methane. This method produces 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.

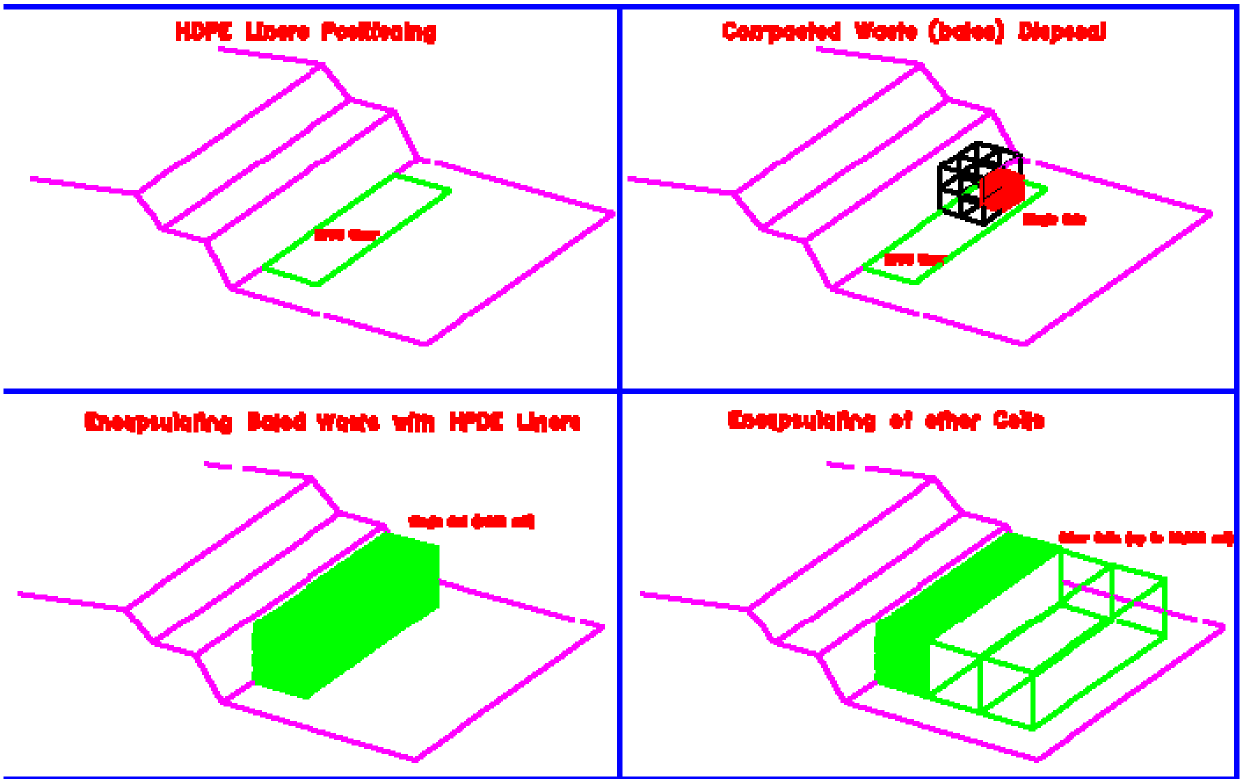


Figure 22. Schematics for Baled Waste

<u>Technical Feasibility</u>

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 materials. Establishing the operation will require minimal equipment purchase and space to house the baling and wrapping machine.

This BMP is feasible for large and small landfills as the space requirements for the baling and wrapping machine are generally not demanding. The baler systems must be capable of handling the liquids that are drawn from the waste during baling and compaction.

<u>Implementation Recommendations</u>

There are two methods for baling waste. One produces rectangular bales and the other produces cylindrical bales. Rectangular bales are recommended 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 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.

(Return to Table 1)

Segregate Organic Wastes in Dedicated Cells (E-4)

Description

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

Technical Feasibility

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

Implementation Recommendations

The Project Team recommends 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.

(Return to Table 1)

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 use. For example, BMPs that pertain to active landfills need not be 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. 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 for each of the BMPs that passed initial screening. Just because a BMP passed the initial screening for applicability does not mean that is has sufficient technical feasibility for ultimate use. This review's objective 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 for the initial screening. This task may be best conducted by an engineering design professional; 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 directly or indirectly conflict 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 should be a short-list of BMPs that have the highest degree of feasibility for the site or project in question. However, further assessment is required.

Evaluating Implementability

The evaluation of implementability essentially includes a thorough assessment of the implementation recommendations for each BMP as detailed above. The goal is to develop a preliminary implementation plan for 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 an engineering design professional; however, there may be one or more BMPs that can clearly be implemented at a particular site or project.

Implementability for Small or Old Landfills

Small landfills or older landfills, including many rural ones, may not generate sufficient quantities of LFG to warrant collection using expensive LFG collection and control systems. Therefore, if a site-specific analysis determines that the gas production from a site is expected to be very low, then each of the BMPs detailed above must be assessed for implementability under that context. Many of the BMPs may not be feasible for these sites and may even have a detrimental effect on LFG collection. It may be appropriate for these sites to focus initially on enhanced monitoring to determine the extent of LFG surface emissions or migration. Subsequent use of other BMPs could be determined based on the results of the monitoring. Certain BMPs, such as the ones for landfill systems, cover systems, and biocovers, may be more feasible for these smaller and older sites while other BMPs related to active LFG systems, enhanced landfills, or other solid waste management strategies may not.

Estimating Cost to Implement the BMP

The cost of implementing a particular BMP can only be assessed on a site- or project-specific basis. There are simply too many variables to provide even estimated or unit costs that would have any value. The relative costs of the various BMPs are ranked as low, medium, and high in the descriptions above. However, these rankings may not hold true for every site or situation. As such, it is critical to complete at least a preliminary estimate of the implementation costs for each BMP that has passed the various evaluation steps detailed above.

The costs should include both capital and annual operating costs. It will be difficult to obtain the necessary accuracy without involving someone extremely knowledgeable in the actual real world costs for the BMPs in question. It is critical for these cost estimates to have a strong degree of accuracy so each BMP can be assessed on its own merits and in comparison to the other BMPs still being considered. 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

Estimating the GHG emissions reduction benefit with any degree of accuracy is extremely difficult since actual reductions that can be achieved are very site-specific and because many of the BMPs provide only an indirect benefit in terms of actual reductions.

To assess the relative GHG emissions reduction potential of the BMPs, the team recommends using the high, medium, and low rankings and make adjustment to those based on site- or project-specific conditions, considering both synergistic and antagonistic effects of the BMPs.

Prioritization and Ranking

Once the above steps are accomplished, rank the final list of BMPs 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 or the low, medium, and high categories 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 are prioritized, a final decision as to which BMPs will be selected for implementation must be made, including implementation timing. At a minimum, the team recommends 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. 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 new construction specifications, 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 an engineering design professional or other expert, and involvement of such a professional is strongly recommended.

Metrics for Assessing 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 for a LFG BMP may be very different from a BMP for increased composting and diversion of organic waste from landfills. Regardless, 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 additional 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. At this time, surface emission monitoring (SEM) level remain the primary metric for assessing methane emissions from landfills.
- 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 include the various monitoring, testing, or assessment techniques 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 includes 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 is 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 includes a comprehensive program of SEM to assess the reduction in surface concentrations of methane

after implementing the BMP. A field testing device such as a flame ionization detector (FID) calibrated to methane could be used. The intent is 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 but 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. Other measurement techniques 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 further details on these other test methods, please see papers by Bogner, Chanton, Barlaz, Huitric, and others in the Bibliography section of this report. As technology develops in these areas, this report should be updated to include more advanced monitoring techniques, including new performance criteria.

- For the criterion of tons of organic waste diverted, the measurement technique includes 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. This is accomplished 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.

The above items only represent examples of measurement techniques that can be used. Any comparable techniques could be feasible as long as they 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.

As noted above, the CEC is sponsoring a landfill methane emissions study where flux chamber testing at several landfills will be used to calibrate a model for the more accurate prediction of methane emissions. Based on the success of this study and its adoption by the State of California for its various climate change programs, it may create a new performance criteria and measurement mechanism to gauge the effectiveness of these GHG BMPs.

Tracking 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 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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