THE WORLD BANK

ESMAP
Energy Sector Management Assistance Programme

Handbook for the Preparation of Landfill Gas to Energy Projects in Latin America and the Caribbean

The World Bank - ESMAP

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ACRONYMS AND ABBREVIATIONS

AE	Applicant entities
CDM	Clean development mechanism
CER	Certified emission reductions
CH_4	Methane
CIDA	Canadian International Development Agency
CO_2	Carbon dioxide
COP/MOP	Conference of Parties/Meeting of Parties
DOE	Designated operational entities
DNA	Designated national authority
EB	Executive board
eCO_2	Equivalent carbon dioxide (this is the currency for discussing GHG emission reductions)
EIT	Economies in Transition
ELECTROBRAS	Brazilian government electrical utility, made up of a consortium of large electricity generators
ERs	Emission reductions (not always GHGs)
ERU'S	Emission reduction units
ERPA	Emissions reductions purchase agreement
ESMAP	Energy Sector Management Assistance Program
GHG	Green House Gas (note that there are many, but carbon dioxide equivalents are the common currency used for evaluation)
GWP	Global Warming Potential
H_2S	Hydrogen sulfide
Handbook	Handbook for the Preparation of Landfill Gas to Energy Projects
HCA	Host country agreement
IC&I	Industrial, commercial and institutional (category of waste type)
IPP	Independent power producers
IRR	Internal Rate of Return
IPCC	International Panel on Climate Change

ACRONYMS AND ABBREVIATIONS

JI	Joint implementation
k	Rate constant used in LFG modeling
kWh	Kilowatt hour
LAC	Latin America and the Caribbean
LBT	Landfill bioreactor technology
LDC	Late developing country
LFG	Landfill Gas
LFGTE	Landfill Gas to Energy
MSW	Municipal Solid Waste
MW	Megawatt
NGO	Non-governmental organization
O_2	Oxygen
O&M	Operating and Maintenance
PCF	Prototype Carbon Fund
PDR	Preliminary Design Report
PP	Project participants
ppb	Parts per billion (used for defining gas and liquid concentrations)
ppm	Parts per million (used for defining gas and liquid concentrations)
PROINFA	Program to foster alternative sources of electrical power in Brazil
PVM	Preliminary validation protocol
ROI	Return on Investment
SP	Sub-project
UNFCCC	United Nations Framework Convention on Climate Change
U.S. EPA	United States Environmental Protection Agency

UNITS OF MEASURE, U.S. EQUIVALENTS AND CONVERSION FACTORS

Unit of Measurement	*Conversion to U.S. equivalent*
1 millimeter (mm)	0.039 inch (in)
1 meter (m)	3.281 feet (ft)
1 m^3/hour (m^3/hr)	0.589 ft^3/minute (cfm)
1 hectare (ha)	2.471 acres
1 tonne	1.102 short ton
0 degrees Celsius (°C)	32 degree Fahrenheit (°F)
1 megawatt (MW)	3,412,141.635 Btu/hour

Note: All monetary amounts mentioned in the text are provided in United States dollars (US$) unless specifically noted otherwise.

PREFACE

This Handbook has been developed for the World Bank to facilitate the development of landfill gas (LFG) management and landfill gas to energy (LFGTE) projects in Latin America and the Caribbean (LAC).

The World Bank and ESMAP have embarked on a project to promote LFG management initiatives in LAC to enable stakeholders to recognise the potential demand for LFG investments and corresponding energy supplies, and carbon emissions reductions. There is emerging potential for LFG management projects to create incentives that will improve the design and operation of the landfill, and as an additional benefit could provide a source of "green" energy for adjacent neighbors of the landfill. The overall World Bank/ESMAP project focuses on the LFG management side of the equation, namely to:

- document the existing experiences in LAC and selected cities elsewhere;
- assess the current constraints to increased LFG capture and destruction or utilization in LAC cities; and
- identify the minimum conditions and preferred institutional arrangements for successful LFG management and utilization projects;
- develop outreach activities to promote this environmentally sound non-conventional energy source; and
- contribute to the implementation of a regional approach aimed at reduction of methane emissions and to develop carbon-trading opportunities.

The overall World Bank initiative takes a phased approach. The first phase aims to assist LAC client countries to better understand the best practice business models and institutional arrangements for development of non-conventional energy sources at large landfills in LAC by means of LFG recovery and utilisation systems.

It is expected that the Handbook will be used by those who own, operate, engineer and regulate landfill sites in LAC as a roadmap for the assessment of candidate projects and to initiate development of LFG management projects. The Handbook is intended as a practical guideline that uses background information and a number of instructive tools to educate, guide and establish a basis for decision-making, technical feasibility assessment, economics assessment, and market evaluation of all aspects necessary for developing successful LFG management projects. While this Handbook is targeted to the LAC region, the principles can be applied to any region of the globe with the adjustment of a few parameters to take into consideration climatic and geographical differences as well as the local economic factors and influences.

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RIGHTS AND PERMISSIONS

EXECUTIVE SUMMARY

Latin America and the Caribbean (LAC) is highly urbanised with, on average, 75 percent of its 500 million inhabitants living mainly in large cities, leading to the concentration of solid waste and corresponding waste management problems. Many LAC cities still dispose of their municipal solid waste in open dumps creating problems with leachate contamination of surface and groundwater, and the release of landfill gas (LFG) to the atmosphere. LFG is approximately 50 percent methane and 50 percent carbon dioxide and is therefore considered a powerful greenhouse gas (GHG). The more important and prosperous cities in LAC have begun to improve disposal practice and have introduced sanitary landfills. Notwithstanding the trend in LAC toward improved landfills, only a few cities in Chile and Mexico actively collect LFG and utilise the energy value inherent in the LFG, or are planning to do so (with Global Environment Fund (GEF) support), such as in Nova Gerar, Brazil and Maldonado, Uruguay. In contrast to this limited beneficial use of LFG in LAC, the experience in North America and Europe is that there are several hundred landfill gas (LFG) management and landfill gas to energy (LFGTE) projects in existence and many more coming on-line each year. Thus, there is a significant opportunity to increase LFG recovery and utilisation at landfills in LAC, provided that the appropriate market conditions exist. The revenue generated from LFG management projects can provide a great incentive to improve the design and operation of landfills, and to advance the overall waste management system in LAC cities.

LFG management could successfully be undertaken and implemented at most landfills in LAC. The capital cost of LFG collection and utilisation infrastructure and the infancy of the carbon and renewable energy markets make the development of these projects most applicable to large and deep landfills (generally greater than 1 million tonnes of waste in place with a depth of more than 15 meters). However, each potential LFG management project should be evaluated based on local conditions including the conditions at the landfill, the opportunity to sell carbon credits, the price of energy, available tax credits, and available "green" incentives. Smaller LFG management projects become much more viable as the value of CER's increase and as the value of energy products increase. In Europe, the energy pricing can support projects of less than 0.5 MW and less than 1 million tonnes of waste in place.

It is necessary that a LFGTE project can be interconnected to an urban power grid or gas distribution network, or is close to a suitable energy end user. In the case of current LAC conditions, this would make the most promising applications to the large and intermediate-sized cities. In LAC, there are currently 117 cities with a population greater than 500,000 people. All together these cities account for a total population of 225 million inhabitants and a cumulative waste generation rate of some 74 million tonnes of solid waste per year. Assuming that one-half of these cities would meet the general criteria for feasible LFGTE projects, there is the potential to generate the equivalent of more than 800 MW of electrical power. This estimate assumes steady state rate of waste generation and 35 percent conversion energy efficiency, both of which are conservatively low assumptions for LAC.

Of equal or possibly greater importance, is the potential to achieve annual emission reductions of more than 40,000,000 equivalent tonnes of carbon dioxide (eCO_2) annually. As the international carbon market evolves, the incentive to generate emission reductions from LFG capture and use will be high in LAC cities. There are potential emission reduction benefits associated with reducing LFG emissions to the atmosphere, but also additional emission reduction benefits can be realised by displacing fossil fuel use if the LFG is used for its inherent energy value. Currently, the international carbon market is in its infancy and there is still uncertainty surrounding the future value of emission reductions generated by LFG management projects. However, current projections for the value of emission reductions from LAC landfills could exceed $100 million USD annually.

Waste composition is the most important factor in assessing the LFG generation potential of a landfill site. The potential volume of LFG is dependent on the quantity and type of organic content within the waste mass (Environment Canada, 1996) since decomposing organic wastes are the source for all LFG produced. Other key factors that influence the rate of LFG production include: moisture content; nutrient content; bacterial content; pH level; temperature; and the site design and operations features of the landfill site.

LFG generation assessments are based on a variety of LFG modeling techniques and pumping field testing programs. LFG modeling is dependent on the model input including input data such as annual waste-in-place quantities, forecasted waste deposition, waste composition, moisture content, and climate. LFG pumping test data may be used in conjunction with the LFG modeling to demonstrate current LFG quality and quantity as well to support projections of the future resource.

All LFG utilisation facilities require an effectively designed and operated LFG collection system that provides a reliable fuel supply. The key objectives for effective LFG control are compatible with LFG utilisation objectives. Although the emphasis on the various objectives can vary based on site specific and location specific conditions, collectively the objectives for these two systems are:

- to protect against odor emissions;
- to protect against gas migration impacts through the native soils into buildings and services;
- to prevent any acute localised ambient air quality concerns associated with LFG emissions;
- to reduce GHG emissions to the atmosphere; and
- to optimize LFG recovery for use as a fuel or energy product.

Both the LFG collection and utilisation systems should be capable of handling the high moisture content inherent in LFG, which typically may cause serious operational issues that can either limit the ability to extract and/or use the LFG efficiently. Depending upon the application, the raw LFG may require some level of gas processing prior to being utilised in order to address these concerns.

The extraction and utilisation of LFG requires ongoing diligence through the entire service life of a project because of the heterogeneous nature of the waste producing the LFG and the changing characteristics of the LFG over time. Therefore, LFG management projects are somewhat more sensitive than typical infrastructure projects and must be operated and managed carefully. The fuel resource recovery is, in most cases, a secondary activity on a large waste management site. Understanding this factor is critical to the success of a project. It is critical to the success of the LFG management industry that the operations and interaction with the waste management activities for each candidate site be considered as crucial to the effective and successful performance of the systems.

When assessing the feasibility of a project, it is not only important to consider the technical options for the project, but also to analyse the potential markets and related legislation to ensure that the project will be economically viable. The Handbook provides a summary of pertinent background materials that are then used as the basis for integrating the business and financial models with the appropriate input data and information specifically for LFG management projects.

Governments may significantly influence LFG management and LFGTE project development through the use of the tax structure that encourages innovation and project development. Competitive access to the energy market and consumers is an additional factor particularly for having a successful LFGTE project. Some countries in LAC, such as Argentina, have a very competitive energy market with ongoing privatisation. Opportunity for consumers to choose green power, and monetary incentives to purchase this power, add to the financial incentives that can help to make LFGTE projects financially viable.

The Kyoto Protocol established the rationale and target objectives for a global emission reduction strategy. When assessing a potential LFG management project, it is crucial that one is aware of all of the current and pending energy sector and environmental regulations that could potentially affect the viability of the project. Prominent issues in the development of solid waste policy include:

- reduction of wastes;
- maximisation of waste reuse and recycling;
- promotion of healthy environmental waste deposition and treatment; and
- extension of waste services.

The international carbon markets are still developing and evolving. The future value of emission reductions generated by LFG management is speculative. However with the United Nations Framework Convention on Climate Change (UNFCCC) development of the Clean Development Mechanism (CDM) project cycle, there may be ways to obtain value from LFG management projects as an incentive to improve landfill design and operation. As an additional benefit, the development of this market could also supplement LFGTE projects to make them more financially viable.

LFG management projects are part of a sustainable integrated waste management policy and act to reduce the GHG emissions from the landfill. By introducing a financial incentive mechanism into the waste management system, they can aid in improving the overall performance of the system. While an aggressive strategy for LFG recovery and utilisation in LAC is warranted, success depends on having good local capacity for urban waste management along with effective national policy frameworks for non-conventional energy and environmental management, and for carbon trading.

LFG management projects are typically expected to operate in excess of twenty years to allow the financial viability of the project. Each project must be analysed separately to determine the particular circumstances for the potential project site. Expanding and maintaining the well field and piping to collect the gas is an ongoing responsibility that must be clearly defined to protect and secure the revenue streams. An understanding of how the landfill site is built and operated is also necessary to determine the nature, scope and costs for a system to collect the LFG as a fuel resource. This factor is sometimes not given the attention and priority that it deserves. Simply stated, it is necessary to understand how much LFG is likely being generated, but it is just as important to understand the physical conditions in the landfill to assess the ability to efficiently collect the LFG fuel for a long project service life.

The major capital cost element of a candidate LFGTE project is the equipment and facilities to use the LFG as an energy resource. For illustrative purposes, the Handbook will use, as an example, the conversion of LFG into electrical power for sale to the respective power grid.

Using all of the information provided in the Handbook, a project team for a potential project at a candidate site should be equipped with the information and background knowledge to assess the potential of a LFG management project. Any economics assessment undertaken should be based on a full life cycle cost analyses for the candidate site and potential project.

The Handbook provides the information noted above in a format that is intended to provide a user-friendly reference document to assist a site-specific project team that is contemplating developing a candidate LFG management project in LAC. The World Bank and the authors of the Handbook have tried to make this document a broadly based reference tool able to provide some of the background and information needs to assist developers, agencies, governments and others in setting up assessments and developing LFG management projects. The use of this manual is not intended to take the place of, or assume the responsibility for, a site-specific due diligence review and business plan for a candidate project.

1

Introduction to the Handbook

Successful use of this Handbook is dependent upon the provision of an information base in all aspects of the LFG management and utilisation systems for solid waste landfills and a strong business/financial understanding of these projects specific to LAC markets. To meet the objectives for the Handbook, it has been organised and presented in three distinct parts, with each part comprised of a number of sections.

Section 1 provides an introduction to the overall format of the Handbook and a brief description of the Sections that comprise Part I, Part II and Part III. It also provides the prospective team with a summary of expected information needed to take the project to the Contract Execution Phase.

1.1 Part I - Understanding the LFG Resource and Potential Applications

Part 1 is comprised of sections that allow the reader to gain a technical understanding of the LFG resource and potential use of the fuel and is organised to provide a basic understanding of both the LFG resource and all of the elements. Part 1 is intended to be broadly applicable to all potential projects within LAC. The extent of the materials discussed will, of necessity, be quite broad and there will be some presumed pre-knowledge for users of the Handbook. Reference materials that provide more detailed background regarding the individual topics presented throughout the Handbook will be identified for those readers that may require additional information regarding specific subject materials. Part 1 of the Handbook comprises the following two Sections:

Section 2: Landfill Gas – Understanding the Resource; and

Section 3: Landfill Gas Utilization Technologies

1.2 Part II - Understanding Pertinent Regulations, Energy Markets and International Carbon Finance

Part II looks at the energy and environmental policies, legislation, regulations and the current energy markets. It also provides an insight into the policies that help mitigate environmental and social problems resulting from existing solid waste management practices and to implement systems that minimise the potential future issues. Legislation for solid waste management has to balance protection and conservation with excessive controls that inhibit economic development. This part also examines the Kyoto Protocol mechanisms for the development of the carbon markets, which could benefit LAC countries. Part II comprises the following Sections:

Section 4: Energy Policies, Legislation, Regulation, and Markets;

Section 5: Environmental Policies, Legislation, and Regulation; and

Section 6: International Carbon Finance.

1.3 Part III - Assessing and Developing LFG to Energy Projects

Following review and assimilation of the materials provided in Part 1 & Part II, it is expected that the reader will have an appreciation of all of the factors and inputs that will need to be considered for developing a project specific feasibility assessment and business case for a LFG management project. The information presented in Parts 1 and II is not intended to be site or country-specific but are focused towards preparing the reader with the pertinent understanding and background to allow a project to be assessed. It is expected that the Handbook will be used by all sectors of the industry and may be used by individual project team members with differing areas of interest and expertise to help identify key questions that must be addressed for every project.

Part III of the Handbook presents the possible approaches and information necessary for assessing LFG management projects at landfill sites and to provide specific guidance for the assessment and development for a specific project in LAC. Pre-investment studies that collectively constitute the feasibility study and market assessment for a prospective project are outlined in detail. After completing the activities and studies as described in the Handbook, the viability of a potential project and its basic business structure can be established, subject to verification of information and assumptions that may have been used for the analysis.

A project that has met the requirements would then proceed to the detailed development phase. Essentially this phase will take the information that has been assembled, and develop it as the basis for contract execution for all of the various agreements that will be necessary to undertake a specific project. Part III comprises of the following sections:

Section 7: Risk Factors Related to Environmental, Financial, and Resource Management Aspects of LFG Management Projects;

Section 8: Pre-investment Studies; and

Section 9: Project Development.

1.4 Expected Outputs

Upon completing the scope of work as outlined in this Handbook, it is expected that a reader will be in a position to be able to:

- understand the characteristics of the resource, specifically culminating in a projection of the LFG quantity/quality generation over time;
- develop an understanding of the jurisdiction's specific energy policies and assess their implications for the project and the market value of applicable energy products;
- develop an understanding of any environmental policies or regulations that may pose constraints to the project;
- undertake a market value assessment and sensitivity analyses for the various options to utilize the LFG from the specific site;
- develop a conceptual design for the LFG capture and destruction or utilization system for the preferred approach for the specific site;
- develop preliminary capital and operating cost estimates to build, operate and maintain the proposed system;
- identify and assess all permits and approvals that may be necessary to construct and operate the proposed facility;
- develop a preliminary project schedule;
- develop a business structure and financial plan to implement the potential project;
- identify all other criteria and constraints that may exist for a specific project; and
- understand the principles of conditional rights to the LFG at the specific site to allow the project to proceed to the next phase.

It is expected that the reader and the organisation represented may need to obtain support and expertise in various areas necessary to undertake LFG management, particularly LFGTE projects. However, the Handbook should be an invaluable tool for assisting in identifying areas of support that are needed and framing the scope of services or nature of any partners that may be necessary to assess the viability of a prospective project in LAC.

1.5 Background

The LAC region is highly urbanised with, on average, 75 percent of its 500 million inhabitants living in cities, mainly large cities, thus leading to the concentration of solid waste and corresponding waste management problems. Many LAC cities still dispose of municipal solid waste (MSW) in open dumps, creating problems of leachate contamination of surface and groundwater, and release of LFG to the atmosphere, including significant volumes of methane, a powerful GHG. The more important and prosperous cities in LAC have begun to improve disposal practices and have introduced sanitary landfills. Notwithstanding the trend in LAC toward improved landfills, only a few cities in LAC actively collect LFG and utilise the energy value inherent in the LFG, or are planning to do so (with GEF support), such as in Monterrey, Mexico and Maldonado, Uruguay. In contrast to this limited beneficial use of LFG in LAC, the experience in North America and Europe is that there several hundred LFG plants for energy recovery and utilisation purposes or flare their LFG as management, and many more plants coming on-line each year. Thus, there is a significant opportunity to increase LFG recovery and utilisation at landfills in LAC region, provided that the appropriate market conditions exist, or can be developed.

Feasible LFG collection and utilisation is normally limited to large and deep landfills (for example, over 1 million tonnes of waste in place with a depth of more than 15 meters), however the conditions for each site must be analysed individually for potential carbon credit sale, energy pricing, tax credits, and other "green" incentives that might be available. For LFGTE projects, it is also necessary that the potential exists to connect the LFG project to an urban power grid or fuel distribution network, or is close to some energy end user (construction of a special purpose gas pipeline is normally limited to 3 km). In the case of LAC, this would limit promising LFGTE applications to the large and intermediate cities. In LAC, there are currently 117 cities of greater than 500,000 population, with a total of 225 million inhabitants and presently generating some 74 million tons per year of solid waste that is deposited in identifiable sites. Assuming that one-half of these cities would meet the above general criteria for feasible LFGTE projects, there is the potential to generate the equivalent of more than 800 MW of electrical power (assuming steady state and 35 percent conversion efficiency).

Of equal, or possibly greater importance, is the potential to achieve annual emission reductions of more than 40,000,000 tonnes of equivalent carbon dioxide (eCO^2) emissions annually. As an international carbon market evolves, the incentive to generate emission reduction credits from LFG capture and use will be high in LAC cities. There would not only be benefits by reducing GHG directly by reducing methane emissions to the atmosphere, and for LFGTE projects also by displacing fossil fuel which would otherwise be utilised for energy purposes. The potential international carbon market in LAC from LFG exploitation could substantively exceed US $100 million a year.

While an aggressive strategy for LFG recovery and utilisation in the region is warranted, success will depend on having good local capacity for urban waste management along with effective national policy frameworks for non-conventional energy and environmental management, and for carbon trading.

A series of LFGTE case studies are being provided as Annexes to the Handbook. These independently prepared case studies will be used to help illustrate the concepts, constraints, and methodologies that have been successfully used to develop LFGTE projects around the world.

The development of LFG as a resource relies heavily on the operation and maintenance of the project in order to achieve success. The extraction and destruction or utilisation of

LFG requires diligence because of the heterogeneous nature of the waste producing the LFG and the changing characteristics of the LFG over time. Therefore, LFG management projects are somewhat more sensitive than typical infrastructure projects and must be operated and managed carefully. The fuel resource recovery is, in most cases, a secondary activity on a large waste management site. Understanding this factor is critical to the success of a project. It is critical to the success of the LFG management industry that the operations phase of projects and interaction with the waste management activities for each candidate site is considered as crucial to the performance of the systems.

PART 1 – UNDERSTANDING THE LANDFILL GAS RESOURCE AND POTENTIAL APPLICATIONS

2

Landfill Gas – Understanding the Resource

2.1 LFG Generation and Generation Factors

LFG is generated as a result of physical, chemical, and microbial processes occurring within the refuse. Due to the organic nature of most waste, it is the microbial processes that govern the gas generation process (Christensen, 1989). These processes are sensitive to their environment and therefore, there are a number of natural and man-made conditions, which will affect the microbial population and thus, the LFG production rate. Short-term studies done on full-size landfills, using data from LFG extraction tests, indicate a range of LFG production between 0.05 and 0.40 m^3 of LFG per kilogram of waste placed into a landfill (Ham, 1989). The mass of waste accounts for both solid materials (75-80% by mass) and moisture (20-25% by mass). This range is a function of the organic content of the waste that is placed into the landfill. The range in LFG production values may at first glance not appear to be large. However, using the population base in LAC and the fuel value of the LFG, the annual quantity of LFG fuel is equivalent to tens of millions of cubic metres of natural gas each year. Typical pipeline grade natural gas has approximately double the heating value or fuel content of a typical LFG.

Waste composition is the most important factor in assessing the LFG generation potential of a site. The maximum potential volume of LFG is dependent on the quantity and type of organic content within the waste mass (Environment Canada, 1996) since the decomposing organic wastes are the source for all LFG produced. Other factors that influence the rate of LFG production include moisture content; nutrient content; bacterial content; pH level; temperature; and the site-specific design and operations plans. Wastes produced in LAC typically have higher organic content and moisture content than most North American or European waste and therefore would be expected to generate LFG at equivalent or higher rates.

Moisture is the primary limiting factor in the rate of waste decomposition (McBean et al., 1995; Reinhart, 1996). The moisture conditions within the landfill are a function of many factors. Landfills are typically constructed and filled in sequential layered pattern. This factor is important in understanding how moisture moves into and through the waste. The layering effect tends to result in substantially different flow characteristics for the movement of leachate and infiltration water into the landfill. Controlling the moisture content and other factors which influence the microbial population that produces LFG can have a great impact on the percentage of potential total LFG that is produced, and the rate at which it is produced. It is possible to somewhat control the rate of LFG production through engineered waste management systems. Conventional sanitary landfills as practised in North America in the 1970s and 80s are generally referred to as "dry tombs" because the approach taken in designing them was to minimise water contacting the waste with a view toward minimising excursions of the resulting leachate into the groundwater. However, this practice also limits the rate of anaerobic activity within the waste. The current trend is towards Landfill Bioreactor Technology (LBT) systems, which augment the amount of water contacting the waste, to rapidly stabilise the wastes. This technique can produce large initial LFG generation rates while decreasing their rate of generation sharply after a few years.

For the purpose of an initial site characterisation, LFG production can be simplified as a function of the size and age of the waste volume, waste type, and moisture content. The volume of greenhouse gases released is directly proportional to the LFG-generating potential. It is also relevant to other potential impacts such as odor complaints and hazardous situations. In general, the more gas that is produced, the higher the likelihood that health, safety and odor nuisance issues will be raised, and equally importantly, that for economically feasible LFG utilisation to exist.

Figure 2.1 provides a method of characterising a site based on its LFG production potential. The first step is to determine the tonnage adjustment factor based on waste composition. This correction factor accounts for the proportion of inert wastes in the landfill, which will not produce LFG, and the proportion of industrial/commercial/institutional (ICI) wastes in the landfill that will produce less LFG than typical domestic wastes. The adjustment factor is determined from the triangle diagram shown in Figure 2.1 based on the proportion of waste types that are in place or

EXAMPLE

10% ICI
60% DOMESTIC
30% INERT

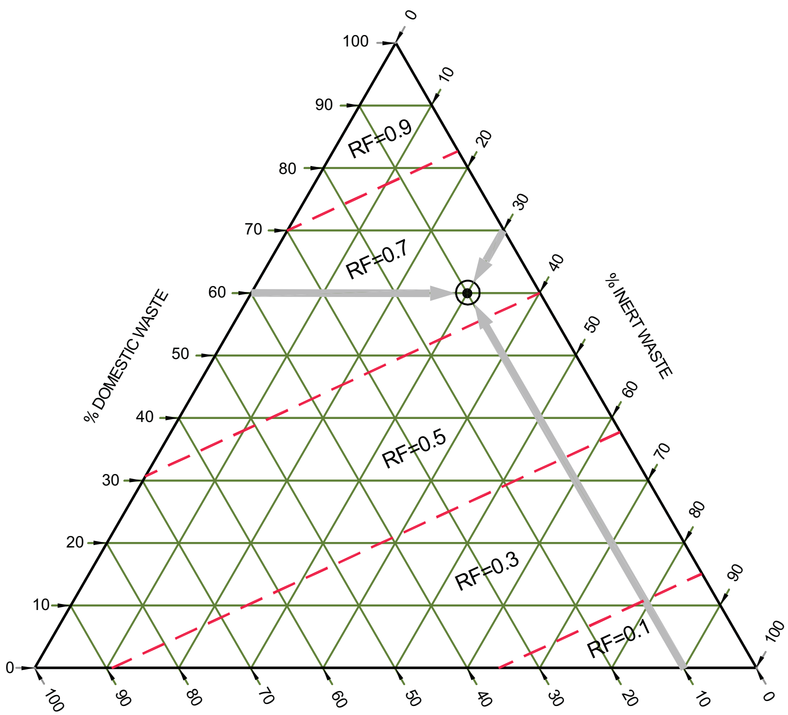
RESULT RF=0.7

EXAMPLE

SITE CAPACITY IS 4,250,000 TONNES X 0.7 RF
SITE IS 75% FULL
SITE IS CONSIDERED WET
→ ADJUSTED CAPACITY = 3,000,000

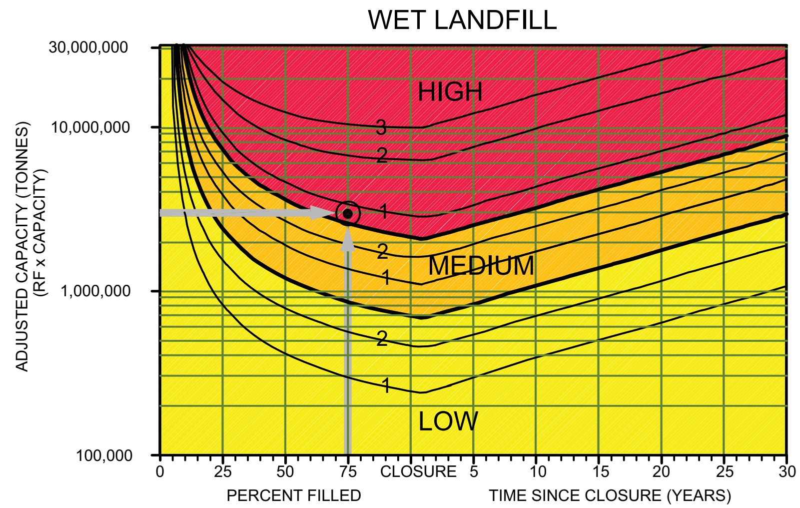
RESULT "HIGH" PRODUCTION

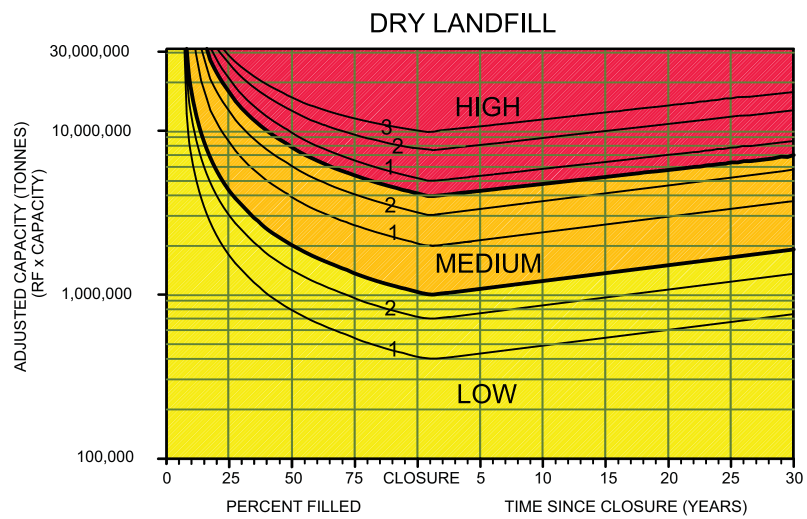
TO FIGURE 3.1b



TONNAGE ADJUSTMENT FACTOR = RF

STEP 1
LFG PRODUCTION





NOTE

A LANDFILL SITE IS CONSIDERED 'WET' UNLESS IT IS EQUIPPED WITH A LOW PERMEABLE COVER OR IT IS IN AN AREA WHICH RECEIVES LESS THAN 635mm OF PRECIPITATION ANNUALLY.

SOURCE: CONESTOGA-ROVERS & ASSOCIATES LIMITED

figure 2.1

PRELIMINARY SITE LFG CHARACTERIZATION
HANDBOOK FOR THE PREPARATION OF LANDFILL GAS TO ENERGY PROJECTS
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will be accepted at the landfill. The landfill capacity is multiplied by the tonnage adjustment factor to determine the adjusted site capacity.

The landfill is then classified as dry or wet. A dry landfill will decompose more slowly than a wet landfill and hence the LFG production rate will be lower, and the production time will be longer. Some of the factors that influence the moisture content of a landfill include precipitation and temperature at the site, type of landfill cover, condition of cover (i.e., slope, integrity), type of leachate collection system, and type of landfill base or natural liner. The classification of the site as dry or wet is mainly a function of the amount of precipitation that infiltrates into the waste mass. A conservative approach to classifying a site as wet or dry based on the average annual rainfall. A landfill where a significant portion of the waste is located within a groundwater/leachate mound should also be considered a wet site. For general discussion within this Handbook, sites located in areas with: less than 500 mm/year will be classified as relatively dry sites; more than 500 but less than 1000 mm/year as relatively wet sites; and sites located in areas with more than 1000 mm/year as wet sites. Most LAC landfills are considered to be relatively wet or wet sites. Further discussion regarding the importance of this aspect of LAC sites will be provided with the modeling discussions and the applicable parameter assignments.

The adjusted site capacity is located on the left axis of the wet or dry landfill chart. This addresses the effect that the size of the site (small, medium, large) has on gas production. The current status of site filling is located on the bottom axis. This is defined as the percentage that the site is filled or the number of years since closure of the site. This addresses the age of the site.

LFG production is determined by the intersection of the adjusted site capacity and the current filling status. LFG production is categorised as "high", "medium" or "low". Each category is delineated by numbers, which indicate an increasing level of severity within the category. The maximum LFG production typically occurs within two years of site closure if the site has had a fairly uniform annual filling schedule. It is important to consider future LFG production potential in assessing and planning the need for LFG controls. Figure 2.1 demonstrates that a site's LFG production increases as it is filled, and then slowly declines after site closure.

Other issues related to the production of LFG, which are of concern, include the LFG subsurface migration hazard and the impact of LFG on air quality.

The primary factors that influence the distance gas migrates from the wastes into adjacent soils are the permeability of the soil adjacent to the landfill and the type of ground surface cover around the landfill. Generally, the greater the permeability of the soil adjacent to the landfill, the greater the possible migration distance. The water content of the soil has an important effect on its permeability with respect to LFG flow. As the water content increases, the effective soil or waste transmissivity to gas flow decreases. In addition, the type of ground surface cover affects the venting of LFG that can escape to the atmosphere. Frozen or paved ground surfaces limit venting of gas to the atmosphere and hence increase the potential migration distance. A landfill liner can greatly reduce the potential for subsurface migration. The presence of heterogeneous soils around the site or sewers and other buried utility service will increase the potential migration distance along those corridors. LFG can migrate a significant distance from the landfill in sewers or sewer bedding. When evaluating the potential for subsurface migration from a site these factors should be considered.

The primary determinants of air quality impacts are the quantity of LFG emitted to the atmosphere, the concentration of trace gas compounds in the LFG, the proximity of the receptor to the site and meteorological conditions.

2.2 The Scholl-Canyon Model

Mathematical models are a useful and economical tool for estimating the LFG generation potential at the site. The results of the model can be used to assess the potential for hazardous LFG emissions/migration, and for assessing the feasibility of the LFG management project.

There are numerous models available to calculate LFG production. All of these models can be used to develop an LFG generation curve that predicts the gas generation over time. The total gas yield and rate at which the gases are generated can vary somewhat with the different models but the most important input parameter that is common to all models is the quantity of decomposable waste that is assumed. The other input parameters can vary depending on the model used, and are influenced by a number of variables including those factors influencing LFG generation, uncertainties in the available information for the site, and how the management of LFG extraction affects LFG generation by inducing any air infiltration. Another important factor is the assumed lag time between the placement of waste and the beginning of the anaerobic decomposition or methanogenic phase within the waste mass. (Augenstein, 1991.)

The heterogeneous and time-variable nature of all landfills lends an inherent difficulty with collecting accurate data from a site without a large ongoing cost outlay. Any model output is only as good as the input data and often there are very broad assumptions necessary with respect to estimating waste quantities and types. Therefore, it is appropriate to use a simple model, which employs fewer parameters that can be more reasonably assigned according to specific site conditions. The predictive success of any model is dependent mostly on the degree of accuracy needed, the reliability of the input data, the experience of the individual analysing the data, and the degree of similarity between the subject site and other sites which have been successfully modeled. (Zison, 1990.)

All models used for determining the estimated LFG production rate of the site should be subject to a thorough sensitivity analysis to determine a range of potential outcomes and analyse which parameters have the greatest influence on LFG production values. Identification of sensitive parameters can lead to directed data collection and future improvement in LFG production predictions. Given the heterogeneous nature of the conditions within the landfill and the typical limitations in the input data that is most often available for a candidate site, it is recommended that a range of values and a sensitivity assessment be established for the LFG generation assessment. Using the upper and lower bounds of a LFG generation versus time profile based on the likely conditions within the landfill, it is possible to assign values and design inputs that are suitable for use in assessing the potential for a site and any risk factors that may be applicable.

First-order kinetic models are frequently used to estimate the production of methane over the life of a landfill. These models are tailored to specific landfills by a number of assumptions about conditions at the site. The empirical, first-order decay model most widely accepted and used by industry and regulatory agencies, including the U.S. EPA, is the relatively simple and straightforward Scholl Canyon Model. This model is based on the assumption that there is a constant fraction of biodegradable material in the landfill per unit of time. The first-order equation is given below:

$$Q_{CH4i} = k * L_o * m_i * e^{-kt} \qquad [1]$$

Q_{CH4i} = methane produced in year i from the ith section of waste

k = methane generation constant

L_o = methane generation potential

m_i = waste mass disposed of in year i

t_i = years after closure

It is typical practice to assume that the LFG generated consists of fifty percent methane and fifty percent carbon dioxide so that the total LFG produced is equal to twice the quantity of methane calculated from Equation [1].

Equation [1] is the basis for the U.S. EPA's LFG Emissions Model (LandGEM), which is available from the United States Environmental Protection Agency (U.S. EPA) website (http://www.epa.gov/ttn/atw/landfill/landflpg.html). The Scholl Canyon Model predicts LFG production over time as a function of the LFG generation constant (k), the methane generation potential (L_0), and the historic waste filling records and future waste projections at a site. The U.S. EPA assigns default values for each of these parameters for a conservative preliminary site assessment. However, these input parameters must be selected with knowledge of the specific site conditions and geographic location. In LAC, differences in the organic content of the waste, the presence of moisture, or the level to which the waste is compacted will vary and in most cases increase the potential for LFG generation from that typically found in the North America and Europe. This model has been selected for use in this Handbook not because it is the only available model, or even the best model available. However, the Scholl Canyon Model: is adequate for the purpose intended; is the most commonly employed and accepted model in North and South America; and has the best available data base for sites in LAC. The Scholl Canyon Model is also simple to understand and apply, and is generally accepted by those financing agencies and institutions that are interested in supporting these types of projects in North America and LAC.

BOX 1: IMPORTANCE OF LFG GENERATION MODELING & ASSESSMENT OF FUEL RESOURCE POTENTIAL

There are 2 major aspects to the LFG assessment. Firstly it must be estimated how much LFG there is being produced at a landfill. Secondly, but much more important, it is necessary to assess what proportion of the LFG can reasonably and reliably be collected over the long life of a project (>20 years).

For example, the Brazilian case study encompasses two sites, the old Marambaia open dump and the new Adrianopolis Landfill. The Marambaia site ceased excepting waste in January 2003 and has a total of approximately 2 million tonnes of waste in place. The Adrianopolis site began operations in February 2003 and is expected to close in 2022. The following picture provides and aerial view of the existing and new landfill disposal areas.

Modeling was undertaken at both sites to evaluate the volume of LFG that each site is expected to generate using the Scholl Canyon Model. The waste disposal volumes were based on historical data for the Marambaia site and projected values for the Adrianopolis site. The results of the modeling indicate that it is possible to collect LFG at the Marambaia site, but as would be expected the LFG generation is presently at its peak and starting into a progressive decline. The Adrianopolis has just opened, and although it has good long-term potential for recovery, it is not yet generating significant quantities of LFG to collect and utilise. These and all of the other case studies consistently reinforce the benefits of early identification and commitment to the development of LFG control systems. If you wait until a site closes to decide to develop the resource, it may be too late. It should also be noted that it may be possible to coordinate the use and transfer of equipment and systems between 2 sites under the control of the same owner. As the LFG in one of the sites is progressively declining and the other increasing, it may be possible to coordinate the use and transfer of some of the resources and facilities, assuming that the contractual arrangements for the LFG control allows this type of coordination.

Figure 2.2 illustrates the LFG generation curve produced using the Scholl Canyon Model with the U.S. EPA default values (k=0.05, Lo=170 m^3 of methane per tonne of waste) for a landfill site with a constant fill rate of 500,000 tonnes per year for 25 years (from 1990 to 2015). Figure 2.2 will be used throughout this Handbook as an illustrative example for the various principles, spreadsheet models and other information that is being provided to assist the reader in understanding and applying the principles being outlined. The graph shows two curves, the theoretical total amount of LFG produced and the LFG collected assuming a typical collection system efficiency of 75 percent. A LFG generation assessment that assumes 75 percent of the fuel can be collected is not unreasonable but would be considered relatively aggressive. A recovery percentage of 50 percent of the fuel is considered conservative and readily achievable, assuming that both the waste characterisation and modeling exercise are based on reasonable data and assumptions.

The methane generation rate constant (k) represents the first-order biodegradation rate at which methane is generated following waste placement. This constant is influenced by moisture content, the availability of nutrients, pH, and temperature. As mentioned previously, the moisture content within a landfill is one of the most important parameters affecting the gas generation rate. Moisture serves as a medium for transporting nutrients and bacteria. The moisture content within a landfill is influenced primarily by the infiltration of precipitation through the landfill cover. Other factors that affect the moisture content in the waste and the rate of gas generation include the initial moisture content of the waste; the amount and type of daily cover used at the site; the permeability and time of placement of final cover; the type of base liner; the leachate collection system; and the depth of waste in the site. Typical k values range from 0.02 for dry sites to 0.07 for wet sites. The default value used by the U.S. EPA for sites with greater than 25 inches (625 mm) of precipitation per year is 0.05 (U.S. EPA, 1994). This value is considered to produce a reasonable estimate of methane generation in certain geographic

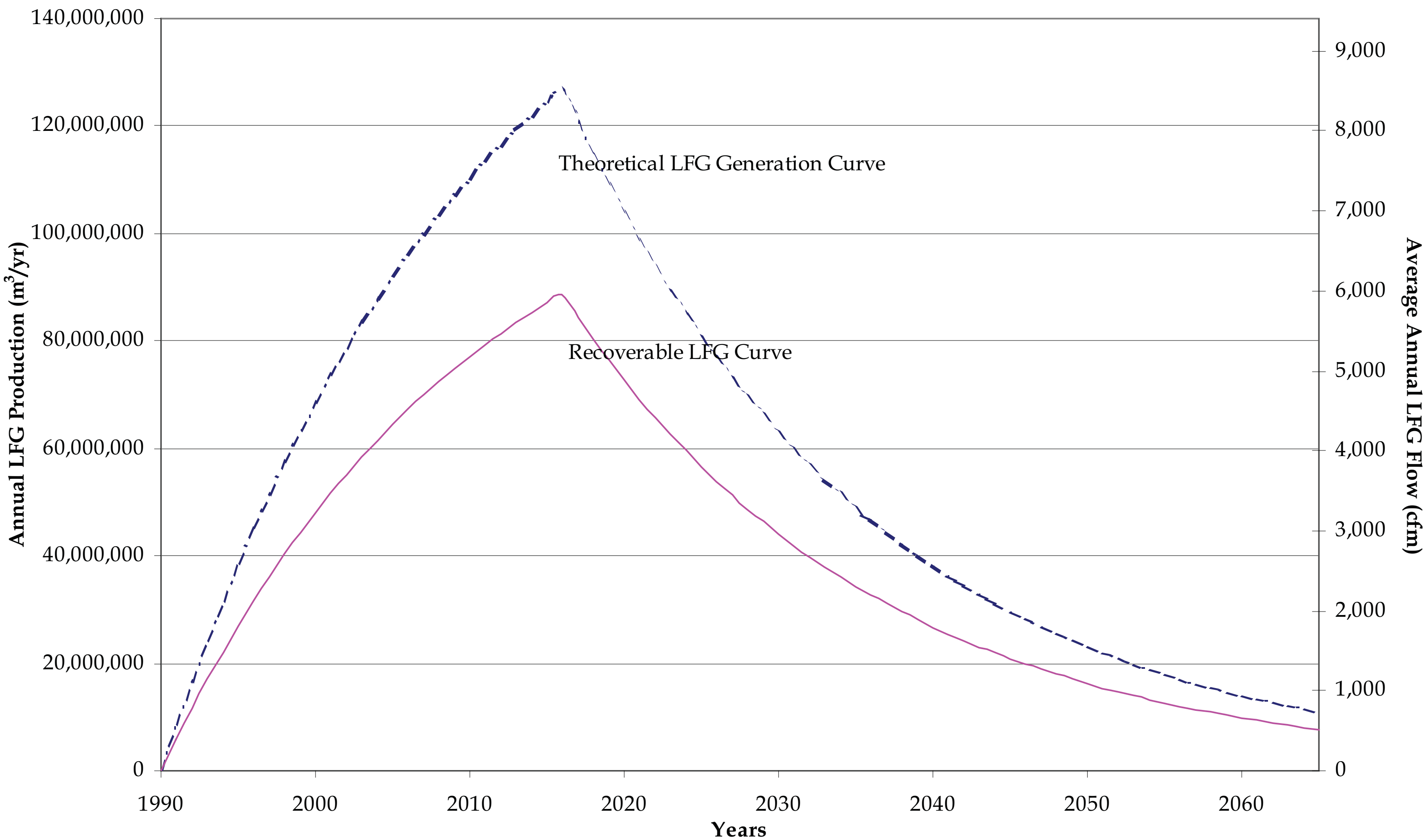

figure 2.2

EXAMPLE LFG GENERATION CURVES
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regions and under certain site conditions. The following table presents suggested ranges and recommended parameter assignment for the rate constant.

Suggested k Value Ranges for Corresponding Annual Precipitation

Annual Precipitation	*Range of k Values*		
	Relatively Inert	*Moderately Decomposable*	*Highly Decomposable*
<250 mm	0.01	0.02	0.03
>250 to <500 mm	0.01	0.03	0.05
>500 to <1000 mm	0.02	0.05	0.08
>1000 mm	0.02	0.06	0.09

The methane generation potential (L_o) represents the total yield of methane (m^3 of methane per tonne of waste). The L_o value is dependent on the composition of the waste, and in particular, the fraction of organic matter present. The L_o value is estimated based on the carbon content of the waste, the biodegradable carbon fraction, and a stoichiometric conversion factor. Typical values for this parameter range from 125 m^3 of methane/tonne of waste to 310 m^3 of methane/tonne of waste. Increased compaction of the waste has no direct effect on the L_o parameter. However, compaction and density of waste do have a direct bearing on the mass of waste in a given volume, and therefore on the potential LFG quantity that can be produced over time, as well as the performance characteristics of the systems that will be necessary to collect the LFG.

There has also been a perception that as recycling and composting programs increase and improve, more organic material, such as food waste and paper, may be diverted from the landfill reducing the quantity of LFG produced. However, recycling initiatives have had more success to date at removing inorganic materials from the waste stream, in both developed and developing countries. As a consequence, typical practice has not seen the applicable L_o value decreased significantly. The U.S. EPA uses a default L_o value of 170 m^3 of methane/tonne of waste. (U.S. EPA, 1994). The model user may increase or decrease the L_o to reflect specific knowledge of the waste characterisation with either higher or lower organic waste contents. The amount (in tonnes) of typical waste landfilled in a particular year is represented by "m" in the Scholl Canyon Model equation. In landfills where there are good data indicating that there is a significant portion of the waste that is inert (will not decompose) such as construction and demolition debris, this parameter could be reduced to represent only the amount of waste that is not inert. However, in many cases there is insufficient data to determine the percentage of the waste that is inert.

It is only recommended that the L_o parameter be reduced or the quantity of contributing waste be decreased if there is clear and concise data quantifying the inert or relatively inert waste stream. As noted earlier, the L_o parameter already is well reduced from the theoretical value that would reflect pure organic waste in recognition of the fact that there is moisture and inorganic materials that comprise some portion of any waste stream. A specific reduction should only be made if there is a readily discernible portion of the waste that is different from the typical waste received at most conventional mixed solid waste landfills. The default assignment of L_o already recognises that there is a mixture of decomposable organic wastes and inorganic wastes being deposited in a typical fill site. If there is good data regarding waste quantities and types, it may be possible to refine the modeling assessment using the following as guideline parameter assignments for the Lo factor. It would be necessary to make the overall LFG generation assessment a sum of the curves generated for the various types of waste.

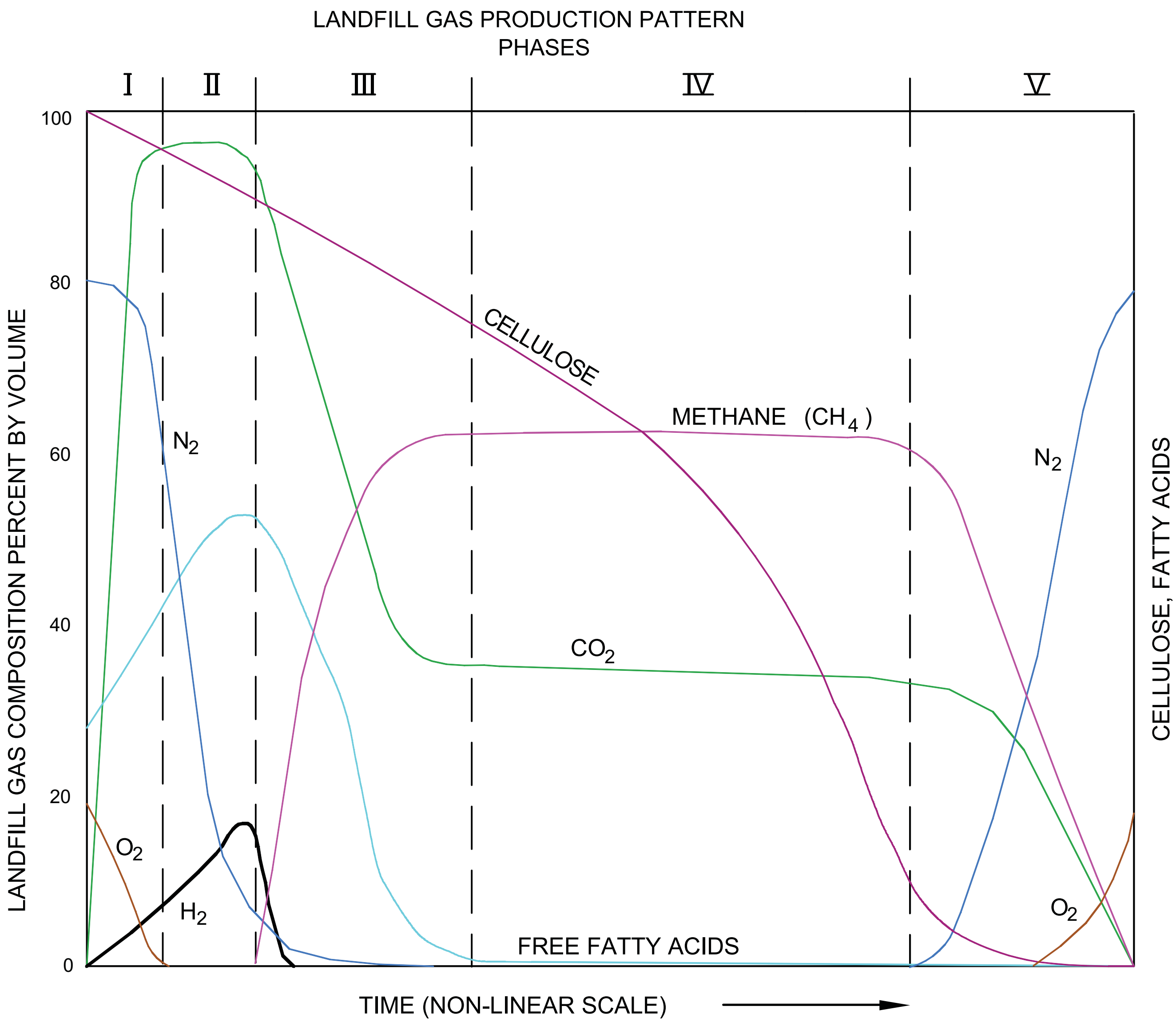
Suggested Lo Values by Organic Waste Content

Waste Categorization	***Minimum Lo Value***	***Maximum Lo Value***
Relatively Inert Waste	5	25
Moderately Decomposable Waste	140	200
Highly Decomposable Waste	225	300

2.3 LFG Composition

The quality of the LFG depends on the microbial system, the substrate (waste) being decomposed, and site-specific variables such as oxygen access to the waste and moisture content (Ham, 1989). LFG is typically described as consisting of approximately 50 percent methane and 50 percent carbon dioxide with less than 1 percent other trace gas constituents, including hydrogen sulfide (H_2S) and mercaptans.

There are four LFG production phases that occur throughout the life of a landfill. Farquhar and Rovers predicted generation of gas in a landfill for typical municipal solid waste (MSW) in the 1970s. A graph of the LFG generation phases is shown as Figure 2.3. The duration of each of these phases is dependent on a number of factors including the type of waste, moisture content, nutrient content, bacterial content, and pH level. Some general guidelines regarding the length of the decomposition cycle for the various categories of waste are provided in the following table. Note that this is a general guideline only. The extreme heterogeneity of the waste in a typical landfill site, together with the environment in a specific landfill has a significant bearing on this factor such that it can not be simply provided on a generic basis.



PHASES	CONDITION	TIME FRAME - TYPICAL
I	AEROBIC	HOURS TO 1 WEEK
II	ANOXIC	1 TO 6 MONTHS
III	ANAEROBIC, METHANOGENIC, UNSTEADY	3 MONTHS TO 3 YEARS
IV	ANAEROBIC, METHANOGENIC, STEADY	8 TO 40 YEARS
V	ANAEROBIC, METHANOGENIC, DECLINING	1 TO 40+ YEARS
TOTAL		10 TO 80+ YEARS

SOURCE:

FARQUHAR AND ROVERS, 1973,
AS MODIFIED BY REES, 1980,
AND AUGENSTEIN & PACEY, 1991.

figure 2.3

TYPICAL LFG PRODUCTION STAGES
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Half-Lives of Biodegradation Byproducts

Waste Category	Minimum Half-Life	Maximum Half-Life
Rapidly Decomposable (food & garden wastes etc.)	½ year	1 ½ year
Moderately Decomposable (paper etc.)	5 years	25 years
Poorly Decomposable (some portions of construction & demolition wastes etc.)	10 years	50 years

The first phase, aerobic decomposition, occurs immediately after the waste has been placed, while oxygen is present within the refuse. Aerobic decomposition produces carbon dioxide, water, and heat. The next stage is the anoxic, non-methanogenic phase where acidic compounds and hydrogen gas are formed and while there is continued carbon dioxide production. The third phase is the unsteady methanogenic phase. During this phase, the carbon dioxide production begins to decline because waste decomposition moves from aerobic decomposition to anaerobic decomposition. Anaerobic decomposition produces heat and water, but unlike aerobic decomposition, it also produces methane. During the fourth phase methane is generated at between 40 and 70 percent of total volume (McBean, 1995). Typically, the waste in most landfill sites will reach the stable methanogenic phase within less than 2 years after the waste has been placed. Depending on the depth of the waste lifts, and the moisture content of the waste, the methanogenic phase might be reached as early as six months after placement. LFG may be produced at a site for a number of decades with emissions continuing at declining levels for up to 100 years from the date of placement. This can be seen in Figure 2.2, which will be used for discussion purposes in the Handbook as a typical representation of a moderately sized site in LAC.

2.4 Potential LFG Impacts

The emission rate at which the release of LFG becomes an issue with regulatory authorities and neighboring property owners is related to a number of physical parameters including: the location of the landfill; the surrounding topography; adjacent land uses; ambient meteorological conditions; and the site characteristics that impact LFG generation and collection (Mosher, 1996).

It is generally the trace constituents, hydrogen sulfide (H_2S) and mercaptans, which are the primary compounds that are associated with nuisance odor emissions from landfills. These compounds typically constitute less than 1 percent of LFG, but odors are compound-specific and can be detected for specific chemical concentrations of as little as

0.001 to 0.005 parts per million (ppm). The level at which these chemicals might be of harm to human-health varies, but is typically orders of magnitude greater than those referenced. This means that the detection of odor is not necessarily an indication of a health concern but it can be a real nuisance and an adverse condition with regard to the quality of life in the area of the landfill.

Odor resulting from the release of LFG operates on a threshold principle. Thus, if the amount of LFG exceeds the threshold level for the particular conditions at the landfill, there will be odor related to the production of LFG. The following analogy can be used to better understand the concept of an odor threshold. Let the volume of a cup represent the total amount of LFG that can be released before reaching the odor threshold. The size of this "cup" for each landfill is determined by a number of factors, including the landfill location, surrounding topography and ambient meteorological conditions. Let water poured into the cup represent the release of untreated LFG. The cup can be "full to the brim" and still not spill any liquid. However, if the capacity of the cup is exceeded, by even one drop, it will overflow and liquid will spill out. Therefore, the amount of water in the cup can vary up to the capacity of the cup, so long as that threshold volume is not exceeded. This concept is analogous for LFG odor emissions. To ensure that nuisance odor is not a concern, the amount of LFG released would need to be lower than the odor threshold of the landfill site, for the given meteorological and other conditions. Therefore, in the situation where LFG odor is a major concern, it is less important how much LFG is collected in comparison with how much LFG is released from the landfill (Mosher, 1996), and whether or not that amount of LFG released exceeds the site's threshold. This issue is somewhat complicated by the fact that the threshold limit is not a fixed number. It varies depending upon time sensitive meteorological conditions and separating distance between the landfill and odor receptors (e.g., residents).

The most important component of LFG from most perspectives is methane, which constitutes approximately 50 percent of the LFG volume produced. Methane is a potential hazard since it is combustible and explosive at concentrations between 5 and 15 percent in air. LFG can migrate below ground surface in the unsaturated soil zones, especially during winter and spring months when the ground is frozen or saturated with moisture at surface. LFG can then accumulate in enclosed structures causing a potential hazard. Methane has no odor and, is therefore, impossible to detect without proper instrumentation.

Methane released from landfills has also been identified as a significant contributor to greenhouse gas (GHG) emissions, which contribute to global warming. Over a 100-year time horizon, in comparison with carbon dioxide, methane is considered to be 21 times more efficient at trapping heat within the atmosphere (IPCC, 1995). This value is currently under review and could potentially be revised upwards in the future, further increasing the incentive for LFG management projects. Methane generated from solid waste and wastewater, through anaerobic decomposition, represents about 20 percent of human-induced methane emissions (IPCC, 1999). LFG emissions to the atmosphere can be reduced through traditional waste reduction measures, such as recycling and composting. Emissions can also be reduced by capturing and flaring the LFG at a high temperature, converting the methane fraction of the gas into less harmful carbon dioxide and water vapor.

2.5 Potential LFG Benefits

Although there are several negative issues that can arise from the presence of LFG, there are also a number of benefits associated with the proper management of LFG, and its potential for use as an energy source. LFG management projects that collect and flare the LFG have the potential to generate revenue through the sale and transfer of emission reduction credits, which provide an incentive and means to improve the design and operation of the landfill and to develop a better overall waste management system.

LFG is approximately 50 percent methane, and can be considered a low/medium grade fuel. This resource can be harnessed in a number of applications including direct fuel use for heating, electrical generation, and commercial chemical byproducts. In addition to mitigating LFG migration and odor concerns, LFG utilisation can also generate revenues from the sale of "green power" and other LFG products that can defray the costs of landfill operation and maintenance and provide incentive to improve landfill design and operation.

Emission reductions represent the global and national objectives for improving global air quality. Emission Credits (GHG Credits) and Green Power energy premiums are two of the key mechanisms that are being proposed to help to achieve the goal of "Emission Reductions". The sale of these credits can be used to improve the economics of a potential project. There is differing terminology used to refer to the emission reductions such as ERs, CERs and GHG credits. These terms refer essentially to the same item, which is best defined as the quantity of emission reductions converted and presented in the common unit of equivalent tonnes of carbon dioxide emission reductions. For the balance of the Handbook, the term CER will be used and the unit of definition will always be equivalent tonnes of carbon dioxide. The CER designation assumes that the emission reductions have been certified to meet a specific set of standards and requirements. There may be other certifying agencies or bodies that may use different acronyms but the principles and underlying basis for recognition and quantification will remain the same.

Before any LFG management project is undertaken, the LFG emissions and resulting CERs must be carefully assessed and the potential markets explored. This is discussed in much more detail in later sections.

2.6 LFG Collection System

There are extensive reference materials and information with respect to the successful means and methods to collect and flare LFG that are generally beyond the scope of this Handbook. However, a basic understanding of the nature and operation of the LFG collection systems is necessary to understand the fundamental elements of a LFG management project and risk factors inherent in the management of the LFG resource. To appreciate the interconnection and interdependence issues, a brief outline of the elements of a collection system is being provided. A typical LFG collection system is comprised of the following components:

- LFG collection field (wells and trenches);
- Collection piping (laterals, subheaders, headers, etc.);
- Condensate drop-out and disposal system;
- Blower system and related appurtenances; and
- LFG flare.

LFG management can be achieved through the use of these components and there is potential, through the development of the international carbon market, for this type of system to generate revenue through the creation of GHG emission reduction credits. Revenue provided by such a system creates an incentive for better landfill design and management, and a contribution towards improvement of the overall waste management system.

Appendix A provides a number of figures illustrating various components of a typical LFG collection and flaring system for review and reference.

LFG Collection Field

A network of vertical LFG extraction wells and/or horizontal LFG collection trenches are installed into the waste to collect the LFG. The basic operating principle is quite simple, apply a vacuum to extract the gases from the waste mass as closely matched to the rate at which the gas is being generated within the influence area of the well or trench as is practical. The idealised target objective is to establish a neutral pressure/vacuum gradient continuously over the entire surface of the landfill. It is important to recognise that the ideal condition cannot be achieved at reasonable cost and therefore, it is important to balance the cost-benefit of installing additional wells in a tighter grid of wells together with a complementary cap system versus the value inherent in the fuel recovery.

The cost increase to extract LFG up to approximately 75 percent of the actual LFG being generated is considered relatively linear in nature. However, to achieve very high recovery efficiencies, it may be necessary to employ a very tight grid of extraction wells/trenches and/or a synthetic cover system, which would result in major capital cost increases relative to the gain in LFG recovery. Figure 2.4 illustrates the relationship between the efficiency of the LFG collection system and the relative cost.

Vertical wells are typically installed in a landfill once filling operations have been completed. Figure 2.5 shows the construction of a typical vertical LFG extraction well. Figure 2.6 shows the construction of a typical horizontal LFG extraction trench. Using vertical LFG extraction wells has the following advantages:

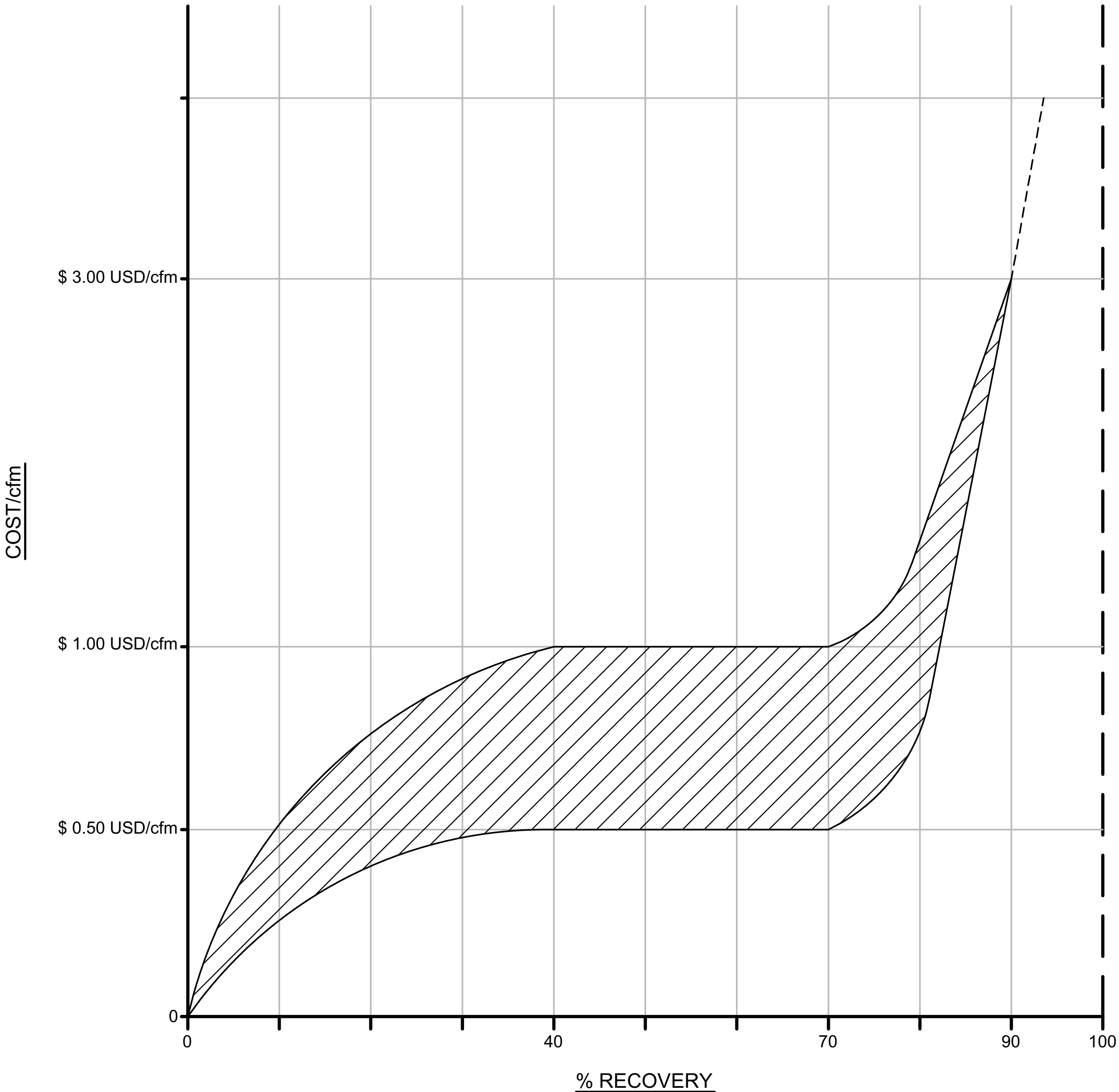

figure 2.4

COST VERSUS RECOVERY EFFICIENCY
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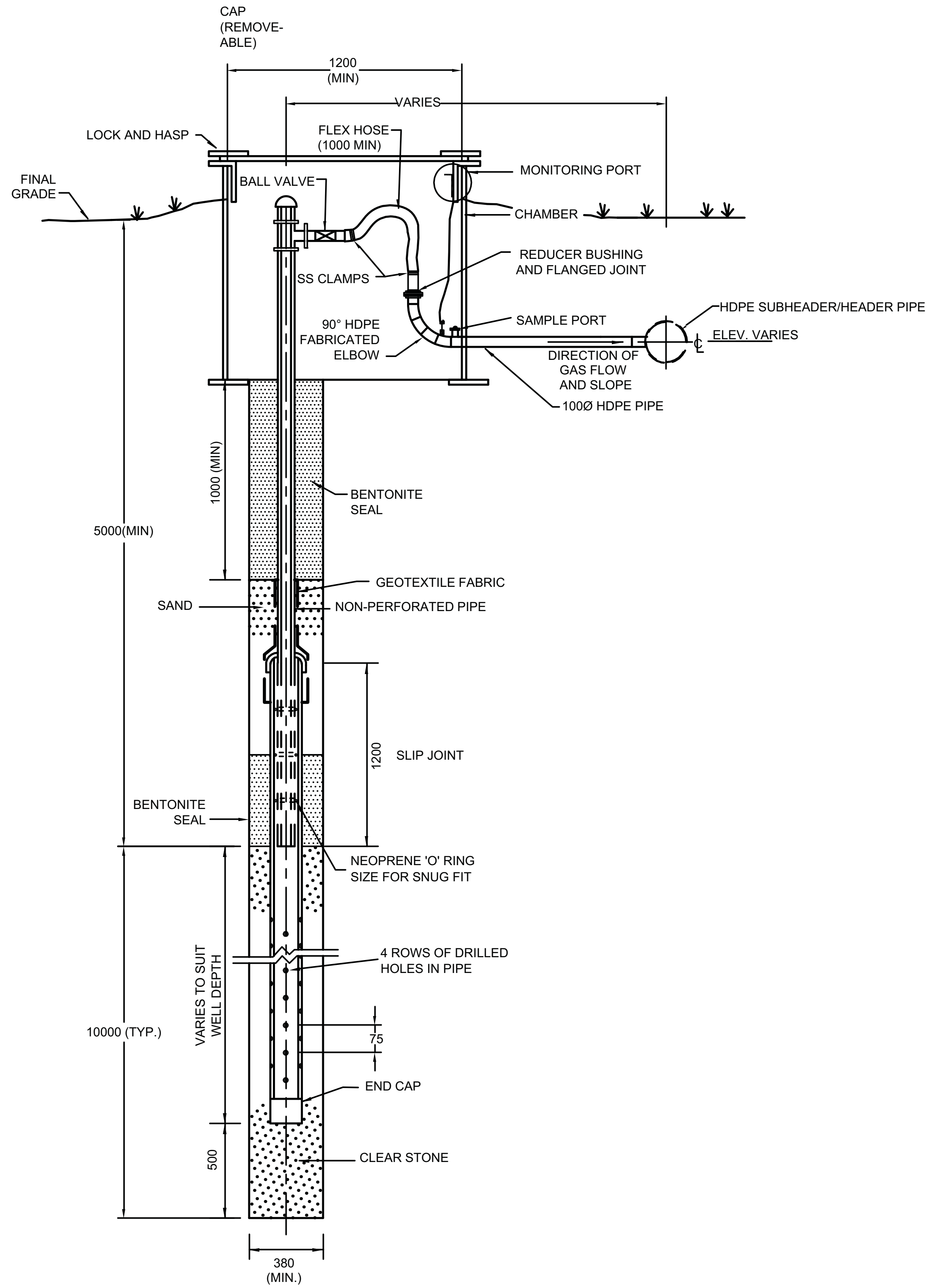

figure 2.5

TYPICAL DETAIL OF A VERTICAL LFG EXTRACTION WELL

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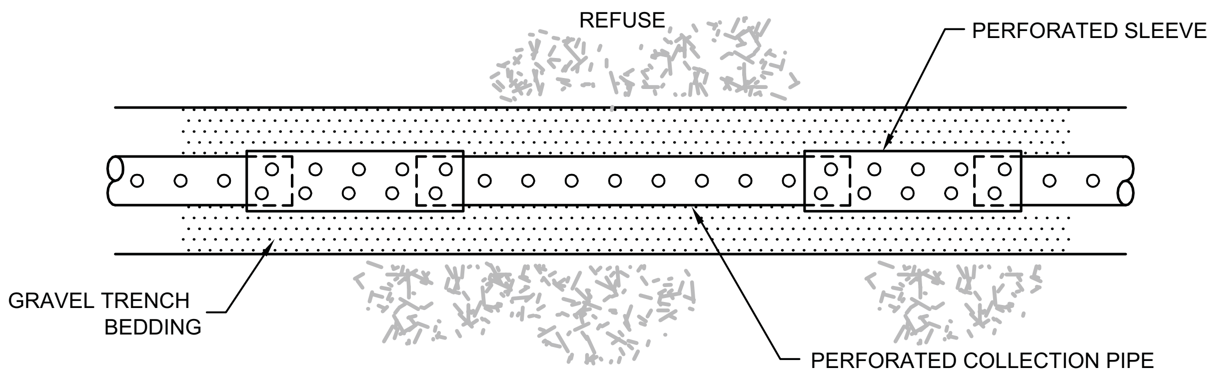
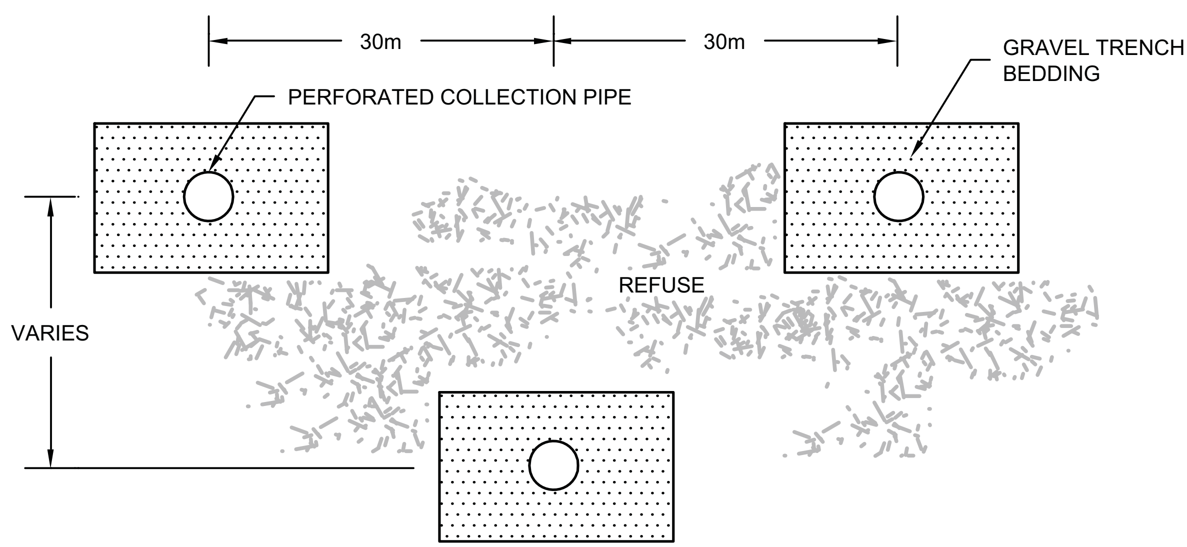


TYPICAL HORIZONTAL COLLECTION TRENCH
PROFILE VIEW



TYPICAL HORIZONTAL COLLECTION TRENCH
CROSS-SECTION

NOT TO SCALE

figure 2.6

TYPICAL DETAIL OF A HORIZONTAL LFG COLLECTION TRENCH
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- improved areal control of gas emissions;
- well field may be expanded to reflect the changing landfill site conditions; and,
- condensate collection may be minimized.

To maximise collection efficiency, wells should be sited in consideration of the waste depth, age and the physical geometry of the site. If there is a concern regarding subsurface migration of LFG, wells placed close to the outer limits of the waste should be grouped closer together to act as a migration control system.

Some of the general rules for the installation of vertical extraction wells are:

- minimum of 3 to 6 m of landfill depth to be maintained above the extraction well perforations to minimize air entering the LFG collection system;
- the depth from surface to perforations should be increased near side slopes; and
- the ability to install wells along the steeper (4:1) side slopes is limited with conventional drilling equipment.

These conditions may not be absolutely identical at every landfill site, however they serve as a good guideline to ensure proper function of the LFG collection system and minimise the intrusion of air into the flare or LFGTE plant.

Horizontal LFG collection trenches are typically used to collect gas while the site is still active. Following the placement and compaction of a lift of waste, perforated collection pipes are installed and then covered with another layer of waste. This allows for LFG to be collected from waste directly below an area where active filling is taking place. While this technique can control LFG emissions in active areas of the site, horizontal collection trenches are not generally suitable for localised gas control.

In general, the operating principles for vertical wells and horizontal trenches are the same. Both types of collectors should be equipped with telescoping sections of non-perforated pipe to allow for refuse settlement, which occurs over time. It has been found that 10 to 15 inches of water column vacuum at the wellhead or trench represents a reasonable compromise between maximising zones of influence and minimising air intrusion into the refuse, while using economical LFG extraction equipment. The radius of the zone of influence with this vacuum ranges from less than 20 m to more 100 m, depending on the waste's heterogeneity and other related characteristics.

The LFG collection system should be used in concert with good leachate management practices. Leachate mounding within the refuse can dramatically impact the rate of LFG recovery because liquid in the extraction wells and collection trenches effectively restricts their ability to collect and convey LFG. In extremely damp sites, the effective LFG fuel recovery may drop to less that 50 percent of the estimated quantity of LFG that may be available.

The costs to install vertical wells can vary dramatically as a function of: local costs for materials such as aggregate, pipe and grout; contractor availability; available equipment types and capacities; and the specific characteristics of the well design. For example the unit cost to install a well to a 30 metre depth in a typical waste mass is higher than for a depth of only 20 metres. Similarly replacement/repair cycles for LFG wells can vary substantively based on the site specific conditions and design. Some typical ranges for LFG installations are as follows:

General Ranges in Vertical Well Costs

Description	Low Range	High Range	Comments
	(US$/vertical metre)	(US$/vertical metre)	
100 to 150 mm diameter wells (<15 metres depth)	$150	$250	
100 to 150 mm diameter wells (>15 metres but less than 30 metres in length	$200	$350	
900 mm diameter wells (any depth)	>$500		These wells are not recommended as cost effective. Refusal to the advancement of a borehole in waste is not an uncommon event that can result in large increases to the cost of deep wells.

LFG Collection Piping

A network of piping is constructed to connect the LFG collection field to the LFG flare or LFGTE plant. A typical LFG collection system includes the following:

- small diameter (minimum 100 mm), short laterals connecting the wells/trenches;
- subheaders which connect the laterals; and
- headers connecting the subheaders to the extraction plant.

There are a several LFG network piping patterns designed to facilitate drainage of liquids and to minimise the length of pipe required for the collection system. Two of the most common layouts are the herringbone and the ring header. The herringbone arrangement has a single main header with subheaders and headers branching from it. This is the most efficient use of piping, and it can be designed to minimise the quantity of condensate, which accumulates in the LFG collection system, by sloping the majority of piping towards the LFG wells.

An on-site ring header may be used when there is no land available for construction of a header system outside the limit of waste. Off-site ring headers reduce some of the problems associated with placement of piping into the refuse. Ring headers should be equipped with valves to allow isolation of portions of the site, and monitoring ports to monitor gas quality and quantity. Dual header systems have been utilised at some large and deep landfill sites that have a long active site life to segregate the methane-rich gas from the deeper portions of the site from the gas collected from near the surface that may be diluted via air intrusion. There are numerous design criteria/constraints related to the piping installations to specify such as minimum and maximum slopes; condensate moisture removal; differential and total settlement stresses; and dead and live load stresses.

The relative costs of the piping systems to collect and transport the LFG to the facility can vary substantively based on site specific conditions and the applicable design basis. For example, above grade piping systems are the least expensive to construct and are often used for temporary systems or for short term repairs but also have successfully been used for full-scale long-term systems. There are advantages and disadvantages to both above and below ground approaches to the installation of the connecting piping systems. The costs for small diameter above grade piping can be less than $30/metre but larger diameter buried piping can cost up to, and more than, $200/metre. The cost is highly influenced by factors such as:

- the nature of the design (e.g., above or below grade);
- the need to remove and relocate any waste;
- the need to add fill or grade areas of the cap and perimeter areas;
- the extent and number of condensate removal traps;
- the cost of petroleum and associated products; and
- the availability and costs for suitable construction contractors.

The specific characteristics of a landfill site will have many direct implications for the design options and related costs of the piping systems. As such, it is highly recommended that these costs be reviewed carefully on a project specific basis. It is also important to note that high density polyethylene (HDPE) piping is highly recommended for most of the LFG piping and its price is largely controlled by the relative cost of petroleum and the proximity to suitable pipe manufacturing facilities.

Blower System and Related Appurtenances

The blower system includes all components that are used to generate and apply the vacuum to collect the LFG and supply it for its subsequent end use. A blower system should be centrally located with sufficient space for expansion, close to the end user (power grid or end user pipelines). The blower system may be enclosed in a building or it may be pad mounted as an exterior installation.

The blower system components include:

- valves and controls as required for safe operation (e.g., a flame arrestor);
- condensate pumping or storage;
- LFG flow metering and recording; and
- blowers or compressors to meet capacity requirements.

The blower system should have the capacity to handle 100 percent of the peak rate of LFG production estimated, plus some allowance for migration control. Some level of backup redundancy is typically recommended for all blower systems that are providing fuel to a revenue-generating LFG utilisation system. Depending upon the size and age of a site, a phased approach to LFG control plant construction is often beneficial if gradual increases in LFG production are anticipated.

The costs of the blower systems are a function of many factors and can only be assigned based on the specific requirements for the overall system. Some of the major factors affecting the blower selection are:

- LFG flow range proposed to be collected;
- Piping system design and head loss criteria;
- Available well head vacuum;
- Length of the piping system; and
- Pressure demand for any flare or utilization system being supplied with LFG.

As a simple guideline, the cost for a blower system for a flaring application can range from $25,000 to $50,000 per 1000 m^3/hour of LFG. If the final application is a utilisation facility, the cost range for the blower system can increase by a factor from 2 to 5, or more, depending upon the fuel supply requirements.

Condensate drop-out system

LFG is extremely moist and therefore produces a lot of condensate within the LFG collection wells and piping. It is important that all the pipes are designed with minimum slopes so that condensate does not remain within the piping, but flows towards a nearby drain or sump. Improper drainage of the condensate can lead to blockages in the pipe, which can disable large parts of the LFG collection system limiting the amount of LFG that can be collected.

A sump and/or moisture separator may remove condensate. At a minimum, a sump should be constructed in the piping system to drain condensate and to prevent flooding of pipelines. Moisture separators remove droplets of liquid from the flowing LFG therefore reducing the detrimental effects that the corrosive condensate may have on the LFG handling equipment.

BOX 2: IMPORTANCE OF CONDENSATE MANAGEMENT TO LFG COLLECTION SYSTEM PERFORMANCE

One of the most common operational problems for LFG collection systems is liquid blockage in the piping or wells, which has the potential to cripple the operation of the system. Blockage of the laterals or subheaders usually results from a build up of condensate. Condensate removal systems should be installed to collect and remove LFG condensate from the piping systems. The blockage problems caused by inadequately sized piping or piping designed with an inadequate slope, can effectively terminate LFG collection from the affected section of the landfill. Another reason for condensate build-up is the uneven or differential settlement of the waste, which can cause a dip or low point in the piping systems that can then fill with condensate. It is for this reason that LFG collection systems should be designed with a great deal of excess capacity and specific consideration in the design for identifying and addressing settlement issues.

A demonstration of the potentially catastrophic consequences that ineffective condensate management can have is the Kemerburgaz LFGTE project in Turkey. During the startup and commissioning phase, it was found initially that two thirds of the LFG extraction wells had no suction pressure, which meant that there was not enough LFG to supply the engines that were being commissioned. Thankfully, this condition was remedied after a week when it was discovered that a section of pipe had been installed such that condensate was collecting and blocking the pipe, preventing LFG extraction from a significant portion of the site.

The LFGTE project in Krakow, Poland has experienced difficulties with the flooding of their horizontal LFG collection trenches because of leachate mounding within the waste mass. In the future, they are planning to use only vertical LFG extraction wells to combat this problem. The LFGTE project in Olsztyn, Poland has experienced such high leachate levels that all the perforations in the vertical LFG extraction wells are blocked and the wells have been rendered dysfunctional.

At the Waterloo Landfill in Canada, the quantity of LFG recovered has not increased to correspond with the quantity of wells that are presently in-place. Conditions at this site serve to reinforce the importance of understanding the landfill and its operation as well as the physical conditions within the landfill. The Site was found to be very wet, hampering the ability to obtain the gas that is being generated in some portions of the Site. Systems to address the presence of condensate and trace gas impurities in the LFG can requires scrubbers and other treatment systems similar to the equipment shown in the attached picture of a portion of the gas treatment room at the Waterloo Landfill Site.

The importance and benefits associated with effective condensate management to both the short and long-term performance of the LFG management systems can not be overstated. This is a critical item to the success of all LFG management projects that is not always given the consideration that is warranted.

Once separated from LFG, condensate must be disposed of in an environmentally sound manner. Condensate is generally more concentrated than leachate and may be considered a hazardous liquid waste in some jurisdictions.

<u>LFG flare</u>

The LFG collected from a site must be disposed of in an environmentally sound manner such as an enclosed drum flare and/or utilisation system. A LFG flare can be used as a backup to the utilisation system in case of lengthy downtimes for both scheduled and unscheduled equipment operating and maintenance events. The need for a backup flare and equipment redundancy is optional depending upon the overall systems reliability and the sensitivity to short term loss of LFG extraction and control capability. High temperature flaring of LFG results in conversion of methane components of the LFG to carbon dioxide and water. As well, this high temperature combustion ensures that the trace compounds in LFG are largely destroyed. Most LFG utilisation systems provide for destruction efficiencies equal to or better than those achieved in the enclosed drum flares.

As with most of the other system components, the cost of flaring systems is a function of the overall design of the LFG management system and the performance requirements that are expected for the flare. There are 2 basic flare designs; the enclosed drum flare discussed above; and a waste gas flare that simply ignites the methane without any extensive combustion controls. This second type of flare is in common use in many jurisdictions but has not been the focus of this Handbook, primarily because its use is not deemed acceptable if there is any intent to qualify for CERs.

To give a simple cost guideline, a waste gas flare capable of combusting 1000 m^3/hour of LFG would cost in the range between $50,000 and $100,000 depending upon the peripheral controls and safety features required. For relative comparison, an enclosed drum flare with a similar capacity with have a cost range about twice that of the waste gas flare. Some components such as the refractory and control systems can vary substantively in price depending upon the performance requirements.

2.7 Operation of LFG Collection System

Active LFG collection and utilisation are highly effective for mitigation of on-site and off-site LFG impacts as well as reduction of GHG emissions to the atmosphere. The LFG capture potential is highly dependent on site design related factors, such as:

- Site configuration (depth of waste, landfill area, depth of water table);
- liner system design;
- cover system design;
- moisture addition/leachate recirculation; and
- operational constraints.

Site configuration has a great impact on the LFG collection potential for a site. Sites that are filled above the natural grade tend to have larger surface areas, therefore increasing the chances of LFG emissions. Sites filled below grade have a greater tendency for off-site LFG migration through the surrounding soils.

A low permeability soil or synthetic liner system combined with a leachate collection system is beneficial in controlling both LFG migration and mounding of leachate within the refuse. The primary purpose for a low permeability liner is to mitigate potential groundwater impacts by allowing leachate recovery from the bottom of the refuse, but it is also recommended for the control of LFG migration.

The permeability of the final cover system is an important factor in LFG management and system performance. Low permeability covers minimise LFG venting to the atmosphere, air intrusion into the waste, as well as moisture infiltration. A low permeability cover can help to improve the performance and areas of influence for vertical extraction wells. However, if the cover system is very tight and allows very little infiltration, it can retard or slow down the rate of decomposition in the upper portion of the landfill that many not be at the optimal moisture content to encourage decomposition. These two competing factors should be considered in the LFG generation assessment.

Moisture addition/rapid waste stabilisation is the current trend in LFG recovery, otherwise referred to as landfill bioreactor technology (LBT) systems. This process increases the amount of water contacting the waste, to rapidly stabilise the wastes, significantly increasing the initial quantities of LFG produced with sharply decreased generation rate following waste placement. This increased initial LFG production rate could be beneficial for some LFG utilisation projects as it could supply larger, more efficient plants. This approach could shorten the payback period for the project, adversely affecting its financial viability unless a series of cells were developed and operating in sequence were utilised. This rapid stabilisation could also potentially increase LFG migration and emissions, and therefore it is best applied at sites with adequate LFG collection capacity as well as a liner and final cover as design elements.

Rapid stabilisation must be critically assessed during the conceptual and preliminary site design stages. At a minimum, the following issues have to be considered:

- increased LFG production rates over a shorter timeframe;
- increased LFG collection and handling capacity;
- greater destruction (flaring and/or utilization) capacity requirements;
- increased landfill settlement;
- higher moisture content of the gas, leading to higher condensate volumes;
- leachate mounding within the site;
- leachate collection system capacity; and
- effect on leachate character.

Daily operations have an important influence on the LFG recovery potential. Using permeable daily cover, such as sand, will result in higher rates of moisture infiltration, therefore leading to higher moisture content of the waste and increased rate of LFG production. The filling sequence and method of waste greatly affects the type of collection field selected. Horizontal LFG collection trenches are best used at sites with relatively shallow lifts over large areas. For sites using low permeability daily cover, the layering/stratification of a site is magnified. This may create perched water conditions, which can increase LFG collection costs as well LFG production rates in some areas of the site.

Some special consideration needs to be made for issues associated with condensate collection, removal and disposal from the piping systems and wells installed in the site and also condensate collected and removed in the LFG utilisation facility. It is also critical to understand the implications of settlement and differential settlement of the waste. The average amount of settlement at a landfill depends primarily on the specific design and operating characteristics of the site. The total settlement that can be expected from a landfill site can range from 20 to 40 percent of the total depth of the waste following initial placement and compaction. In simple terms, a 30 metre deep landfill could experience total settlement from 6 to 12 metres by the time the process is completed. The rate of settlement is at its peak when the site is still actively receiving waste. Both the load related settlement and decomposition related settlement are typically at their peak during the active site life. More important than total settlement is differential settlement. Settlement in localised areas can be much greater and much more rapid than the average depending on the material landfilled, the amount of compaction it receives, and other factors such as air intrusion or the infiltration of surface water. Features such as vertical gas wells can be localised problem areas if not taken into account during both the design phase and as a key consideration of the operations and maintenance phase of any project.

2.8 Best Management Practices for Operations of LFG Projects to Maximise Energy Recovery Potential

Optimising LFG collection is directly related to maximising LFG utilisation potential, realising economic benefits from the sale of LFG energy and reducing GHG emissions. It must always be understood that the landfill operation itself is the primary purpose of the site activities and all other systems or supporting activities, whether beneficial or not, must remain subservient to this activity. One problem area that has been noted throughout the history of the LFG management projects is that improper operation of a LFG collection system to support a utilisation system can pose risks of landfill fires and fuel quantity reduction that are both dangerous and counterproductive for both of the systems. Understanding the links and interactions between these two systems is important to developing and sustaining a viable project through the entire term of a 20-year or longer contract term, which can be critical for a LFGTE plant.

LFG COLLECTION FIELD

A well designed, constructed and operated LFG recovery system can collect 75 percent or more of the LFG produced at a site. It is important for a collection system to be designed and operated to match the site's changing LFG generation potential without over or under drawing on the collection field. In addition to the changing LFG generation rate over the life of the landfill, the effective LFG generation rate also varies somewhat over the short term as a function of factors such as; meteorological conditions; differential settlement; equipment efficiencies; and cover system conditions. The collection field must be adjusted to match the changing effective generation rate. The LFG collection field must be periodically monitored and adjusted to optimise the effectiveness of the collection system. The adjustment of valve settings to reduce or increase LFG flows from low or high production areas of the landfill is required to maximise LFG collection without overdrawing from those areas of the site that may be susceptible to air intrusion. One principle that is often misunderstood or ignored, even by those working in the LFG industry, is that the operating basis for an individual well or trench must be based solely on LFG quality at that individual well or trench. Operating a well or trench on the basis of target recovery rates or expected performance yields is counter-productive.

Air intrusion into the landfill must be minimised since it has a negative impact on the natural decomposition of waste. Within a few months following placement, the waste-in-place has typically reached a stable phase of anaerobic (oxygen-free) decomposition. At this point, introducing oxygen will return this environment into aerobic conditions, with the result of: reducing methane generation and an associated decline in potential fuel recovery; increased localised rates of differential settlement; higher subsurface temperatures in the waste; and potentially increased odor problems. This condition may also lead to landfill fires and increases the potential for spreading any fires that are started.

Field monitoring at each of the collection points (wellheads/trenches) should include:

- vacuum;
- differential pressure;
- temperature;
- LFG composition (methane and O_2 content); and
- valve position

Monitoring of each collection point should start with vacuum/pressure measurement to avoid interference with the action of extraction for the LFG sample. The essential monitoring data to collect is the vacuum, LFG composition and valve position. The following indicates readings under ideal operating conditions to maximise energy recovery at each collection point:

- Vacuum maximum 20 inches WC;
- methane 45 to 55 percent by volume;
- O_2 less than 2 percent by volume.

Table 2.1 presents a simple diagnosis tool to highlight some common problems in the operation of the LFG collection and utilisation facilities and their probable solutions.

Table 2.1 – Common LFG Collection System and Fuel Recovery Issues

Diagnosis	*Potential results*	*Recommended solution*
$O_2 > 2$ percent v/v	• Diluting LFG fuel therefore reducing energy recovery • Increased rates of differential settlement • High subsurface temperatures • Odor problems • Landfill fires	• Adjust valves and rebalance based on gas quality • Check well head for indications of differential settlement stresses
$CH_4 < 45$ percent v/v	• Same as above	• Adjust valves and rebalance based on gas quality • Check well head for indications of differential settlement stresses
$CH_4 > 55$ percent v/v	• Increased energy content per unit LFG recovered • Odor problems • Vegetation stress • Increased emissions and migration	• Adjust valves and rebalance based on gas quality • If gas quality and quantity are indicative of additional gas in area, add wells to system
Vacuum > 20 " WC with high relative flow rates	• Potential air intrusion • Increased rates of differential settlement • Landfill fires • Odor problems	• Adjust valves and rebalance based on gas quality • If gas quality and quantity are indicative of additional gas in area, add wells to system
Vacuum < 10 " WC with low relative flow rates	• Blockage/breakage of extraction piping • Condensate issues • Odor problems • Vegetation stress Increased emissions migration	• Check well head for indications of differential settlement stresses • Identify and address for blocked piping

As part of the regular monitoring program the well head valves should be adjusted to maximise effectiveness. This adjustment must be made based upon review of historic performance data and within the context of the overall field operation. For instance any great variation of vacuum readings from historical monitoring may indicate defects with the LFG collection piping, such as break or flooding of pipe runs due to excessive settlement. For this reason all the data collected must be looked at as a whole.

At a closed landfill site the LFG generation potential is decreasing with time, therefore some areas of the site may require reduced LFG collection to match this decreased generation. At active landfills LFG generation potential increases until a few years past closure. Therefore, LFG collection system design at active sites must allow for progressive expansion to accommodate the increasing LFG generation.

LFG COLLECTION PLANT

Proper operation and regular maintenance of the LFG collection plant (including condensate drop-out(s), blower(s), flare and associated equipment) enhances collection system efficiency and maximises equipment life.

Regular inspection should be undertaken at the LFG collection plant to record the gas flow, flare temperature, combustible and oxygen concentrations of LFG, bearing temperatures, motor run times and any other critical parameters. Only personnel familiar with the operation of the LFG collection system should carry out correction of irregularities or adjustment to the system operation.

Minor maintenance procedures, such as greasing bearings, changing belts, and calibrating detectors may be carried out on a monthly cycle. Major system shutdown and equipment overhaul should be undertaken annually as per equipment manufacturer's recommendations.

SYSTEM INTERCONNECTION AND INTERFERENCE ISSUES

Active LFG collection must tie in with other active systems on a site, such as active landfilling operations, leachate collection, base liner and final cover systems. The overall site design must take into considerations all systems in a progressive manner to ensure interconnection of systems and potential progressive site expansion. Some of the interconnection/interference issues with active LFG collection include:

- Connecting the LFG collection system to the leachate collection system. The quantity and quality of LFG that may be collected from the leachate system can be significant. A valve must be installed at the connection point to allow adjustment of flow and pressure applied onto the leachate collection system. The risk of this connection is that if excessive vacuum is applied oxygen may be pulled into both the LFG and leachate collection systems. Oxygen intrusion into both of these systems can be both a safety and operational hazard.

- Ongoing landfilling operations may result in air intrusion into the LFG collection system as well as the landfill itself. At active landfills, care must be taken to protect/cover the LFG collection pipes with adequate waste/interim cover prior to activation to minimize air intrusion. Excessive air intrusion will dilute the LFG collected, reducing its energy content, may cause landfill fires. At open sites another risk is heavy equipment damaging exposed or shallow buried piping.

- Progressive expansion of LFG collection field is beneficial in increasing LFG collection capacity but may interfere with existing liner and final cover systems. Following LFG collection field expansion (installation of wells/trenches and associated laterals) any interruption to the final cover must be replaced to its original condition.

Generally, it is always important to remember that a LFG management system is a supplementary operation to the core business of landfilling on the candidate site. This factor must always be considered when looking at installing and operating LFG collection systems in areas of a site that are still receiving waste and cover materials.

3

Landfill Gas Utilization Technologies

All LFG utilisation facilities require a LFG collection system, which is optimised to maximise the recovery of the LFG without causing air intrusion. The collection and flaring of LFG is by itself an effective means of LFG management by reducing odor and migration problems. In addition, flaring LFG in an enclosed drum flare effectively converts the methane in LFG to carbon dioxide, effectively reducing its GHG potential. The implications of this fact, in concert with the development of an international carbon market are discussed further in Section 6. Flaring the LFG does not, however, recover any of the energy from the LFG. This section discusses a number of technologies available to recover some of the energy from the LFG and potentially provide a supplementary source of income to the landfill through the sale of LFG related products.

An effective collection system, associated with a LFG utilisation facility, would also protect against odor and other emissions, but as a byproduct of the fuel recovery rather than as the primary objective. In an effectively designed and operated LFG collection system, these two sets of objectives can be made fully compatible.

However, LFG is a wet gas with variable concentrations for a number of trace gases, which must be considered in the design of a LFG utilisation system. The high moisture content of LFG guarantees the presence of moisture in the collection system, which may cause problems related to condensate removal/interference with the ability to collect the LFG through the piping system. In addition, some of the trace gases present in combination with moisture may cause corrosion of the equipment. Other operational restrictions such as health hazards such as the danger of explosion from the presence of LFG in confined spaces prevent the use of LFG for household domestic use. The release of contaminants to the atmosphere through air emissions also requires consideration when selecting what type of utilisation facility to develop. Depending upon the application, the raw LFG may require some level of gas processing prior to being utilised in order to reduce these concerns.

LFG can be classified into three categories, based on the level of pretreatment/processing prior to utilisation. These are:

Low-grade LFG fuel - Utilisation of LFG as a low-grade fuel typically requires minimal processing, involving condensate removal chamber(s) as part of the LFG collection system and moisture knockout pots to reduce the amount of moisture in the gas stream.

Medium-grade fuel - Additional gas treatment devices are used to extract more moisture (with contaminants) and finer particulate matter. The process typically involves compression and refrigeration of LFG and/or chemical treatment or scrubbing to remove additional moisture and trace gas compounds such as mercaptans, sulfur compounds, siloxanes, and volatile organic compounds.

High-grade fuel - Utilisation of LFG as a high-grade fuel involves extensive gas pretreatment to separate the carbon dioxide and other major constituent gases from the methane and to remove impurities including mercaptans, sulfur compounds, hydrogen sulfide and volatile organic compounds, and gas compression to dehydrate the gas.

Low- and medium-grade fuel produced from LFG has a heating value of approximately 16.8 MJ/m3. This heat value is roughly one-half the heating value of natural gas. LFG that has been further processed and treated to produce high-grade fuel has a higher heating value (37.3 MJ/m3) than low and medium grade fuel, and can be substituted directly for natural gas in pipeline applications (CRA, 1996).

Figure 3.1 provides a visual tool to aid in understanding the following discussion on the various applications for the three grades of fuel that can be produced from raw LFG. It also illustrates the increasing degree of processing that is required to transform the LFG from a low-grade fuel into a more refined fuel source.

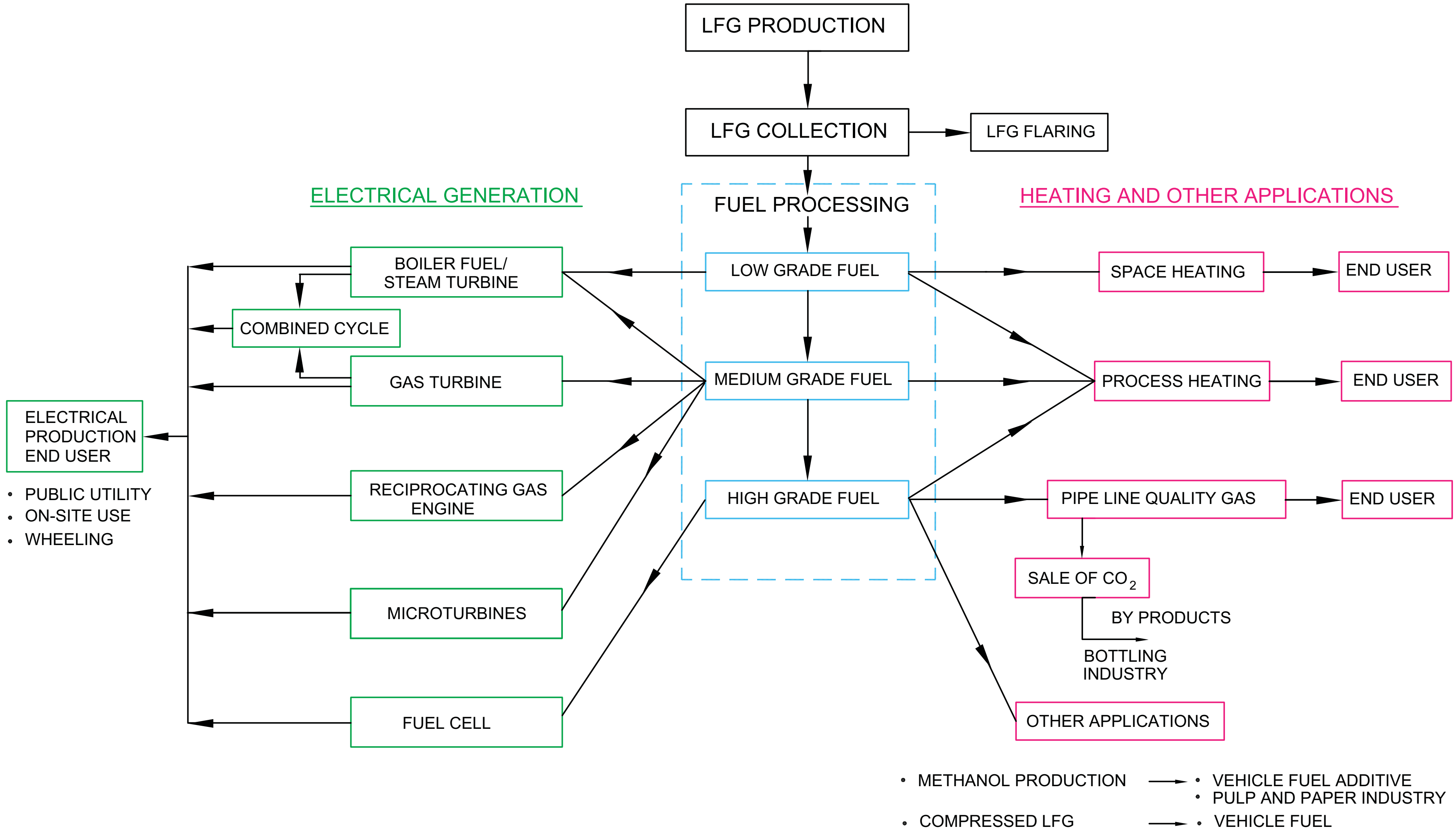

figure 3.1

LFG UTILIZATION OPTIONS

HANDBOOK FOR THE PREPARATION OF LANDFILL GAS TO ENERGY PROJECTS

The World Bank

CRA

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