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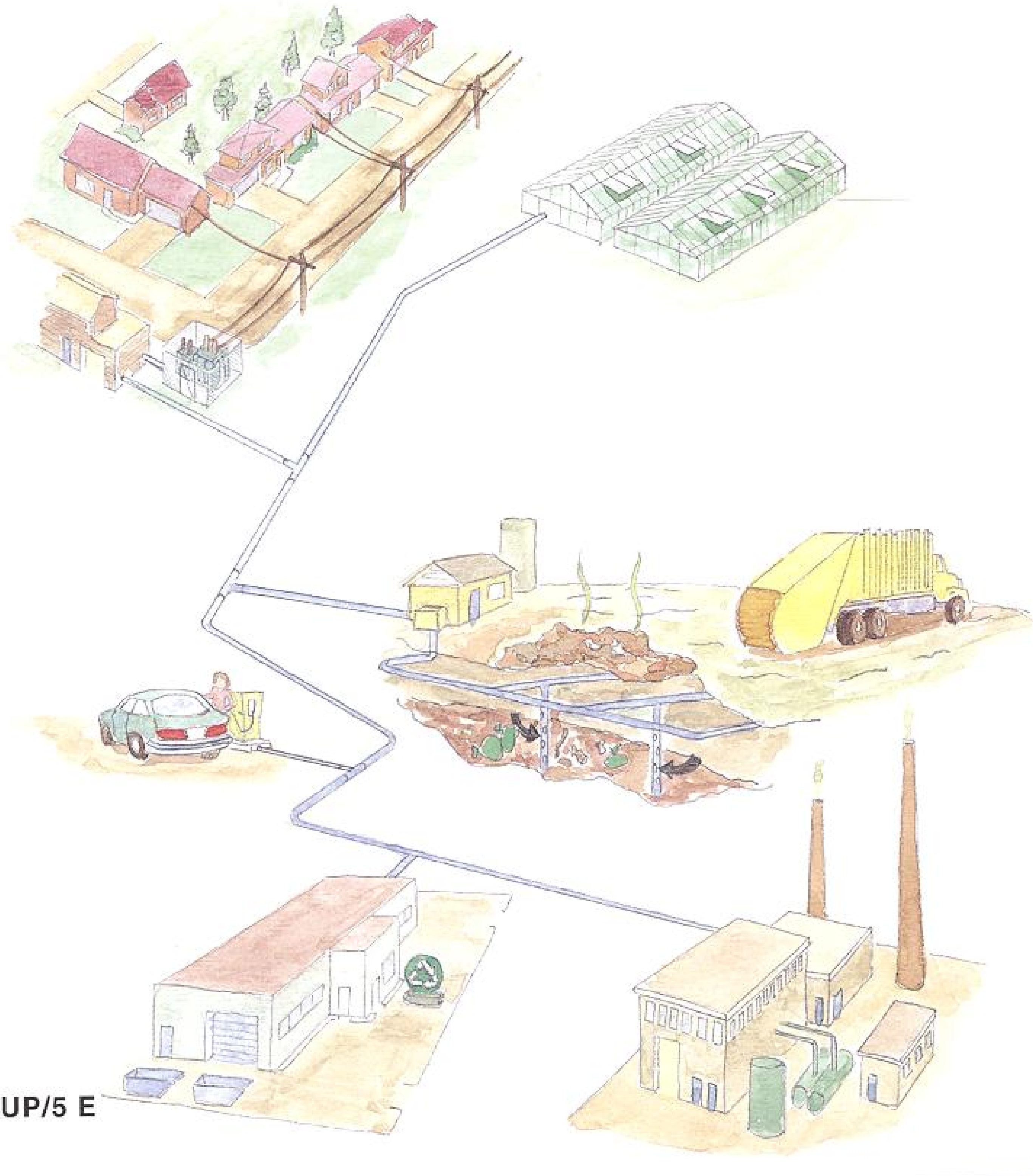
Guidance Document for Landfill Gas Management



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Hazardous Waste Branch | Direction des déchets dangereux

Canada

Guidance Document for Landfill Gas Management

By Conestoga-Rovers & Associates Limited
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Readers' Comments

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Review Notice

This report has been reviewed by members of the Hazardous Waste Branch, Environment Canada and approved for publication. Approval does not necessarily signify that the contents reflect the views and policies of Environment Canada. Mention of trade names or commercial products does not constitute recommendation or endorsement for use.

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Background to the Guide

Landfill gas is produced at landfill sites containing decomposable organic wastes. The major constituents of landfill gas are methane and carbon dioxide, which are by-products of the biological decomposition of organic material. Trace concentrations of a variety of other compounds may also be present in landfill gas. The trace compounds may include hydrogen sulphide, mercaptans and volatile organic compounds, which can create nuisance odours, degrade air quality and may have adverse health effects. The methane component of landfill gas is a potential energy resource, a potential explosion hazard and a greenhouse gas contributing to global warming.

Landfill gas is one of the major contributors of anthropogenic methane emissions to the atmosphere from Canadian sources. Landfill gas accounts for approximately 26 percent of the nation's total methane emissions (Environment Canada, March 1995). Methane is a greenhouse gas with a 100-year horizon global warming potential, that is, 24.5 times greater than carbon dioxide by weight (Intergovernmental Panel on Climate Change, 1994). In 1992, Canada was one of 150 countries to sign the Framework Convention on Climate Change at the United Nations Conference on Environment and Development. Canada has established the goal of stabilization of net emissions of greenhouse gases at 1990 levels by the year 2000.

The "Guidance Document for Landfill Gas Management", known as "The Guide", was prepared to encourage recovery of a greater proportion of the landfill gas generated at Canadian landfill sites. This document is one component of Canada's efforts to achieve the objective of controlling greenhouse gas emissions.

The Guide is designed to provide decision-makers with a basic understanding of and guidance concerning landfill gas, its potential impact, the need for controls, and the real environmental and economic benefits that may result from its collection and utilization. This document represents a compilation of information from a variety of sources, including academic literature; existing and proposed regulations, guidelines and standards; and the practical experiences of landfill site owners and operators, landfill gas developers, landfill engineers, and landfill equipment manufacturers. The Guide is a reference tool that covers the issues that relate to landfill gas and outlines a framework for developing an approach to effective landfill gas management.

The information in the Guide is presented in such manner as to encourage the reader to develop a general understanding of landfill gas issues, and then to determine whether there may be specific issues or opportunities relating to landfill gas at a specific site. The generation, composition and characteristics of landfill gas are briefly discussed. The potential impacts and hazards that may result from release of landfill gas into the environment, and human exposure to it, are then presented. Finally, the potential benefits of landfill gas collection and utilization as a resource are examined.

A straightforward method of characterizing landfill sites is presented, which takes into account many of the factors that contribute to the potential benefits and impacts of landfill gas. The site screening process requires a few site characteristics as input information, and is carried out by following four steps detailed in three charts. The outcome of the process is a better understanding of a particular site, and the magnitude and sensitivity of the potential landfill gas benefits and impacts. This allows the development of an action plan outlining the appropriate steps to be taken to address concerns or to make the best use of landfill gas as a resource.

The current status of government regulations, guidelines and standards pertaining to landfill gas in Canada are highlighted. These are compared with similar statutes in the United States and Europe. A wide variety of regulatory approaches is apparent. Where regulations exist, they are primarily concerned with controlling odours and air quality impacts, and eliminating the hazards posed by the migration of landfill gas.

The various methods that are available to assess the potential benefits and impacts of landfill gas are outlined. This includes a discussion of gas production modelling and estimating techniques. Migration and air quality monitoring and assessment are also presented.

Considerations for the design of landfill sites and engineered systems for control of emissions and migration are described. Recommendations are provided for design practices and parameters. Detail drawings and photographs of all of the major system components are included to illustrate equipment and applications. Cost guidelines are presented to allow for an understanding of the size and scope of landfill gas control systems and to aid in project planning and budgeting. Procedures pertaining to health and safety, and operation and maintenance of landfill gas control systems, are outlined.

The various methods of utilizing landfill gas as a resource are discussed. The advantages and disadvantages of each are presented and criteria for selecting the appropriate utilization method are defined. A generic plan for developing the landfill gas resource is presented, which includes, as its core, an approach to assessing the economic feasibility of the various utilization options. Cost guidelines for utilization systems are presented as an aid in determining their feasibility. The primary impediments to landfill gas utilization are related to their perceived risk due to a lack of knowledge of the potential resource, current low energy rates and limitations on access to markets.

Case studies of selected Canadian landfill gas control and utilization projects present a record of various experiences. In most cases, any technical problems encountered were overcome. Administrative difficulties such as permit requirements, zoning and market access agreements have adversely affected some landfill gas utilization projects, and in some cases resulted in significant delays. As the timeframe for landfill gas utilization is generally limited to 20 to 30 years immediately after filling, delays in initiation may affect the economic viability of the project. There are several Canadian landfills that are currently being considered as candidate sites for landfills utilization. There are many more sites where landfill gas utilization might be technically and economically feasible.

1.0 Introduction

1.1 Background

Landfill gas (LFG) is produced from the decomposition of wastes placed in a landfill. LFG is composed primarily of methane (CH_4), carbon dioxide (CO_2), trace levels of sulphur compounds and volatile organic compounds (VOCs). Methane and carbon dioxide are greenhouse gases. Methane is also potentially explosive. Sulphur compounds and VOCs contribute to odour and air quality concerns.

LFG is one of the major anthropogenic sources of methane emissions to the atmosphere in Canada, accounting for about 26 percent of the nation's total methane emissions (see Figure 1.1) (Environment Canada, March 1995). This estimate includes a reduction of about 15 percent for methane produced by landfills that is currently being collected and combusted. It is estimated that medium-sized landfills (2 to 8 million tonnes capacity) produce about 42 percent of the total methane emissions; large landfills (greater than 8 million tonnes capacity) produce about 30 percent, and small landfills (less than 2 million tonnes) produce about 28 percent (Hickling, 1994).

Recovery and utilization of LFG can contribute significantly to a reduction in greenhouse gas emissions. LFG utilization has also been well-established as a technically and economically viable endeavor at several locations across the country. Numerous small and large projects have been carried out in the United States, Europe and, to a lesser extent, Canada.

In 1992, Canada was one of 150 countries to sign the Framework Convention on Climate Change at the United Nations Conference on Environment and Development. Canada has established a national goal to stabilize net emissions of greenhouse gases at 1990 levels by the year 2000. Methane and carbon dioxide are both greenhouse gases, however, methane is the more potent of the two with a 100-year horizon global warming potential (GWP) 24.5 times that of carbon dioxide by weight (Intergovernmental Panel on Climate Change, 1994).

Controlling release of LFG to the atmosphere is an important component in Canada's approach to stabilizing emissions of greenhouse gases. This report, "Guidance Document for Landfill Gas Management", known as "The Guide", has been prepared to aid in achieving Canada's methane reduction goal. By providing a practical tool to educate and guide decision-makers, it encourages optimization of LFG management in Canada. Application of this guide and implementation of controls, where appropriate, will result in a reduction of the LFG component of greenhouse gas emissions and the mitigation of other impacts associated with LFG emission and migration. When economically feasible, utilization of the collected LFG can provide a source of revenue to fund these initiatives and may also provide a reasonable return on investment.

Uncontrolled release of LFG may result in environmental impacts and may also pose hazards to public health and safety. Owners and operators of landfills, regulatory agencies and the public are becoming more concerned about these potential impacts.

1.2 Objectives

When making decisions regarding LFG management and utilization issues, owners, operators, and regulators of Canadian landfills are faced with a number of questions.

These include the following:

- What are the concerns about LFG at this site?
- Which concerns warrant action?
- What are the current regulatory requirements?
- What is the most efficient course of action?
- What are the costs associated with addressing these concerns?
- Is it possible to recover some of those costs by utilizing LFG, and what are the risks associated with such a project?

The answers to these questions can be complex. Decision-makers often do not have the information available to answer them. The primary objective of this document is to bridge the information gap by providing the following:

- background information regarding the nature and potential impacts of LFG;
- a discussion of the various benefits of an effective LFG management program;
- a straightforward method for categorizing landfills based on potential LFG production rates and impacts;
- a description of the tools available to assess LFG production, migration and potential impacts;
- a review of the current regulatory status in Canada and elsewhere;
- a review of current practices for the design and operation of sites and landfill control systems that optimize LFG recovery;
- a review of options for utilization of LFG and a method to assess cost and feasibility; and
- a discussion of the experiences of Canadian landfill owners, operators and LFG utilization developers, and identification of barriers to LFG management.

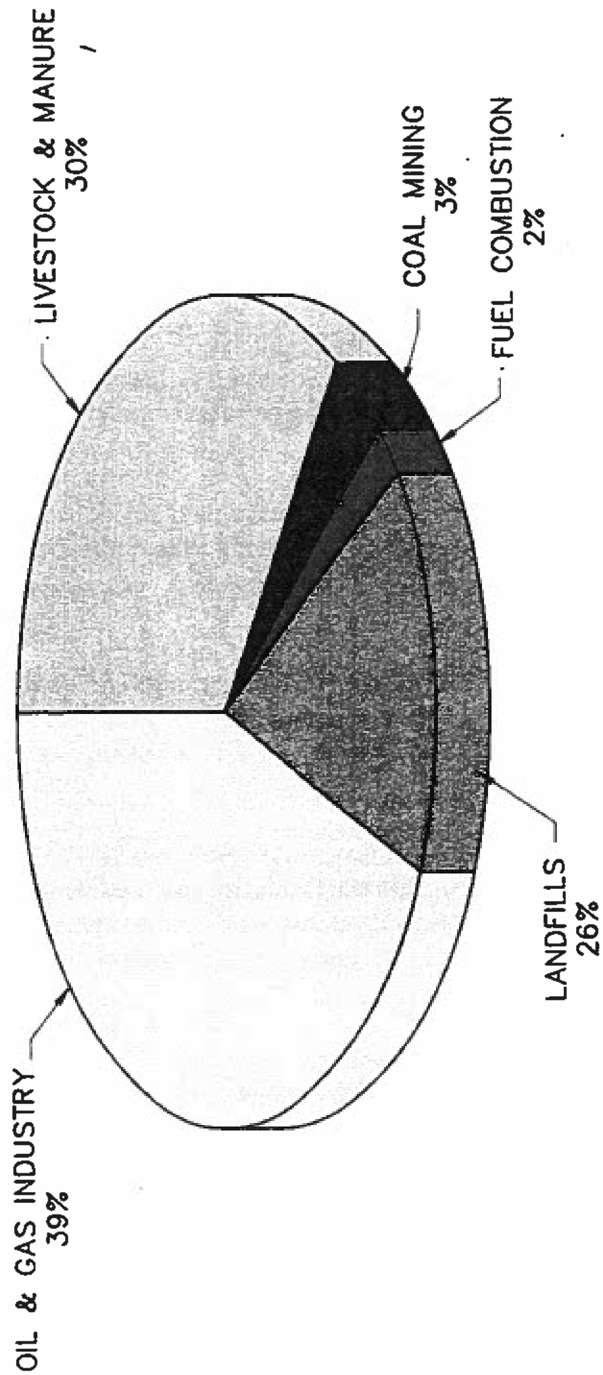


figure 1.1
METHANE EMISSIONS BY SOURCE

SOURCE:
ENVIRONMENT CANADA MARCH, 1995.

1.3 Organization and Use of the Guide

This Guide is intended to be used by landfill owners, operators, consultants and regulatory agencies. It provides the user with a guide to assessing, controlling and utilizing LFG.

Section 2.0 provides a brief introduction to LFG, its generation, control, potential impacts and the benefits of its utilization. A basic understanding of LFG, including its production mechanisms and its potential impacts, is required to determine the need to investigate the issue further.

Section 3.0 provides a preliminary screening approach to determine whether LFG assessment, control and utilization should be considered for a given landfill. The sites are characterized in a general manner to determine whether more detailed assessments are needed.

Section 4.0 provides an overview of the current status of regulations that are applicable to LFG. Review of the regulations, policies and guidelines pertaining to LFG in the various Canadian jurisdictions reveals a variety of approaches.

Procedures for LFG assessment are provided in Section 5.0. The section outlines current technologies for predicting LFG generation rates, assessing potential migration pathways and determining potential hazards and environmental impacts.

Design and installation procedures for passive and active gas control systems are described in Section 6.0. The section provides information regarding design and operational practices to optimize recovery of LFG. It includes typical designs for LFG system components and general design and construction guidelines.

LFG utilization is discussed in Section 7.0, which includes options for utilization, feasibility assessment, review of the economics and common impediments to development. LFG recovery and utilization is an established industry, and there are numerous projects that have been successfully implemented based on their economic viability.

A summary of the pertinent experiences of Canadian landfill owners, operators and LFG utilization developers is presented in Section 8.0, with the Canadian case details included in Appendix A. The cases included in the section and corresponding appendix were selected to provide a reasonable cross-section of geographical location, landfill size, LFG issues, types of control systems installed and utilization options.

Appendix B lists regulatory agencies and contacts. Appendix C provides useful mathematical data and conversions. Appendix D contains a list of abbreviations and a glossary of terms.

2.0 Landfill Gas

2.1 General

This section provides a general introduction to landfill gas (LFG) outlining its generation process, composition and characteristics, potential impacts, and potential benefits. Detailed information on the topic is available from a number of publications, which the reader is urged to review to develop a more thorough understanding of LFG and the factors affecting its generation and composition. Two recommended publications include:

- *Solid Waste Landfill Engineering and Design*, Prentice Hall by McBean, Rovers and Farquhar (1995); and
- *Methane Generation and Recovery from Landfills*, by Emcon Associates (1980).

2.2 Landfill Gas Generation

LFG is generated by anaerobic (without oxygen) decomposition of degradable organic wastes. The basic biological processes leading to the generation of methane from landfills have been well known for many years. The primary process of LFG production is the decomposition of cellulose by bacterial action according to the following simplified chemical reaction (Augenstein and Pacey, 1991):

$$\underset{\text{(cellulose)}}{n\,C_6H_{10}O} + \underset{\text{(water)}}{n\,H_2O} \rightarrow \underset{\text{(methane)}}{3n\,CH_4} + \underset{\text{(carbon dioxide)}}{3n\,CO_2}$$

Farquhar and Rovers (1973) defined the stages of decomposition of organic material in landfills. These definitions have been modified by Rees (1980) and Augenstein and Pacey (1991) and are presented in Figure 2.1.

The difficulty in predicting LFG generation is not to predict what will happen (since this is known) but rather to predict the rate, extent and timing of the reactions that will occur to produce LFG for a specific site. Modelling techniques for predicting LFG production are presented in Section 5.2.

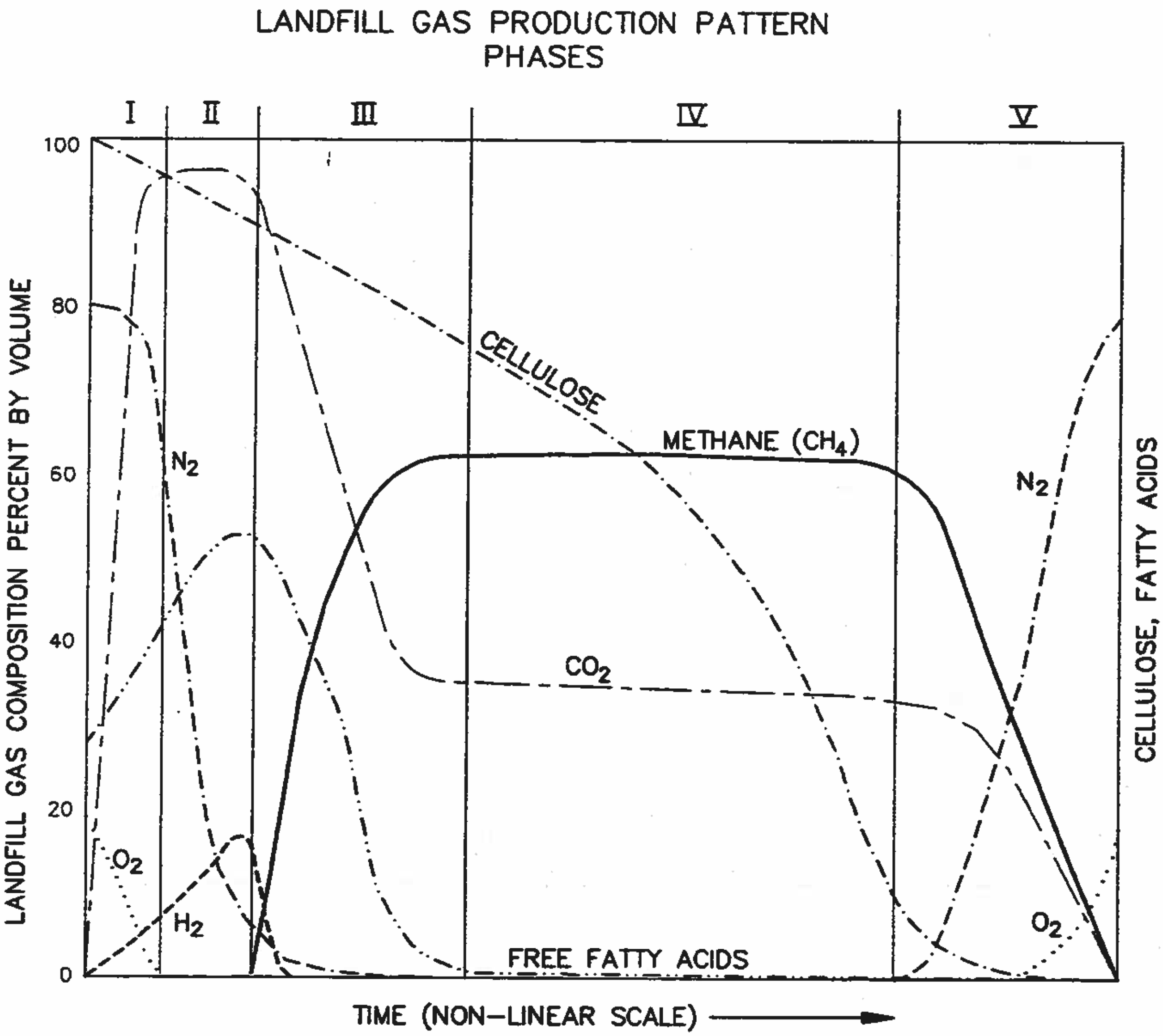
Two primary variables related to the prediction of LFG production include the following:

1. the total volume of LFG that will be produced for a given mass of refuse (referred to as total or ultimate yield); and

2. the time over which the LFG will be produced.

The variables related to LFG production are a function of many factors related to the physical, chemical and biological characteristics of a specific landfill. Some of these factors can be controlled or varied in order to manage or influence LFG production. Brief descriptions of some of the factors that affect the rate and yield of LFG production are provided below (from McBean *et al.* 1995, Environment Canada 1992, and Crutcher *et al.* 1988).

Waste Composition — This is probably the most important factor affecting LFG generation rates and yield. The total amount of LFG that can be generated from a unit mass of waste is dependent on the quantity and type of the organic content of the waste.



PHASES	CONDITION	TIME FRAME – TYPICAL
I	AEROBIC	HOURS TO WEEKS
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 2.1

TYPICAL LANDFILL GAS PRODUCTION PATTERNS

Moisture Content — The amount of moisture within a landfill is considered to be one of the most important parameters controlling gas generation rates. Moisture provides the aqueous environment necessary for gas production and also serves as a medium for transporting nutrients and bacteria. The moisture content in the landfill is strongly influenced by climatic conditions (temperature, rainfall, etc.), initial moisture content of the waste and specific landfill design such as type of base liner, type of leachate collection system, type of cover and programs such as rapid stabilization either with or without leachate recycling.

Temperature — The temperature within a landfill tends to be higher than ambient air temperatures since the anaerobic decomposition that occurs in landfills is an exothermic process, i.e. gives off heat. Temperature conditions within a landfill influence the type of bacteria that are predominant and the rate of gas production. The rate of decomposition, and gas production, decrease with decreasing temperature. Landfill temperature is influenced by the depth of the landfill. Where the landfill is deep, temperatures tend to equilibrate. Where a landfill is shallow (i.e. <12 m), temperatures are often more influenced by surface effects and weather conditions.

pH and Buffer Capacity — The pH of the waste and leachate significantly influences the rate of gas production. The generation of methane in landfills is greatest when neutral pH conditions exist.

Nutrients — Bacteria in a landfill require various nutrients for growth, primarily carbon, hydrogen, nitrogen and phosphorus. In general, municipal solid waste contains the nutrients necessary to support the decomposition process that generates methane gas. Numerous toxic materials, such as heavy metals, can retard bacterial growth in portions of a site and consequently slow gas production.

Refuse Density and Particle Size — The particle size and density of the waste influence gas generation by affecting the transport of nutrients and moisture throughout the landfill. Also, the smaller particle sizes of shredded refuse are believed to increase the rate of LFG production.

It is clear from the description of these factors that the rate and ultimate yield of LFG production is highly variable from site to site. Various workers have estimated that LFG may be produced at rates ranging from less than 0.003 m^3/kg/yr up to 0.040 m^3/kg/yr (McBean *et al.* 1995). Production of LFG may continue in excess of 50 years and can result in a total yield of LFG from 0.06 m^3/kg up to 0.53 m^3/kg.

2.3 Landfill Gas Composition

LFG consists primarily of carbon dioxide and methane. The proportions of these compounds vary over time and from landfill to landfill. For general purposes, LFG is often considered to consist of 50 percent carbon dioxide and 50 percent methane.

LFG also contains a number of trace constituents that are key to understanding potential LFG impacts and the benefits of implementing controls. Some of the trace compounds present are attributed not to the biological decomposition process but to chemical products and reactions within the wastes. These chemical products are a component in all landfill sites to varying degrees. The trace gas constituents and concentrations are dependent on the composition of the refuse which varies from landfill to landfill. Table 2.1 lists compounds that are commonly found at varying concentrations in LFG.

2.4 Potential Impacts

LFG, like leachate, is generated to some degree by all landfills. LFG moves from the waste through either the landfill cover or adjacent soil and eventually enters the atmosphere. Impacts of LFG are largely dependent upon the pathway by which the gas is exposed to humans or introduced into the environment.

Table 2.1 Landfill Gas Components

Compound	Typical Concentration
Primary	
Methane (CH_4)	30 to 60% (volume)
Carbon Dioxide (CO_2)	20 to 50% (volume)
Oxygen (O_2)	<2% (volume)
Nitrogen (N_2)	<10% (volume)
Moisture (H_2O)	Saturated
Trace Compounds (Total < ~4000 ppm)	
Hydrogen Sulphide	
Mercaptans	
Vinyl Chloride	
Hexane	
Toluene	
1,1,1-Trichloroethane	
Chloromethane	
Xylenes (m,p,o)	
Dichloromethane	
Trichlorofluoromethane	
cis 1,2 Dichloroethene	

Notes:

- This list represents trace constituents that are commonly found in LFG. Concentrations and compounds vary greatly from site to site.
- Assumes LFG production phase is at anaerobic, methanogenic steady stage.
- Low concentrations of oxygen and nitrogen may be present as a result of being entrained in the site or may be drawn into the site by active gas extraction.

Sources: CRA 1994; United States Environmental Protection Agency (USEPA) 1993; and Environment Canada 1995.

The generation and presence of LFG can result in a variety of adverse impacts, including emission of greenhouse gases, safety and health hazards, and nuisance effects such as odour. Each of these impacts have prompted the implementation of LFG control systems. Figure 2.2 provides a schematic illustration of the principle impacts that can occur as a result of LFG generation.

An inventory of 27 major landfill sites with active gas extraction systems that have been installed or are under construction in Canada up to December 1995 was carried out. The location and a brief description of these projects are shown on Figure 2.3 and Table 2.2, respectively. Approximately 80 percent of these systems have been implemented to control nuisance odours. Approximately 15 percent of the installations were completed to recover and use the gas for economic purposes. The remaining controls were installed to alleviate other hazardous situations. It should be noted that the collected LFG is used beneficially at over half of the landfills that installed controls to address odour issues. Further discussion of the principal adverse impacts from LFG is provided in the following text.

2.4.1 Creation of Nuisance Odours

Release of LFG into the air may contribute to odours in the vicinity of the landfill. LFG odours are caused primarily by the hydrogen sulfide and mercaptans (thiols) that are present in trace quantities in the gas. These compounds may be detected by sense of smell at very low concentrations (0.005 and 0.001 parts per million, respectively). Although hydrogen sulphide and mercaptons present health concerns at much higher exposure concentrations, their LFG impacts relate to nuisance odours. To date, the majority of Canadian LFG control systems have been installed to address nuisance odour issues. Odour can also be mitigated to some extent by use of suitable cover systems, but final cover cannot be considered a viable stand-alone measure except at small landfills. The greatest period of concern for nuisance odours is when the site is receiving wastes and final cover has not yet been installed.

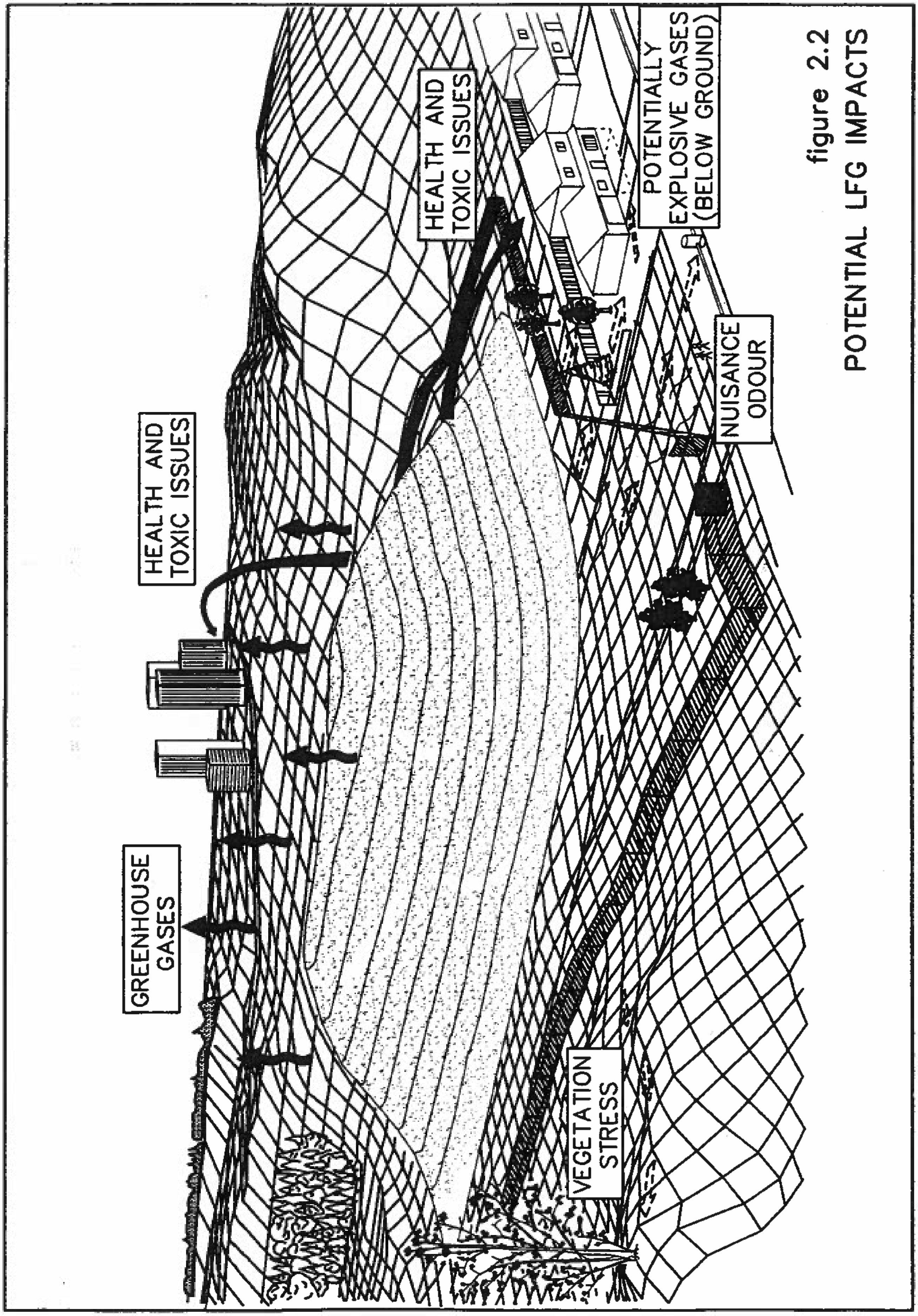


figure 2.2
POTENTIAL LFG IMPACTS

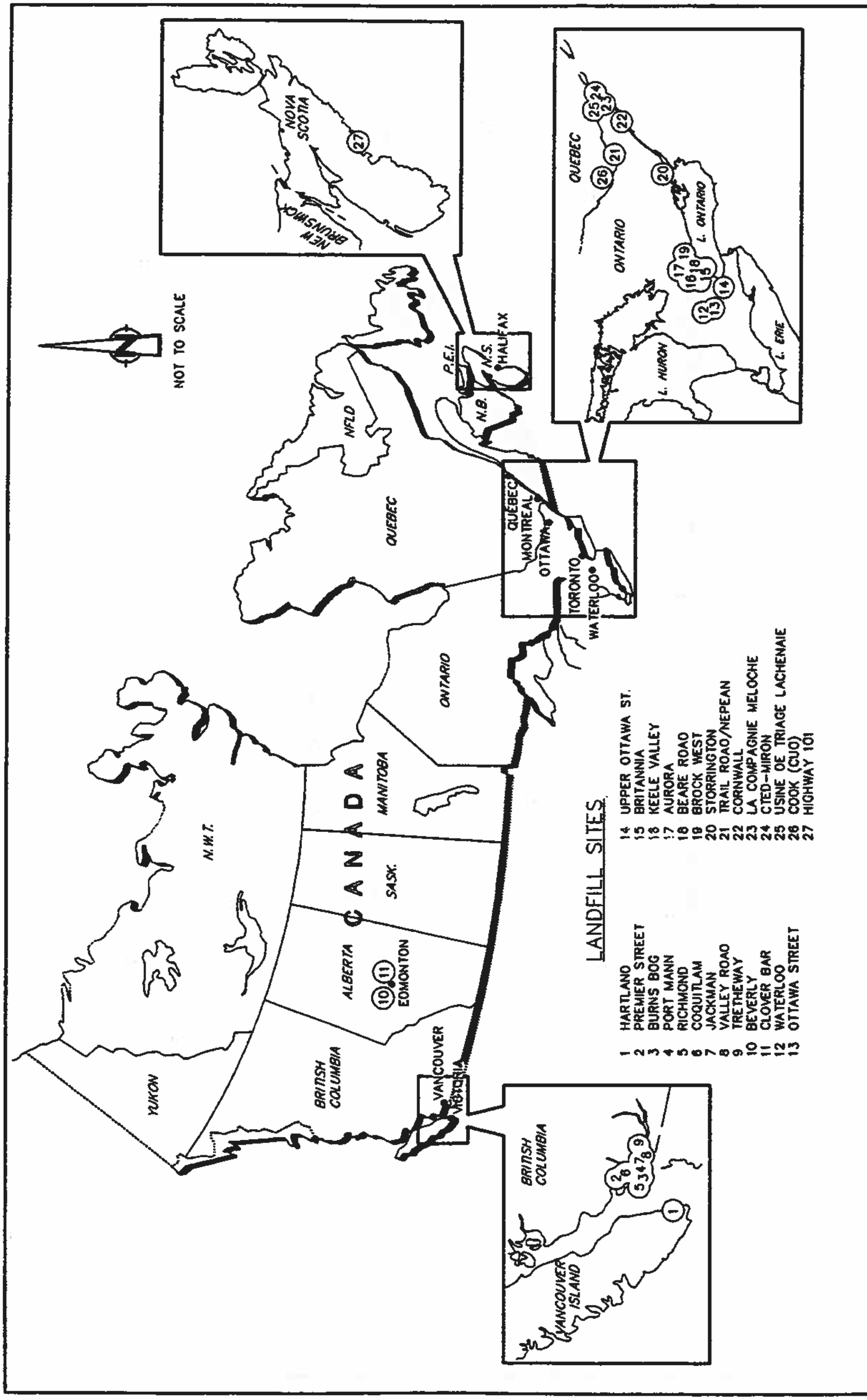


figure 2.3
MAJOR LANDFILLS WITH ACTIVE LANDFILL GAS EXTRACTION *

* INSTALLED OR UNDER CONSTRUCTION DECEMBER 1995

Table 2.2 Major Canadian Landfill Sites with Active Gas Extraction Systems Installed or Under Construction

	Landfill Name	Location	Filling Period	Capacity (million tonnes)	Gas Collection System: Type	Year Installed	Control Capacity (m^3/hr)	Utiliz-ation	Comments
1	Hartland	Victoria, B.C.	1954-1996	10.0	wells - flare	1991	1,880		utilization under consideration
2	Premier Street	North Vancouver, B.C.	closed in 1989	2.0	80 wells - flare	1983	1,360	X	system upgraded in 1989/90, operating at 850 m^3/hr, utilization and flaring
3	Burns Bog	Delta, B.C.	1966-active	30.0	wells - flare	1993	3,400	X	utilization and flaring
4	Port Mann	Surrey, B.C.	1968-1996	4.0	80 wells	1991	2,040	X	gas utilized by Domtar Gypsum
5	Richmond	Richmond, B.C.	closed in 1986	1.1	70 wells	1986	510	X	utilized at Lafarge Canada cement kiln
6	Coquitlam	Coquitlam, B.C.	closed in 1983	2.5	125 wells	1994	1,020	X	gas utilized at a paper recycling plant (Newstech De-inking)
7	Jackman	Langley, B.C.	closed in 1989	0.5	48 wells - flare	1993	425	X	greenhouse utilizes up to 340 m^3/hr
8	Valley Road	Matsqui, B.C.	1984-1990	0.5	30 wells - flare	1991	355	X	gas utilized for heat in winter (no flaring)
9	Tretheway	Matsqui, B.C.	closed	0.5	wells, flare and air curtain	1983	335	X	flare no longer operating, gas utilized to heat building
10	Beverly	Edmonton, Alt.	1968-72	2.0	wells - flare	1982			landfill is now a golf course
11	Clover Bar	Edmonton, Alt.	1975-active	14.0	wells	1992	3,000	X	utilization for electrical generation
12	Waterloo	Waterloo, Ont.	1973-2020	11.1	wells/trenches - flares	1995	4,800		utilization under consideration
13	Ottawa Street	Kitchener, Ont.	closed	–	perimeter and on-site wells - GAC			X	gas utilized from 1982-1994 at cement kiln, gas treatment/flaring
14	Upper Ottawa Street	Hamilton, Ont.	1950s-1980	1.4	wells - flare	1990	2,040		flaring system operated intermittently
15	Britannia	Mississauga, Ont.	active	9.5	collection from toe drain-flare	1995	3,400		
16	Keele Valley	Vaughan, Ont.	1983-2000	25.0	wells/trenches - flares	1986	20,390	X	future 20,390 capacity - utilization for electrical generation
17	Aurora	Aurora, Ont.	closed	2.0	wells - flare	1991	2,210		

Table 2.2 Major Canadian Landfill Sites with Active Gas Extraction Systems Installed or Under Construction (continued)

					Gas Collection System				
	Landfill Name	***Location***	***Filling Period***	***Capacity (million tonnes)***	***Type***	***Year Installed***	***Control Capacity (m^3/hr)***	***Utiliz-ation***	***Comments***
18	Beere Road	Scarborough, Ont.	closed	9.8	wells	1995	4,080	X	collection system for utilization only
19	Brock West	Pickering, Ont.	active	19.0	wells - flare	1986	20,390	X	utilization for electrical generation
20	Storrington	Kingston, Ont.	closed in 1991	1.0	wells - flare	1994	850		
21	Trail Road/Nepean	Nepean, Ont.	1980-active	8.8	wells - flare	1991	10,200		utilization under consideration
22	Cornwall	Cornwall, Ont.	1975-1988	2.3	wells - flare	1991	595		system operated intermittently
23	La compagnie Meloche	Kirklend, Que.	1980-1990	3.5	100 wells - flare	1990	7,645		planned utilization
24	CTED - Miron	Montreal, Que.	1968-active	33.0	280 wells - flare	1980	40,780		25 MW electrical utilization to commence Spring 1996
25	Usine de triage Lachenaie	Lachenaie, Que.	active	3.6	> 80 wells - flare	1995	8,495	X	utilization - 4 MW electrical
26	Cook (CUO)	Aylmer, Que.	1975-1991	1.6	flare	1994	2,500		flaring only
27	Highway 101	Sackville, N.S.	1977-1996	4.0	perimeter wells	1994	680		utilization under consideration

2.4.2 Release of Greenhouse Gases to the Atmosphere

Global warming is thought to be caused by increases in atmospheric concentrations of greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons (CFCs), nitrous oxide (N_2O), water vapour and non-methane hydrocarbons. These gases are normally present in the atmosphere and serve as a "thermal blanket" for the Earth. Greenhouse gases allow solar radiation to pass through the atmosphere while absorbing a portion of the infrared radiation that is emitted back from the Earth's surface (see Figure 2.4). The absorption of radiation warms the atmosphere to regulate the climate. The earth would be about 30°C colder without the presence of the greenhouse gases (Government of Canada, Canada's National Report on Climate Change, 1994).

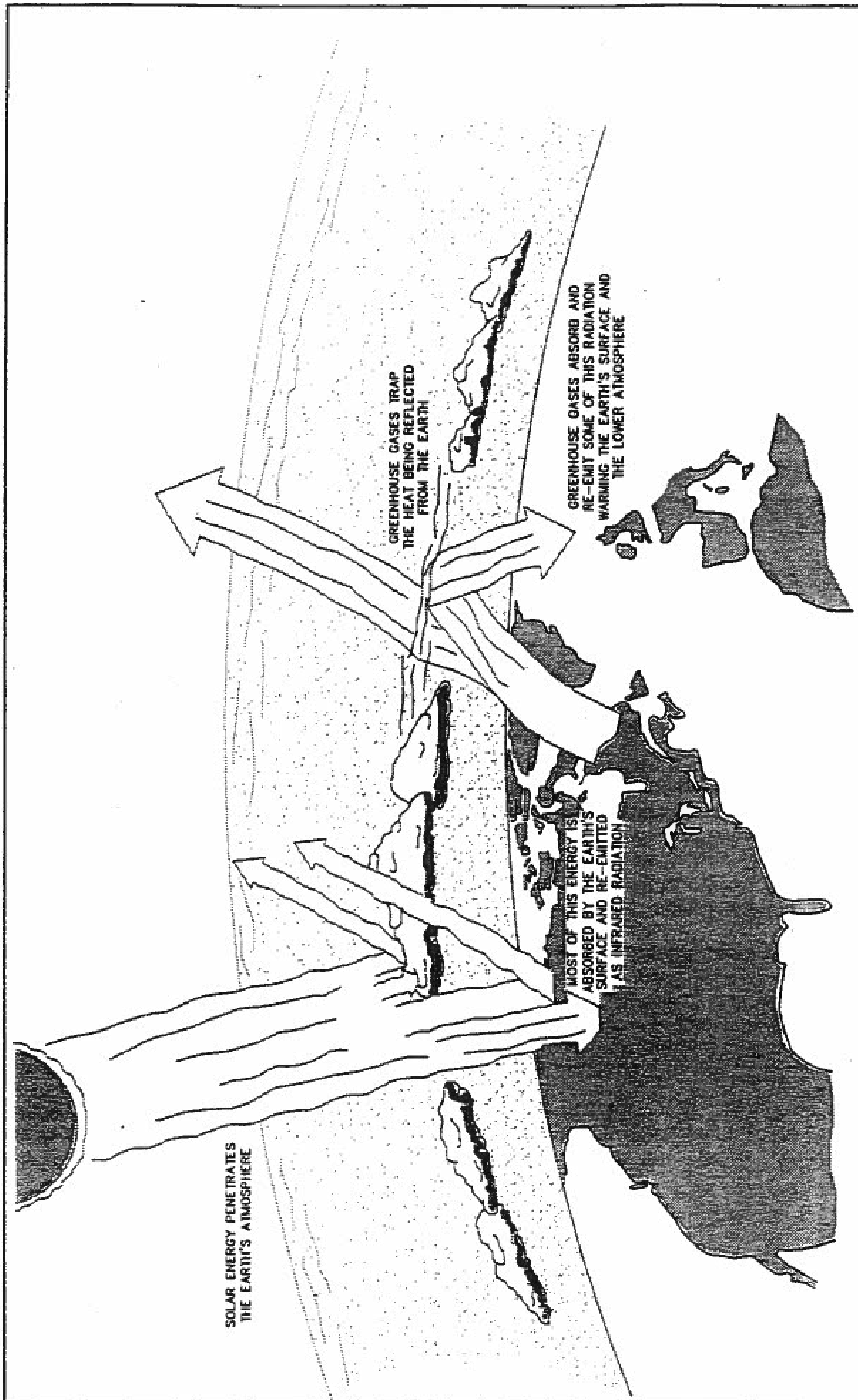
LFG emission is a major source of anthropogenic CH_4, accounting for 4-15 percent of the global atmospheric CH_4 budget (Thorneloe, 1991). Methane is a more "powerful" greenhouse gas than CO_2 because of its inherent radiative characteristics as well as the effects it has on other atmospheric molecules. Each unit mass of CH_4 has about 24.5 times more potential warming effect than each unit mass of CO_2. On a global basis, atmospheric CH_4 is increasing at about 1 percent per year and atmospheric CO_2 is increasing at about 0.4 percent per year. Methane is thought to be responsible for approximately 20 percent of the current increase in global warming (Thorneloe and Peer, 1990). The primary source of man-made carbon dioxide is the combustion of fossil fuels (Environment Canada, 1992).

2.4.3 Health Issues and Toxic Effects

LFG may create suffocating or toxic conditions. Inundation of a confined space by LFG will displace the available oxygen in that area, creating an oxygen deficient atmosphere. Health effects are generally associated with the trace gases found within the LFG, such as vinyl chloride and hydrogen sulfide. Some of the trace compounds in LFG are toxic at sufficient exposure concentrations and some compounds are considered carcinogenic over long-term exposure.

2.4.4 Explosions

Risk of explosion occurs when the concentration of methane in the air exceeds its lower explosive limit. The lower explosive limit of methane is approximately 5 percent by volume in air, hence only a small proportion of LFG, which contains 50 percent by volume methane is required to create an explosive condition. The risk of explosion is also associated with confined spaces that have limited ventilation. LFG explosions have occurred in structures on or near landfill sites. These occurrences are generally attributed to LFG migrating through the soil and accumulating within structures. An explosion can occur when explosive concentrations of LFG exist in a confined area in the presence of a source of ignition. It is very important to note that LFG can be lighter or heavier than air depending upon the proportions of the gases that may be present. It is also important to note that an older site may still pose a significant LFG migration hazard. The quantity of gas produced begins to decline shortly after site closure, however, the general gas composition remains essentially the same except for a reduction in volatile organic compounds (VOCs). As migration is strongly influenced by the physical setting of the site, hazards may still be present well into the declining phases of gas production.



SOURCE:
CANADA'S NATIONAL REPORT ON
CLIMATE CHANGE, 1994.

figure 2.4
GREENHOUSE PHENOMENON

2.4.5 Vegetation Stress

Vegetation stress is a sign of LFG migration through the subsurface and occurs because plant roots are deprived of oxygen. Deterioration of vegetation on and near landfills may be both an aesthetic and a practical problem. In areas where vegetative cover is diminished, erosion of the cover may occur. This may lead to a "cascade" effect resulting in increased LFG emissions.

Vegetation stress alone is generally not sufficient cause to implement LFG controls. It is, however, an indication of significant LFG migration in the subsurface, which may lead to other problems. Potential LFG impact to vegetation is also a concern when selecting cover vegetation and final landscaping of the closed landfill.

2.5 Potential Benefits

The primary benefits of recovering LFG are the control of potential adverse impacts and the reduction of liability for the site owner. Numerous LFG control projects indicate that nuisance odours, explosion and toxic hazards can be effectively mitigated by implementing LFG recovery systems. Proven methods for controlling LFG are presented in more detail in Section 6.0.

LFG has numerous beneficial uses that stem primarily from the energy content of its methane component. Many of the technologies for utilization of LFG are now well established and have proven to be economically feasible given suitable site conditions and access to markets. The most common uses that have been implemented to date include the following:

- electrical power generation
- direct use as fuel
- pipeline gas supplement
- synthesizing of products such as methanol

Utilization of LFG to produce energy has the added benefit of offsetting consumption of fossil fuels that would be required to produce an equivalent amount of energy. LFG is a relatively "clean burning" fuel when compared to most other fuels. It has been estimated that as much as 90 megawatts (MW) of electricity could be produced by the utilization of a reasonable portion of the LFG generated by Ontario landfills alone (MacViro, 1991). The offset in coal consumption to produce an equivalent quantity of power would result in a reduction of greenhouse gas emissions equivalent to 1.2 million tonnes of carbon dioxide per year (MacViro, 1991).

Where economically feasible, LFG utilization will generate revenue to offset some or all of the costs of environmental landfill controls. LFG recovery and utilization systems have been installed or are currently under construction at the 27 Canadian sites listed in Table 2.2.

Reduction of LFG emissions to the atmosphere is one of the many strategies available to reduce climate change. Reducing global methane emissions by 15-20 percent would stabilize methane in the atmosphere at current levels (Thorneloe and Peer, 1990).

3.0 Preliminary Site Characterization

3.1 General

This section outlines a straightforward method for characterizing landfill sites, which is intended as a preliminary step to gauging sensitivity of landfill gas issues and potential impacts. The preliminary site characterization process is intended to provide a screening tool to assist in the evaluation of the site and the need for any follow-up actions.

It should be recognized that the impacts due to LFG can be assessed only with site-specific information. This characterization process is not intended to act as a substitute for detailed site investigations or assessments. Rather, the process serves as a triggering mechanism to indicate that further evaluation and investigation are appropriate. While every effort has been made to make this characterization system conservative, in all cases regulatory requirements take precedence. The preliminary site characterization is also intended to assist the decision-maker in planning and developing work programs and budgets.

The four primary reasons for implementing LFG controls are:

1. to mitigate health hazards
2. to mitigate environmental impacts
3. to address nuisance odours
4. to generate revenue by utilizing the gas

Regulations governing LFG management, if they are in place in the province or territory, are defined to address the first two reasons. In all cases, applicable regulations and guidelines, either now or in the future, may require specific action within the jurisdiction of the regulations. For example, this could take the form of a requirement to have active LFG control for a site above a certain size or capacity range regardless of its LFG production potential. If this is the case, the decision-maker can still use this screening process to better understand the urgency and best method of approaching and satisfying the regulatory requirements.

There are numerous factors that influence the magnitude of these potential impacts or benefits. This preliminary site characterization will define the factors that typically have the greatest influence on each of these impacts or benefits including:

1. LFG production potential
2. distance to potential receptors for gas emitted into the atmosphere
3. the potential for subsurface migration of LFG into structures

Charts are provided which classify a landfill site based on each of these factors. The classifications are then used to determine the appropriate or suggested course of action. This characterization system is intended only as the initial step in evaluating potential LFG issues.

The system of site characterization is based on use of existing, accepted models for estimating LFG impacts. To estimate LFG production rates for various sizes of sites, a first order decay model United States Environmental Protection Agency (USEPA, 1994) was employed. The following conservative input values were used:

- 20-year filling period
- total LFG yield = 0.340 m^3/kg (USEPA, March 1994)
- gas generation rate constants
  - 0.02/yr for dry sites
  - 0.07/yr for wet sites

To evaluate the subsurface LFG migration hazard, a number of runs were carried out using a two dimensional finite element model (Metcalf *et al.*, 1987). Representative physical parameters for the different soil types evaluated were applied. The following conservative assumptions were applied to the migration model runs:

- frost cover is present 120 days per year
- source pressure is +5 inches water column
- source methane concentration is 50 percent by volume

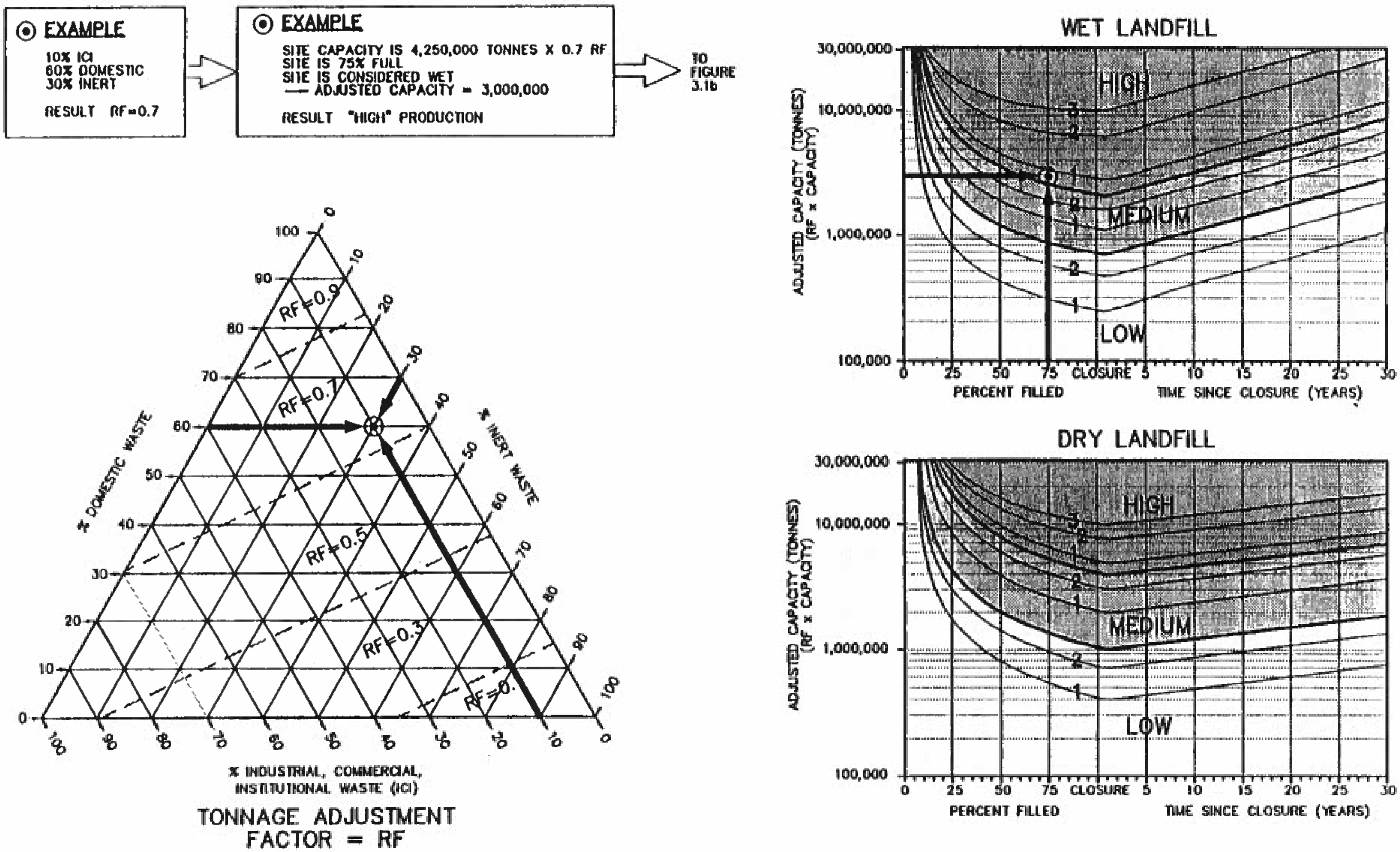
To estimate air quality impacts a Gaussian dispersion model was applied. Conservative assumptions regarding meteorology were made. Emission rates were based on the LFG production estimates shown in Figure 3.1a.

Guidelines for the development of recommended action plans based on the preliminary site characterization are described. Section 3.6 gives an example and step by step instructions for the preliminary site characterization process. The site characterization is applicable to existing as well as future conditions at a site.

3.2 Landfill Gas Production Potential

For the purpose of an initial site characterization, 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 odour complaints and hazardous situations. In general, the more gas that is produced, the higher the likelihood that health, safety and odour nuisance issues will be raised, and that a potential for economically feasible LFG utilization exists. (Refer to Section 2.)

Figure 3.1a provides a method of characterizing 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 that will not produce gas, and the proportion of industrial/commercial/institutional (ICI) wastes in the landfill that will produce less gas than typical domestic wastes. The adjustment factor is determined from the triangle diagram shown in Figure 3.1a based on the proportion of waste types that are in place or will be accepted at the landfill. The landfill capacity is multiplied by the tonnage adjustment factor to determine the adjusted site capacity.



NOTE

A CANADIAN 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.

STEP 1
LFG PRODUCTION

figure 3.1 a)
CANADIAN LFG SITE CHARACTERIZATION

SOURCE: CONESTOGA-ROVERS & ASSOCIATES LIMITED

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 base or natural liner. These factors are explained in detail in Section 2. Most Canadian landfills are considered to be relatively wet. This is a function of the amount of precipitation that infiltrates into the waste mass. A conservative approach to classifying a site as wet or dry is to assume that the site is wet unless it is covered by an impermeable cap and has no moisture addition, or it is located in an area that receives less than 635 mm of precipitation annually. A landfill where a significant portion of the wastes are located within a groundwater/leachate mound should also be considered a wet site.

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, i.e. new, open or closed.

LFG production is determined by the intersection of the adjusted site capacity and the current filling status. LFG production is categorized as "high", "medium" or "low". The gradation of production within the category should be noted. 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 3.1a demonstrates that a site's LFG production increases as it is filled and then slowly declines after site closure .

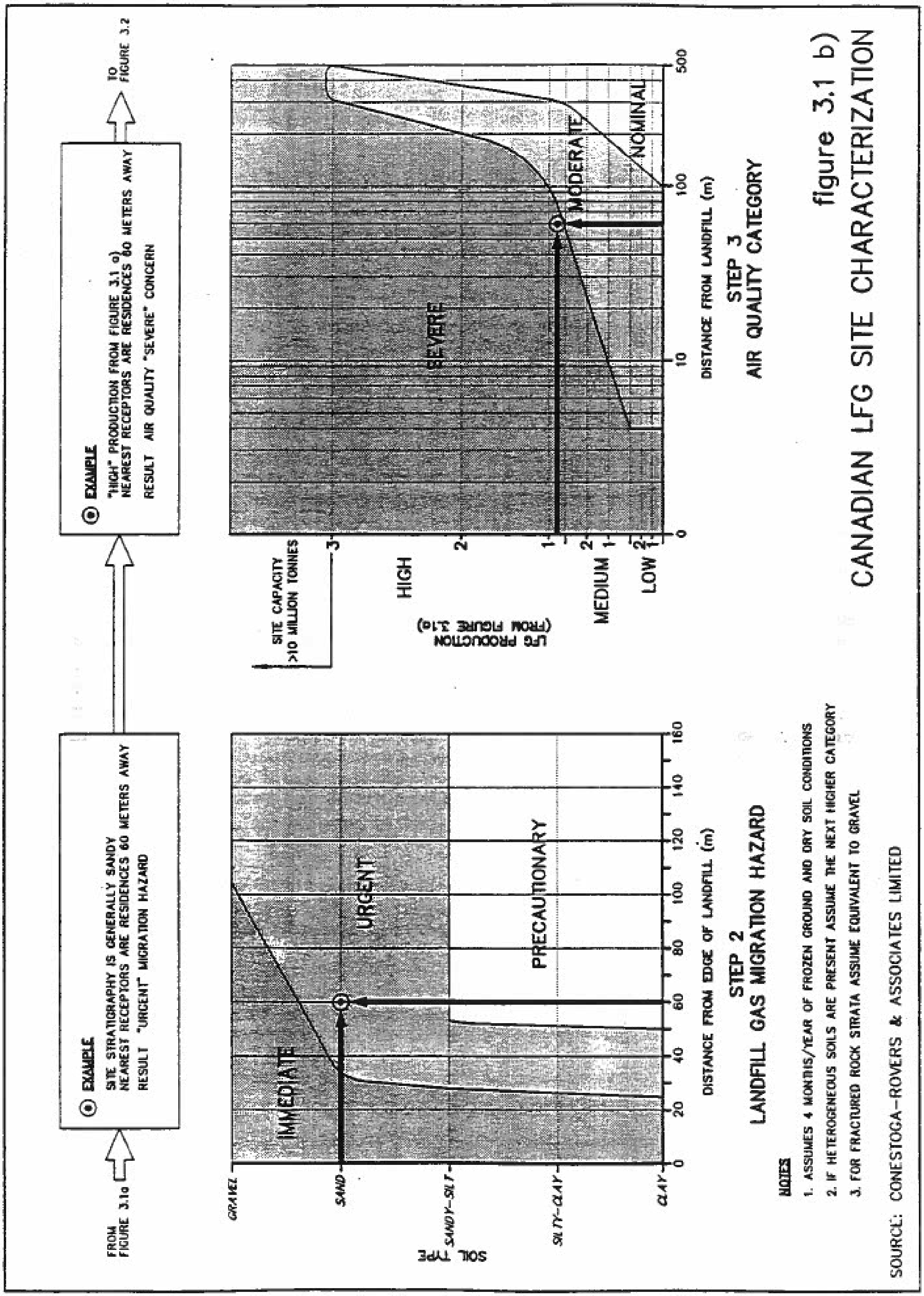
3.3 Subsurface Migration Hazard

The second step is to determine the gas migration hazard. The primary factors that influence the distance gas migrates from the wastes 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 gas flow. As the water content increases, the gas permeability decreases. To be conservative, the chart shown in Figure 3.1b assumes dry soil conditions.

The type of ground surface cover affects the quantity of gas 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. The classification chart assumes that the ground surface was frozen for four months of each year.

Other factors influence the potential migration distance. A landfill liner will greatly reduce the potential for subsurface migration. The presence of heterogeneous soils around the site or sewers and conduits will increase the potential migration distance along those corridors. Gas may migrate a significant distance from the landfill in sewers or sewer bedding. These factors are not included in this generic classification but should be considered when evaluating the potential for subsurface migration from a site. For sites in heterogeneous soils or sites with underground utility services near the wastes, it is recommended that a higher potential for LFG migration hazards be assumed.

The left axis of the migration hazard chart on Figure 3.1b represents the type of soil surrounding the landfill. The bottom axis shows the distance from the edge of the landfill to the nearest structure. The LFG migration hazard point is located at the intersection of the soil type and the distance to the nearest structure. The LFG migration hazard is defined as "immediate", "urgent" or "precautionary". The actions to be taken are in accordance with the level of urgency conveyed by these terms.



NOTES
1. ASSUMES 4 MONTHS/YEAR OF FROZEN GROUND AND DRY SOIL CONDITIONS
2. IF HETEROGENEOUS SOILS ARE PRESENT ASSUME THE NEXT HIGHER CATEGORY
3. FOR FRACTURED ROCK STRATA ASSUME EQUIVALENT TO GRAVEL

SOURCE: CONESTOGA-ROVERS & ASSOCIATES LIMITED

figure 3.1 b)
CANADIAN LFG SITE CHARACTERIZATION

3.4 Air Quality

Step 3 categorizes the site based on the potential for air quality impacts. The primary determinants of air quality impacts are the quantity of LFG emitted to the atmosphere, the proximity of the receptor to the site and meteorological conditions. The model that was used to develop the air quality chart on Figure 3.1b, assumes meteorological conditions that tend to result in greater air impacts. This is therefore considered a conservative approach.

The gas production category from Figure 3.1a, and gradation within that category, is used to categorize air impacts. The gas production category and gradation are located on the left axis of the air quality chart. The distance from the edge of the landfill to the location of receptors is located on the bottom axis of the chart. The level of concern for air quality is defined by the intersection of the gas production category gradation and the distance that the receptor is from the landfill. Air quality concern is defined by the three terms "severe", "moderate", and "nominal", with "severe" considered the highest level of concern and "nominal" the lowest.

3.5 Landfill Site Classification

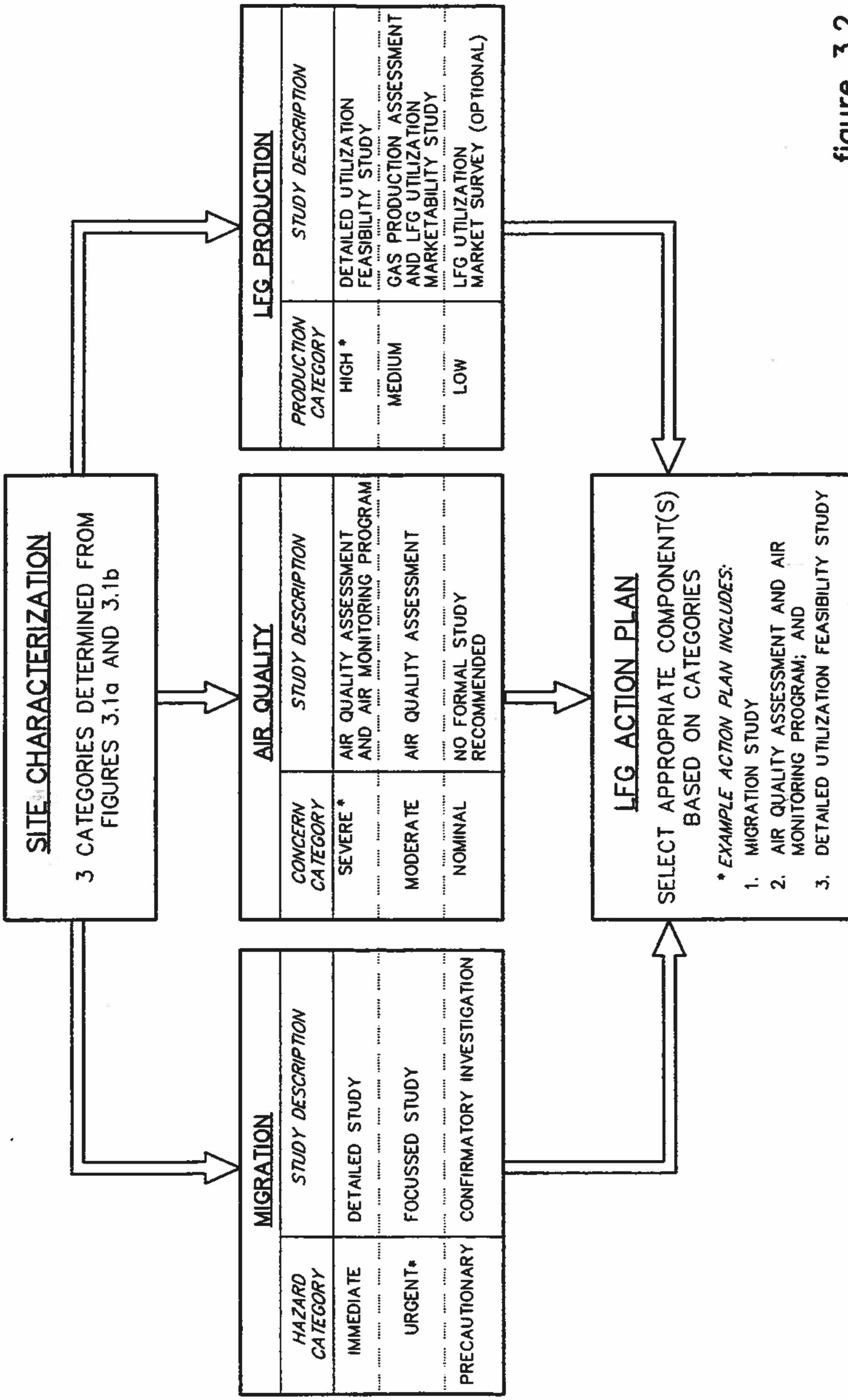
The end result of following the three steps outlined above is to determine the site categories for gas production (high, medium, low), LFG migration (immediate, urgent, precautionary), and air quality (severe, moderate, nominal). These categories are then referenced to Figure 3.2 to determine the appropriate actions to be included in the design of a LFG action plan.

A migration assessment should be selected as a component of the action plan. The scope of the migration assessment may include: 1) a detailed study of the entire site and surrounding lands; 2) a focussed study targetting specific areas around the site; or 3) a confirmatory study to check the soil adjacent to specific buildings. The study that is carried out is dependent upon the defined migration hazard category. Section 5.3 describes methods of conducting migration assessments.

An air quality study may be a component of the LFG action plan. The air quality assessment may consist of air quality modelling alone or air quality modelling combined with an air monitoring program. The air quality assessment that is carried out is dependent upon the air quality concern defined for the site. For sites where the air quality concern level is nominal, no formal air quality study is recommended. If such a site had an odour problem in the past, it would be recommended to upgrade the level of study to an air quality assessment. Methods for carrying out air quality modelling and monitoring are described in Sections 5.7 and 5.8.

The action plan may include a study to consider the possibility of LFG utilization. Consideration of utilization may consist of conducting a site gas assessment and marketability study, or carrying out a detailed feasibility study. The level of effort that is applied to consideration of utilization is dependent upon the gas production category that is defined. For a site with low gas production potential, an optional market survey is indicated. This could include a former survey of all potential users within the area or an informal check for nearby LFG utilization opportunities. It is recommended that at least an informal examination of possible utilization opportunities be conducted. As demonstrated by the case studies, there are numerous sites where innovative approaches have resulted in a beneficial use of the gas that would otherwise have been wasted. The components of utilization studies are discussed in Section 7.5.

The action plans are designed to further define site conditions to allow decision making regarding the next appropriate steps. Within the action plans are differing levels of activity varying from no further action to conducting detailed assessments and field investigations.



* FROM EXAMPLE IN FIGURES 3.1a AND 3.1b

figure 3.2
ACTION PLAN SELECTION
PRELIMINARY SITE CHARACTERIZATION

3.6 Example Site

The following parameters are assumed for an example site characterization which is demonstrated in Figures 3.1a, 3.1b and 3.2:

Design capacity	=	4,250,000 tonnes
Filling status	=	75 percent filled
Moisture content	=	Sand cover (permeable) ∴ wet
Waste composition	=	10 percent industrial commercial institutional (ICI) 60 percent domestic (municipal) 30 percent inert (construction waste, rubble, soil, etc.)
Surrounding soil	=	Sand
Distance to nearest structure	=	60 metres (residence)
Distance to nearest receptor	=	60 metres (residence)

Step 1 (Figure 3.1a)

- Determine tonnage adjustment factor using triangular chart and waste composition. RF = 0.7
- Calculate adjusted capacity. Design Capacity × RF = 4,250,000 × 0.7 = 3,000,000T.
- On wet landfill chart, locate 3,000,000 tonnes on left axis and 75 percent filled on bottom axis. LFG production is "**high**", within the first gradation.

Step 2 (Figure 3.1b)

- On the LFG migration hazard chart, locate "soil type = sand" on left axis and "distance to nearest structure (60 m)" on bottom axis. LFG migration hazard is "**urgent**".

Step 3 (Figure 3.1b)

- On air quality category chart locate the gas production below the first gradation of the "**high**" category on the left axis. Note this gas production classification was determined in Step 1. Locate the distance from the landfill to the nearest receptor on the bottom axis. The air quality concern is "**severe**".

Step 4 (Figure 3.2)

- From the previous steps:
  - LFG production is "**high**"
  - migration hazard is "**urgent**"
  - air quality category is "**severe**"
- Select an action plan which includes:
  - a LFG migration study focussed to identify specific areas of concern
  - an air quality assessment and an air monitoring program
  - a detailed assessment of the feasibility of LFG utilization

4.0 Landfill Gas Regulatory Status

The following describes the current status of various Canadian federal and provincial regulations and guidelines pertaining to landfill gas (LFG) management. For the purpose of comparison, current American and European regulations and guidelines are reviewed.

It should be recognized that these regulations and guidelines are in a state of flux. As technical understanding improves, the guidelines are updated accordingly. As an example, the default parameters defined in Tier 1 of the United States Environmental Protection Agency's (USEPA's) New Source Performance Standards for municipal solid waste (MSW) landfills are currently in the process of being revised to reflect a better understanding of the LFG production process and the potential impacts of LFG. It is expected that an additional 400 sites will require controls. Many other jurisdictions follow the regulatory lead established by the USEPA.

This document is intended as a general guide to good LFG management techniques, and is independent of any local regulations or guidelines. Where regulations exist, they are primarily concerned with addressing local impacts such as odour, air quality and migration of gas in the soil. In all cases, governing regulations and guidelines supplement or take precedence over the practices described herein.

4.1 Canadian Guidelines and Standards Relating to Landfill Gas Management

Few provinces have regulations, guidelines or standards relating directly to LFG control, though many provinces are currently working to develop these guidelines. In the absence of landfill-specific legislation, LFG issues are dealt with under more general legislation such as provincial acts and regulations relating to environmental protection, water quality, air quality and waste management. Further, allowable air emissions from a source may be governed by conditions imposed in a permit. Table 4.1 provides an overview of regulations and guidelines potentially relevant to LFG, for each province and territory, and federally. Jurisdictions that do not have guidelines or regulations relating directly to LFG include the provinces of Alberta, Saskatchewan, Manitoba, New Brunswick, Nova Scotia, Prince Edward Island, Newfoundland, Yukon, Northwest Territories and the federal government. LFG issues are dealt with under general environmental, air quality, or waste management regulations.

The provinces of British Columbia, Ontario and Quebec have, in addition to general environmental protection regulations, guidelines and criteria relating specifically to LFG controls. Excerpts from these regulations and guidelines are provided in the following text.

Table 4.1 Provincial Guidelines, Regulations and Standards Relating to Landfill Gas

Province	Regulations/Policies/ Guidelines Relating Indirectly to Landfill Gas	Regulations/Policies/ Guidelines Relating Directly to Landfill Gas
Alberta	• Environmental Protection and Enhancement Act • Alberta Ambient Air Quality Guidelines • Wastewater and Storm Drainage Regulation, Environmental Protection and Enhancement Act • Waste Disposal for Small Communities • Waste Management Regulation, Public Health Act	
British Columbia	• Waste Management Act	• Landfill Criteria for Municipal Solid Waste, June 1993
Manitoba	• The Environment Act • Guidelines for Various Air Pollutants — Atmospheric Emission Criteria • Guidelines for the Siting of a Class 1 Waste Disposal Ground in Manitoba • Guidelines for the Siting of Class 2 and Class 3 Waste Disposal Ground in Manitoba • Waste Disposal Grounds Regulation (MR 150/91)	
New Brunswick	• Water Quality Regulation, Clean Environment Act • Air Quality Regulation, Clean Environment Act • Site Selection Guidelines for Municipal and Industrial Sanitary Landfills	
Newfoundland	• Air Pollution Control Regulations, Department of Consumer Affairs and the Environment • Waste Material Disposal Act	
Northwest Territories	• Environmental Act • Guidelines for the Planning, Design, Operation and Maintenance of Solid Waste Modified Landfill Sites in the Northwest Territories, March 1990	
Nova Scotia	• Waste Disposal Site Regulation, Environmental Protection Act	
Ontario	• Waste Management Regulation, Environmental Protection Act • Air Pollution Regulation, Environmental Protection Act	• Guidance Manual for Landfill Sites Receiving Municipal Waste, November 1993 • Guidelines for Assessing Methane Hazards from Landfill Sites, November 1987 • Interim Guide to Estimate and Assess Landfill Air Impacts, October 1992
Prince Edward Island	• Environmental Protection Act • Air Quality Regulations, Environmental Protection Act	
Québec	• Environment Quality Act • Quality of the Atmosphere Regulation • Hazardous Waste Regulation	• Projet de règlement sur les déchets solides, version technique, mars 1994. • Solid Waste Regulation • Le biogaz généré par les lieux d'enfouissement sanitaire, 1993

Table 4.1 Provincial Guidelines, Regulations and Standards Relating to Landfill Gas (continued)

Province	Regulations/Policies/ Guidelines Relating Indirectly to Landfill Gas	Regulations/Policies/ Guidelines Relating Directly to Landfill Gas
Saskatchewan	• Clean Air Act • Environmental Management and Protection Act • Municipal Refuse Management Regulation, Environmental Management and Protection Act • Refuse Disposal Guidelines for Small Communities, November 1989	
Yukon	• Environment Act • Interim Solid Waste Management Procedures and Guidelines, August 1990	
Canada	• Canada Water Act • Ambient Air Quality Objectives, Clean Air Act	

British Columbia

"Landfill Criteria for Municipal Solid Waste, June 1993" provides criteria which are to be incorporated into permits, waste management plans and operational certificates. This document provides a comprehensive set of standards relating to LFG control and monitoring, some of which follow:

- Section 4.2 — *LFG Management and Odour Nuisance* requires an assessment of LFG emission potential to determine the need for collection and management of these gases. Non-methane organic compounds are the preferred indicator in conducting the assessment and subsequent management of LFG. At those sites where limited volumes of LFG are generated, an assessment must still be undertaken to determine the need for passive LFG venting. Air quality criteria guidelines must not be exceeded, nor may a public odour nuisance be created.
- Section 6.4 — *Gas Venting or Recovery and Management Systems* states that LFG recovery and management systems are mandatory on landfills exceeding 100,000 tonnes and emitting over 150 tonnes per year of non-methane organic compounds as determined by using the USEPA gas emission rate model (see Section 4.2). Utilization for energy recovery is the preferred method of handling collected gases. Incineration and flaring, followed by direct venting to the atmosphere, are alternative disposal methods. The lower explosive limit (LEL) for combustible gas concentrations must not be exceeded in the soil at the property boundary. Twenty-five percent of the LEL must not be exceeded at or in on-site or off-site structures.
- Section 7.15 — *Monitoring* requires that a monitoring plan, which addresses LFG and ambient air quality, be submitted for approval by ministry authorities.
- Section 7.6 — *Record Keeping* requires that the owner and/or operator of a landfill maintain information regarding monitoring results for gas and, in cases where gas collection is undertaken, volumes of gas recovered.
- Section 7.17 — *Annual Report* specifies that an annual operations and monitoring report be submitted to the ministry detailing LFG monitoring data and interpretation, and, the amount of LFG collected and its disposition.
- Section 8.1 — *Closure Plans* states that a closure plan must be developed that will account for the collection, storage and treatment or use of LFG for a minimum of 25 years.
- Section 8.5 — *Operation of Gas Recovery and Management System* states that LFG recovery and management systems, when required, should be designed as an integral and long-term component of the site.

Ontario

The document "Guidance Manual for Landfill Sites Receiving Municipal Waste, November 1993" discusses various aspects of gas control, including:

- gas migration control facilities
- preferred methods of dealing with migrating gas
- investigations for gas migration
- gas interceptor systems
- design standards for barriers, and passive and active venting systems
- safety considerations during construction
- emission standards for gas control facilities
- contingency flaring

The rationale behind gas control measures is to ensure the safe use of adjacent lands and to protect structures from migrating gas. Monitoring of LFG may be required as part of the overall monitoring program.

The Ontario Ministry of Environment and Energy has also prepared documents titled "Guidelines for Assessing Methane Hazards from Landfill Sites, November 1987," "Interim Guide to Estimate and Assess Landfill Air Impacts, October 1992," and "Land Use On or Near Landfills and Dumps, April, 1994".

The assessment technique described in the Interim Guide uses an approach similar to the USEPA method for predicting gas emission rates (see Section 4.2). Based on the emission rate which is determined, dispersion calculations are then performed to predict ground level concentrations of compounds of concern at the nearest Point of Impingement (POI). Vinyl chloride is generally the compound of concern. Predicted concentrations may not exceed the applicable Ambient Air Quality Criteria. A similar model based on odour assessment is described in the interim guide.

Québec

Sanitary landfill sites in Québec are governed by the "Règlement sur les déchets solides". This regulation is currently undergoing an in-depth review. The new requirements are included in a document entitled "Projet de règlement sur les déchet solides, version technique, mars 1994".

All sanitary landfill sites in Québec must be designed to capture and ensure the elimination of gas generated by the wastes. Landfill sites must be managed in such a way as to prevent the following:

1. migration and accumulation of explosive gases in concentrations above 25 percent LEL in air, in buildings, and structures on and around the landfill site.
2. migration and accumulation of explosive gases in concentrations above 100 percent LEL in ambient air and in the unsaturated zone of soil and rock within the property limits of the landfill site.

The operator of a landfill site must prepare and implement a monitoring program for LFG to assure that established standards for emissions are not exceeded. The monitoring must continue for a minimum of 30 years following the closure of the site, unless exempted by the Ministry. A minimum of four sampling events for explosive gas concentrations is required each year.

A document entitled, "Le biogaz généré par les lieux d'enfouissement sanitaire" was prepared in 1993 by the Ministère de l'Environnement et de la Faune du Québec to assist site operators. This document summarizes issues associated with LFG and describes recommended practices for the management of LFG.

4.2 American Landfill Gas Regulations

4.2.1 Federal

There are currently two American federal legislative instruments that deal with implementation of LFG controls. These are:

- Resource Conservation and Recovery Act (RCRA), Subtitle D
- Clean Air Act, Proposed New Source Performance Standards and Emission Guidelines (NSPS), 40CFR, Part 60.

RCRA Subtitle D

The RCRA Subtitle D regulations pertaining to LFG specify that the following criteria must be met:

- Methane concentrations within on-site structures must be maintained below 1.25 percent by volume (25 percent LEL).
- Methane concentrations in soil must be maintained below 5 percent by volume (100 percent LEL) at the landfill property boundary.

Requirements for monitoring to ensure compliance are specified. Procedures for responding when the criteria have been exceeded are stipulated. These components of the RCRA were promulgated on October 9, 1991.

New Source Performance Standards and Emission Guidelines (NSPS)

The NSPS are proposed under Section 111 of the Clean Air Act (CAA). The NSPS were published in the Federal Register in May 1991 and have been undergoing review and revision since that time. It is currently expected that the component of the NSPS that relates to LFG will be promulgated in early 1996. The following are the major components of the NSPS which pertain to LFG:

- Sites with design capacity less than 2.5 million tonnes (megagrams (Mg)) are exempt.
- Control requirements are determined based on an estimate of the rate of production of non-methane organic compounds (NMOCs) as a component of LFG.
- Controls are required for sites producing greater than 50 Mg of NMOCs in a year.
- A three-tiered approach determines the need for LFG controls.
- Tier 1 utilizes mathematical modelling with defined input variables to estimate NMOCs.
- Tier 2 allows actual field NMOC concentration data to be used along with defined input variables in the mathematical modelling.
- Tier 3 allows for field testing to determine the actual rate of NMOC production.
- Requirements for re-evaluation are defined.
- Test procedures and parameters for the design of LFG control systems are stipulated.

All municipal solid waste (MSW) landfill sites larger than the 2.5 million-tonne capacity exemption are required to go through the tiered evaluation procedure. Tier 1 is the least costly and most conservative evaluation approach. Tier 3 represents a costly evaluation technique, which may yield reasonable NMOC emission data. Tier 2 falls in between Tier 1 and Tier 3 in terms of cost and results. It is estimated that the proposed regulations will require the implementation of LFG controls at more than 400 additional American landfills.

4.2.2 State

Regulations pertaining to LFG vary from state to state. The federal legislation discussed above is considered a minimum. Regulations which are more stringent than the RCRA and NSPS requirements may be adopted by individual states. In many cases, these more stringent requirements are already in place. Table 4.2 presents a few examples of state regulations pertaining to LFG that are over and above the promulgated federal regulations.

Table 4.2 Selected Examples of Additional American State and Local Regulations Pertaining to Landfill Gas

State	Reference	Topics Addressed
California — SCAQMD(1)	Regulation XI, Rule 1150.1	• control of emissions from active landfill sites • methods and best technologies for disposal of collected gas • air monitoring requirements
New Jersey	Solid and Hazardous Waste Management Regulations, Title 7, Chap. 26, 2A	• odour control requirements • recovery and utilization
Pennsylvania	Municipal Waste Management Regulations, Title 25, Chap. 288, C	• gas control and monitoring
Illinois	Solid Special Waste Management Regulations, Title 35, Subtitle G, Chap. 1, i), 811	• encourage gas processing • requirements for treatment or incineration of gas
Alabama	Solid Waste Management Regulations, Dept. 335, Div. 13, Chap. 4	• gas control to be considered in design of facility • monitoring and reporting requirements defined

(1) South Coast Air Quality Management District — encompassing Los Angeles, Riverside, Orange and part of San Bernardino Counties.

As an example, the South Coast Air Quality Management District (SCAQMD) specifies temperature (815°C, 1500°F) and retention time (0.5 sec) criteria for MSW LFG flares under its description of Best Available Control Technologies (BACT).

4.3 European Guidelines and Standards Relating to Landfill Gas Management

Table 4.3 presents information concerning European LFG regulations, guidelines and standards. From this it can be seen that there is a wide range of regulatory approaches. Similar to regulations in Canada, these range from an absence of regulation to compulsory LFG controls mandated by law.

Table 4.3 Status of European Guidelines, Regulations and Standards Relating to Landfill Gas

Country	Status
Ireland	• No LFG regulations
Italy	• LFG recovery required by law, LFG utilization is encouraged
Netherlands	• No LFG regulations for gas control or emissions
Portugal	• No LFG regulations for gas control or emissions
Spain	• LFG collection and management systems are required for municipal solid waste landfills
United Kingdom	• LFG collection systems required, LFG emissions and venting regulated

Source: *Landfill Gas From Environment to Energy*, Commission of the European Communities, 1992.

5.0 Site Assessment Technologies

5.1 General

As described in Section 2.0, there are a number of potential impacts associated with the production and migration of landfill gas (LFG). Add to that the variety of site conditions and adjacent land uses, and it is evident that various assessment technologies are required to address these variables. This section presents a brief outline of site assessment techniques. Application of site assessments is discussed in Section 3.5.

5.2 Landfill Gas Production Modelling

LFG models are the most common method used to estimate LFG production from a site over time (Augenstein and Pacey, 1991). These models are typically used to:

- size LFG collection systems
- estimate gaseous emissions to the environment
- evaluate the benefits of LFG utilization projects

The cost of modelling LFG production is relatively low. Generally available features and data for a specific landfill need to be defined to predict a range of gas production with time. Several models have been developed by various researchers and companies. Most models predict gas production over time from landfilled wastes. The yearly tonnage is typically used as a unit batch and therefore the models predict gas production for a specific volume of waste landfilled in a year. Total gas production from a landfill is simply the sum of yearly outputs computed over time by applying the model to the yearly tonnage of waste. Typically, these models include a time interval before generation starts (lag time) and, depending on the model, intervals of rising, constant and falling production. These curves generally follow the theoretical methane generation curve shown in Figure 2.1.

The models attempt to include the major factors that are known to affect LFG production rate and yield. These factors are discussed in Section 2.2 and include: waste composition, moisture content, temperature, pH and buffer capacity, nutrients, refuse density, particle size, and annual tonnage. Factors that are input into models must be based on knowledge of conditions at a specific landfill. Since landfill conditions can be highly variable or unknown, difficulties arise in attempting to model the LFG production. Figure 5.1 outlines variables than can influence gas generation and the uncertainties that can exist in available information.

Figure 5.2 shows a typical curve representing LFG generation for a unit mass of waste. This curve uses a first order decay model with default values as specified by the United States Environmental Protection Agency (USEPA) ($Lo = 170\ m^3\ (CH_4)$/tonne of refuse, $k = 0.05$/yr). Figure 5.3 shows an example of a LFG production curve for a fictional site with a design capacity of 10 million tonnes filled over a period of 20 years as calculated using the LFG generation curve from Figure 5.2.

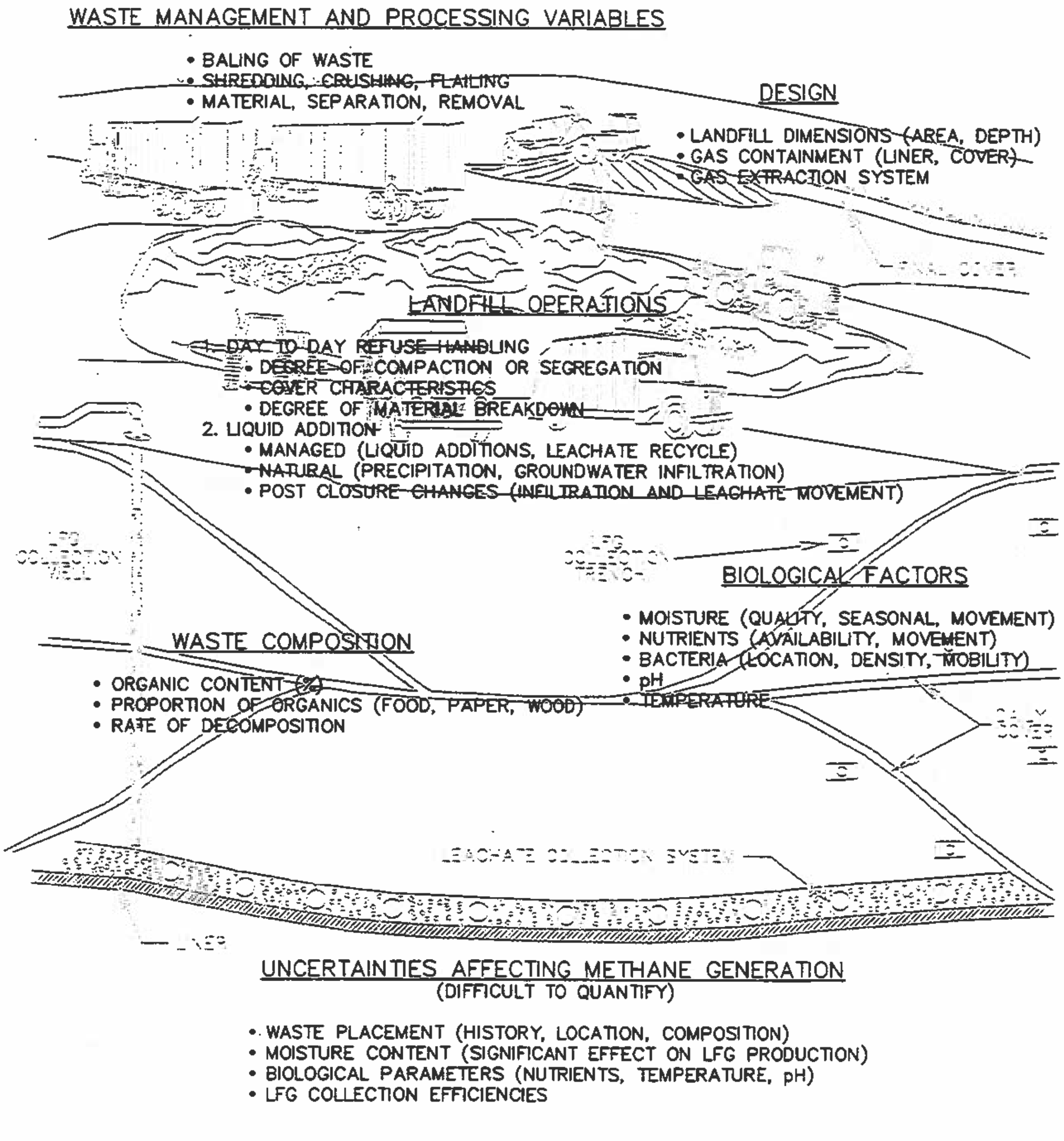


figure 5.1

VARIABLES INFLUENCING LFG PRODUCTION

SOURCE: YABROFF R.D., 1991

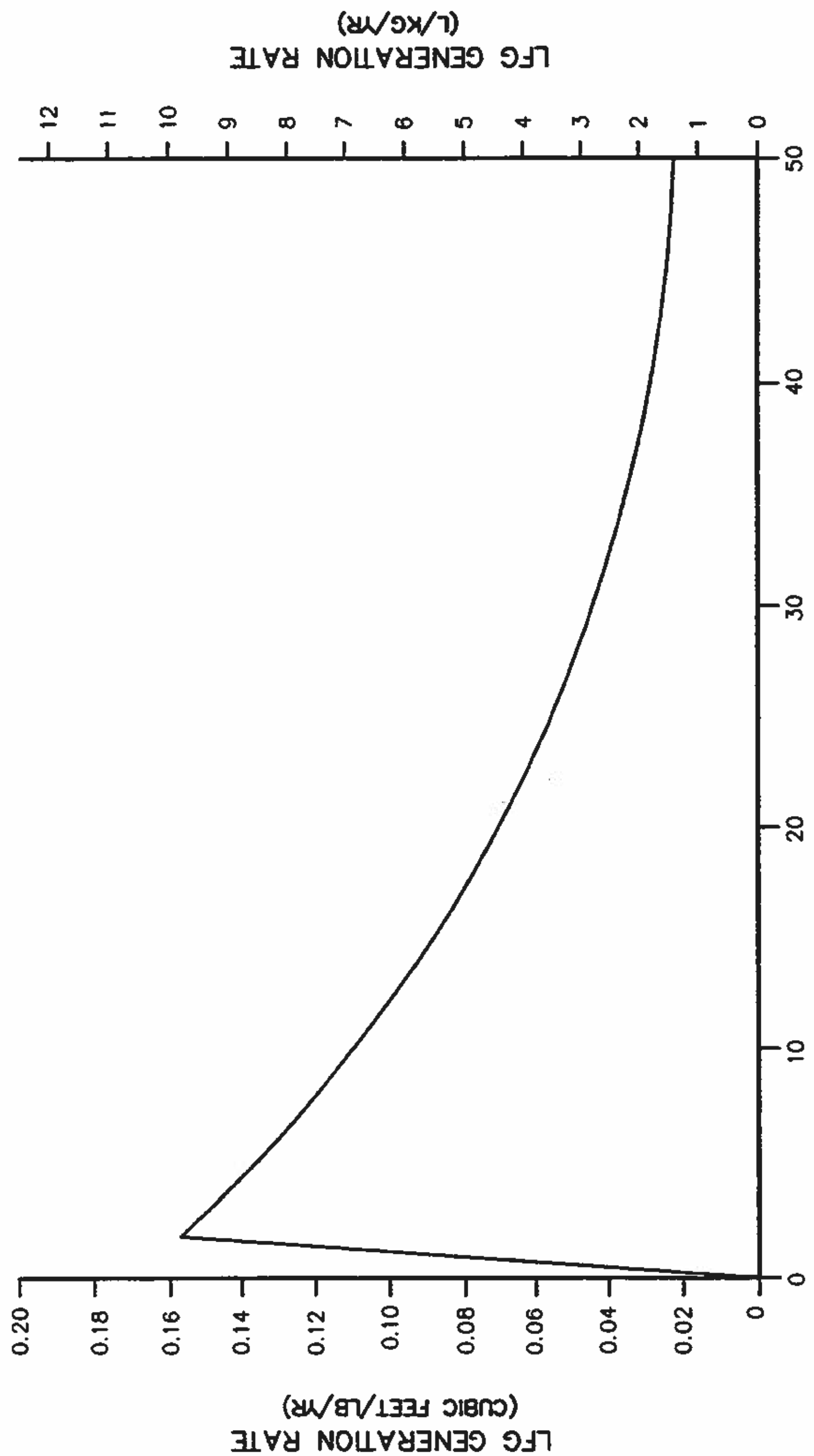


figure 5.2
LFG GENERATION CURVE

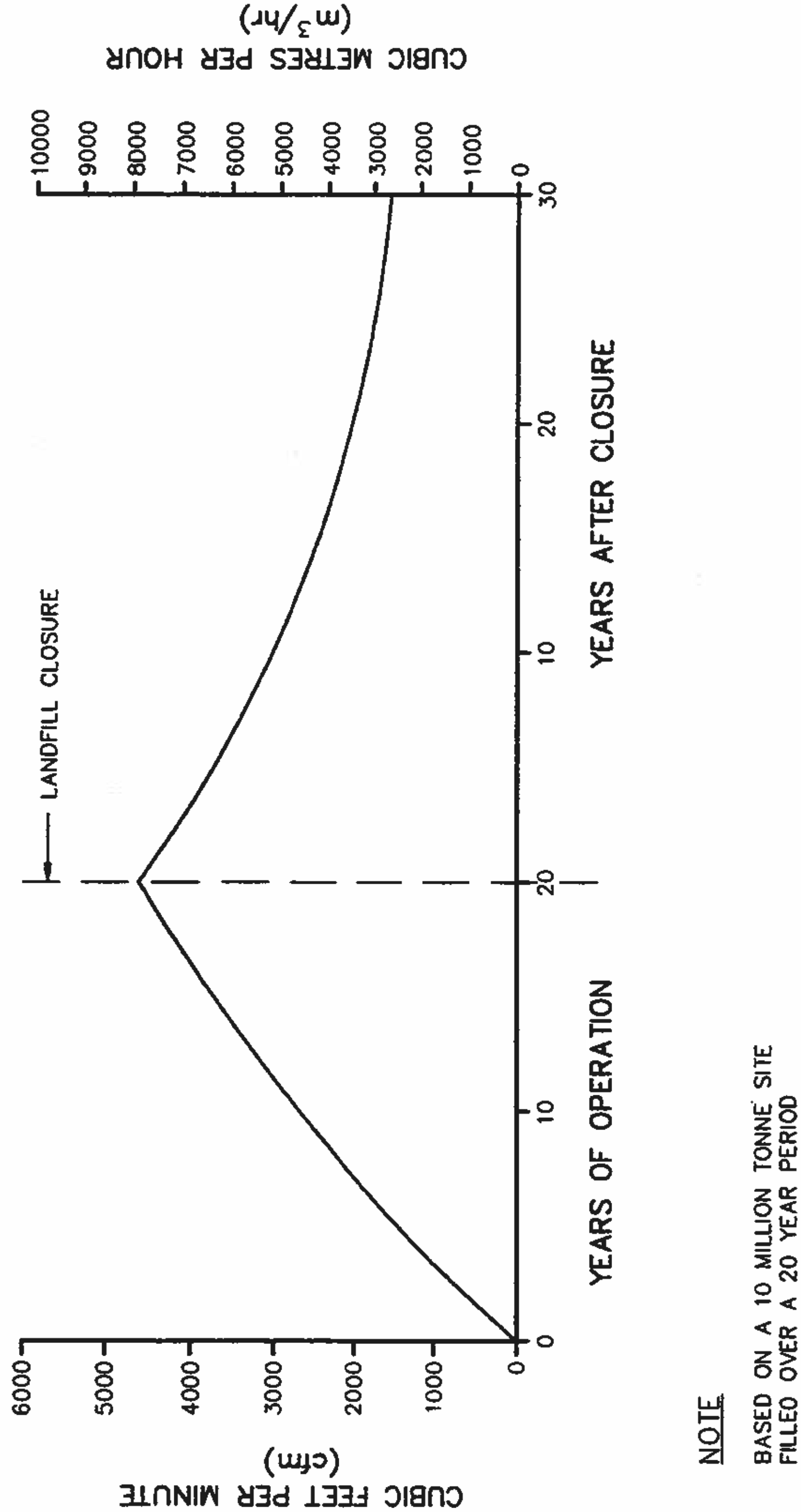


figure 5.3

TYPICAL LFG PRODUCTION ESTIMATE

5.3 Migration Assessment

Field activities for migration assessments typically include the installation of gas probes along the perimeter of the landfill. Perimeter gas probes are used to monitor LFG migration beyond the limit of refuse typically at or near the property line or nearby structures. These perimeter probes are usually permanent installations for on-going monitoring. The perimeter gas probes should be monitored for combustible gas content and probe gauge pressure on a regular basis. Water levels within probes installed near the water table or in areas of perched water tables should be monitored to determine seasonal fluctuations in the water table at each location. The water level is monitored with a small-diameter electronic water level indicator. It is expected that correctly installed gas probes should generally remain dry, but a varying water table surrounding the site may cause periodic flooding of some probes.

Immediately following each monitoring event, the data collected should be reviewed. The objectives of the review are:

- to verify unusual and/or erroneous readings;
- to identify problems and, if necessary, initiate remedial action (i.e. repair damaged probes, calibrate or repair equipment, etc.);
- to bring to the attention of the individuals responsible for detailed assessment and contingency plans, those readings that may indicate gas presence;
- to identify the occurrence of LFG migration;
- to develop any remedial actions that are warranted; and
- to assess the effectiveness of any actions that may have been taken.

A more detailed evaluation of the data should be performed on an annual basis and should include an analysis of all prior readings for trends. This analysis is an important tool in anticipating the occurrence of migration and assessing the effectiveness of any remedial measures that may have been taken. The annual review should also consider any modifications to the monitoring program that may be required as a result of the conditions observed at that time. In-depth analysis of monitoring data from perimeter probes is complex and must consider not only the monitoring results but also must take into account the following:

- barometric pressure
- frost conditions
- soil stratigraphy
- hydrogeology
- the status of LFG controls (if applicable)

The detection of combustible gas in the soil constitutes evidence of migration. Gradients of combustible gas concentrations may be helpful in indicating the extent, range and direction of migration. However, interpretation of concentration gradients may be complicated by physical and/or chemical processes acting upon the gases as they move through the soil.

Gauge pressures as measured at the gas probes provide an indication of the motive force responsible for advective movement of gas in the soil. Gauge pressures which are consistently positive in probes where combustible gas is detected give an indication of the magnitude of the force behind the migration.

It has been shown that barometric pressure has a strong influence on subsurface pressures, and that changes in subsurface pressures lag behind changes in barometric pressure. This time lag is dependent on many factors, including the depth of the probe, permeability of soil or refuse, daily cover, final cover, degree of saturation, presence of frost or frozen ground cover, and rate of change in barometric pressure. Due to the many factors that influence the time lag, it is difficult to determine absolute subsurface gas pressures (i.e. subsurface gauge pressure with the barometric pressure influence removed). Reduction of probe pressures to absolute values may be misleading. Barometric pressure should be considered when analyzing data, as large fluctuations before monitoring can lead to an erroneous interpretation of the data.

Probe pressures provide data that is useful for analyzing long-term trends. Due to the numerous factors affecting subsurface pressures, trend analysis of subsurface pressures should be based on review of annual average gauge pressures at each probe. This will help eliminate the daily and seasonal barometric fluctuations that will be most evident in individual readings.

An analysis of the data should include consideration of the site stratigraphy and hydrogeology, as these characteristics impact gas migration. Low permeable soils inhibit migration more than high permeable soils. Stratified layers of high permeable soils overlain by low permeable soils will tend to increase migration distance by confining the gas and limiting venting to the atmosphere. This is similar to the effect that frost or frozen soil has on migration. Nearby underground utility corridors with granular bedding can also provide a preferential pathway or conduit for gas migration.

5.3.1 Gas Probe Installation

Standard drilling methods are used for gas probe and extraction well installations. The hollow-stem continuous-flight auger is among the most frequently used installation tools for gas probes. The inside diameter of the hollow stem should be selected to suit the number of probes to be installed in the borehole. A 108 mm (4.25 inch) hollow-stem auger is sufficient to install a three level, 50 mm diameter, gas probe system.

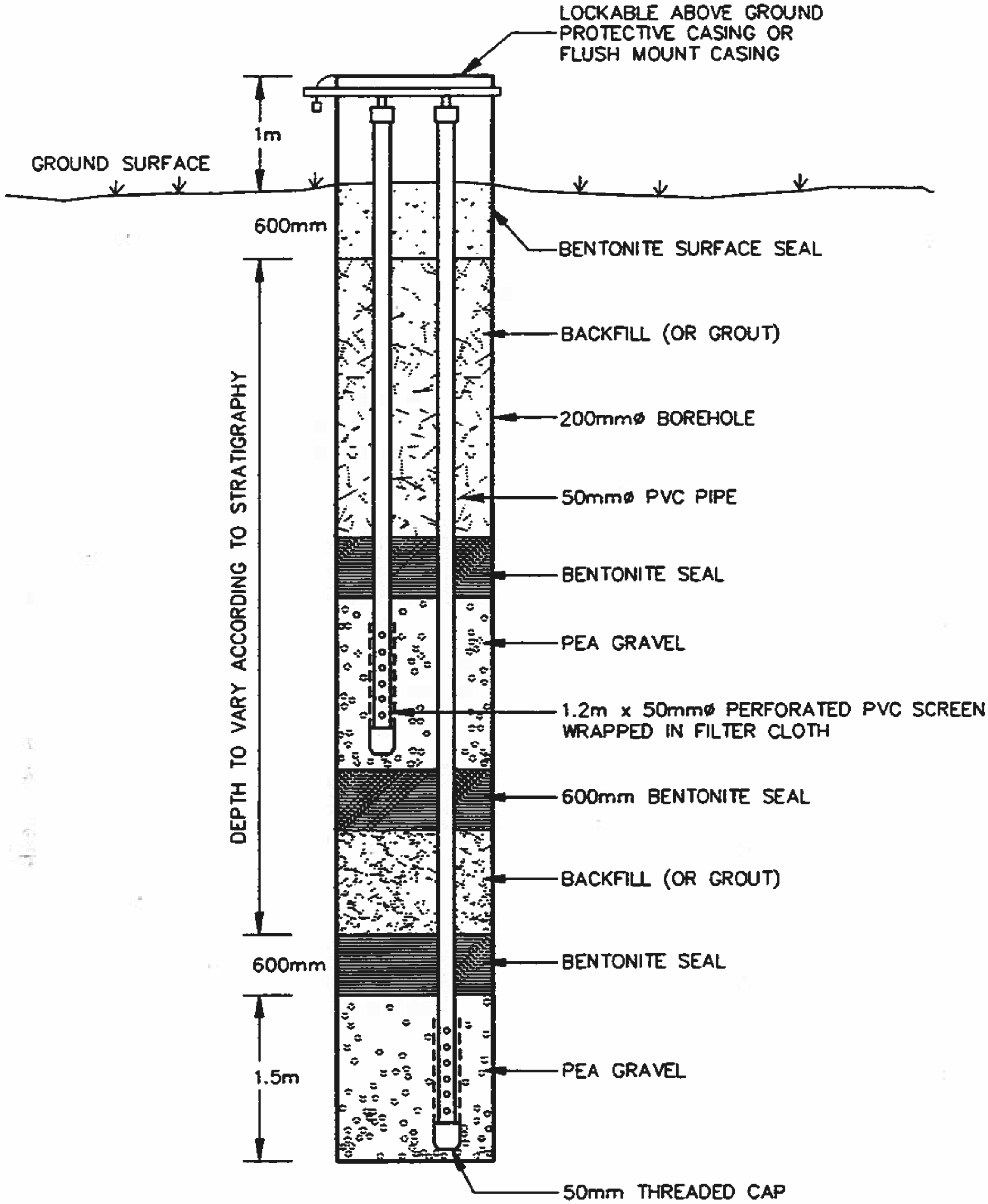
The probe diameter should be small to reduce the volume of gas that must be purged from the probe during monitoring but should be large enough to allow water levels to be measured. Typically a 50 mm diameter gas probe is suitable. Probes are generally constructed from polyvinyl chloride (PVC) pipe. Glued joints should be avoided for probes which may be sampled for trace gas analyses. Solvent cements contain volatile organic compounds (VOCs) which would then appear in the analytical results.

Figure 5.4 shows a typical detail for a two-level probe nest. It should be recognized that installation of multi-level gas probes requires supervision by an experienced drilling technician. To function properly, the perforated portion of the probe must be located in the more permeable strata. The integrity of the borehole seals between the probe levels is critical to the proper functioning of the probe. As an alternative to multi-level probe nests, probes may be installed at the desired levels in individual, adjacent boreholes. While this increases costs somewhat, the installation procedure is simplified.

The length of perforated screen (1.2 m) is designed to allow differentiation of vertical gas measurement zones. Some probe designs include larger perforated sections. It should be recognized that the larger the perforated section is, the less certainty there is regarding the vertical extent of migration. Probes that are screened for most of their depth (if depth > 3 to 4 metres) can act only as general indicators of migration.

To prevent interference by atmospheric conditions, probe perforations should generally be located more than 1.5 m below ground surface and equipped with seals as shown in Figure 5.4.

Gas probe locations will be selected primarily to provide a good geographical distribution across the site, given the site conditions anticipated, and to match the site's specific characteristics (i.e. traffic patterns, drainage patterns, etc.). Any known sensitive areas such as buildings on or near the site, previously identified permeable soil zones and underground service alignments should be targetted for probe installation.



NOTE: GAS PROBE DEPTHS AND SCREEN LOCATIONS TO BE VERIFIED IN THE FIELD, BASED ON LOCAL SOIL CONDITIONS.
CONNECTIONS AND ADAPTORS ARE <u>NOT</u> TO BE GLUED

figure 5.4

TYPICAL MULTILEVEL GAS PROBE DETAIL

Drilling on landfills is complicated by the following factors, which necessitate appropriate safety precautions:

1. the presence of explosive gases
2. the presence of hydrogen sulfide (H_2S)
3. the presence of organic vapours
4. the potential unstable nature of the refuse
5. the presence of refuse material, (e.g., mattresses, steel cables, etc.) that can hamper the removal of the augers

A detailed discussion of health and safety issues related to LFG is provided in Section 6.5.

5.4 LFG Extraction Testing

LFG quality and production rates for in-place refuse may be estimated by conducting LFG extraction testing. Extraction testing involves installation of one or more extraction wells and monitoring probes in the refuse. During the test gas is actively extracted from a well and test wells, and probes are monitored to observe the influence that this has on them.

Extraction wells and probes should be located so as to encompass the considerable variations in conditions affecting LFG production within the landfill. If the site is still in operation, the locations of probes and wells should be selected to minimize disturbances to landfill operations. The design of test probes is similar to that of the migration monitoring probe shown in Figure 5.4. Figure 5.5 shows a typical test extraction well. Figure 5.6 shows an extraction test layout. Method 2E of the USEPA also provides a detailed description of a method for determining gas production rates in the field (CFR 40, Part 60, Appendix A, 1991).

The refuse probes are located along lines radiating outward from the extraction wells. Probes can be placed at various depths within the refuse in each probe nest. Multiple probe depths are useful for determining the vertical distribution as well as the radial distribution of internal pressures and gas composition surrounding the gas extraction wells.

The duration of the extraction test is a function of the level of information required and the known history of the site. Ideally, the extraction test should be performed for as long a period as practical. The exact duration of the test is dependent upon the extraction rate that is applied and the length of time required to exhaust stored LFG from within the zone of influence. An extraction test may need to be run for a week or more to fully establish a steady-state zone of influence. An intensive, "snapshot-type" test may be performed over a shorter duration using specialized equipment and techniques.

Extraction testing is a means of obtaining an indication of pressure and gas composition distribution surrounding an extraction well. The zone of influence is estimated based on observations of probes in the refuse. The generation rate is based on the flow rate of LFG extracted from the well and the mass of refuse that is estimated to be contained within the zone of influence. The results of the extraction testing also give an indication of the extent of air intrusion and the zone of influence resulting from a selected withdrawal rate. In addition, the applied vacuum required to achieve a given flow rate provides information for the gas collection system design regarding well spacing, blower requirements and well flow rates that may be expected.

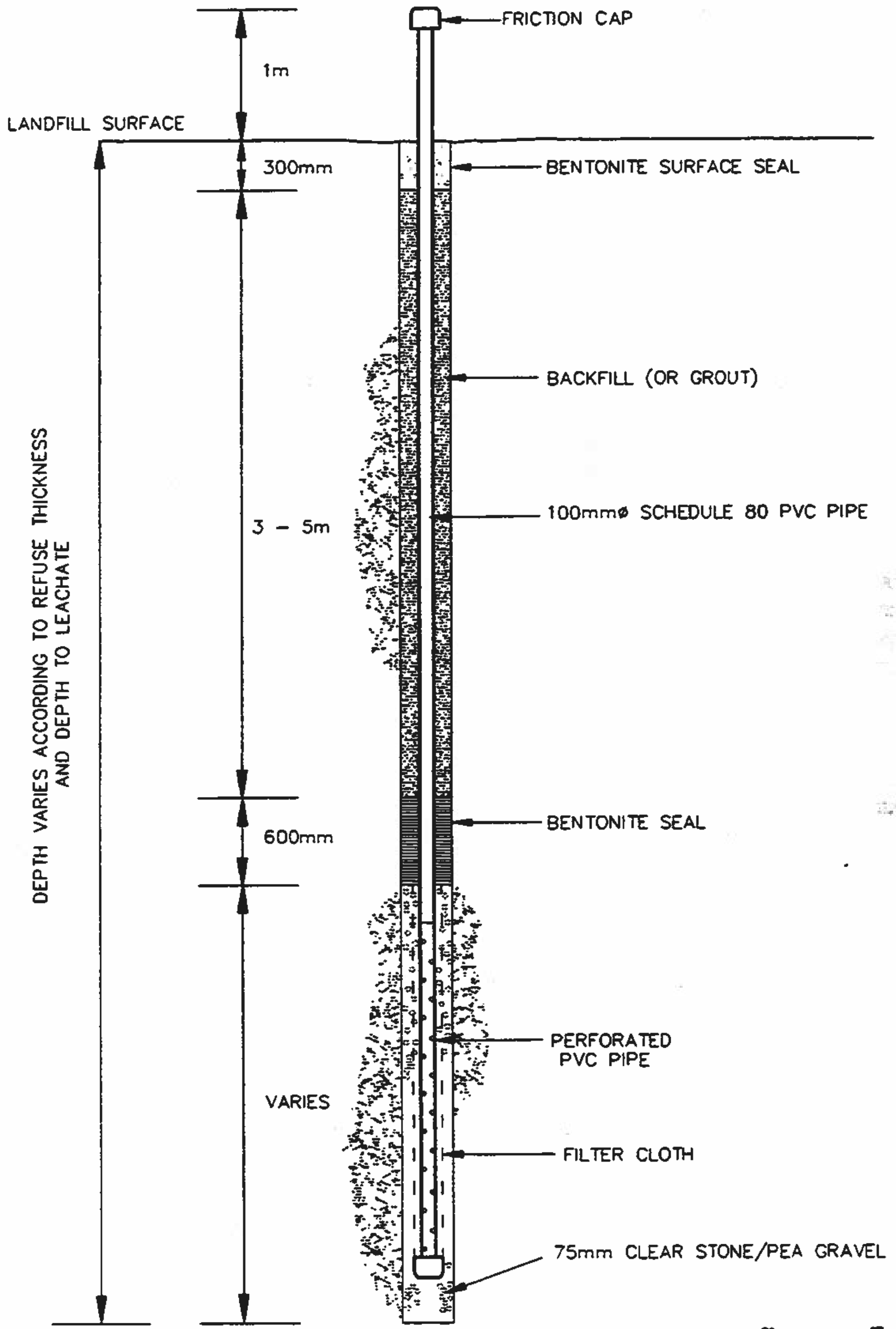


figure 5.5

TYPICAL GAS EXTRACTION TEST WELL INSTALLATION

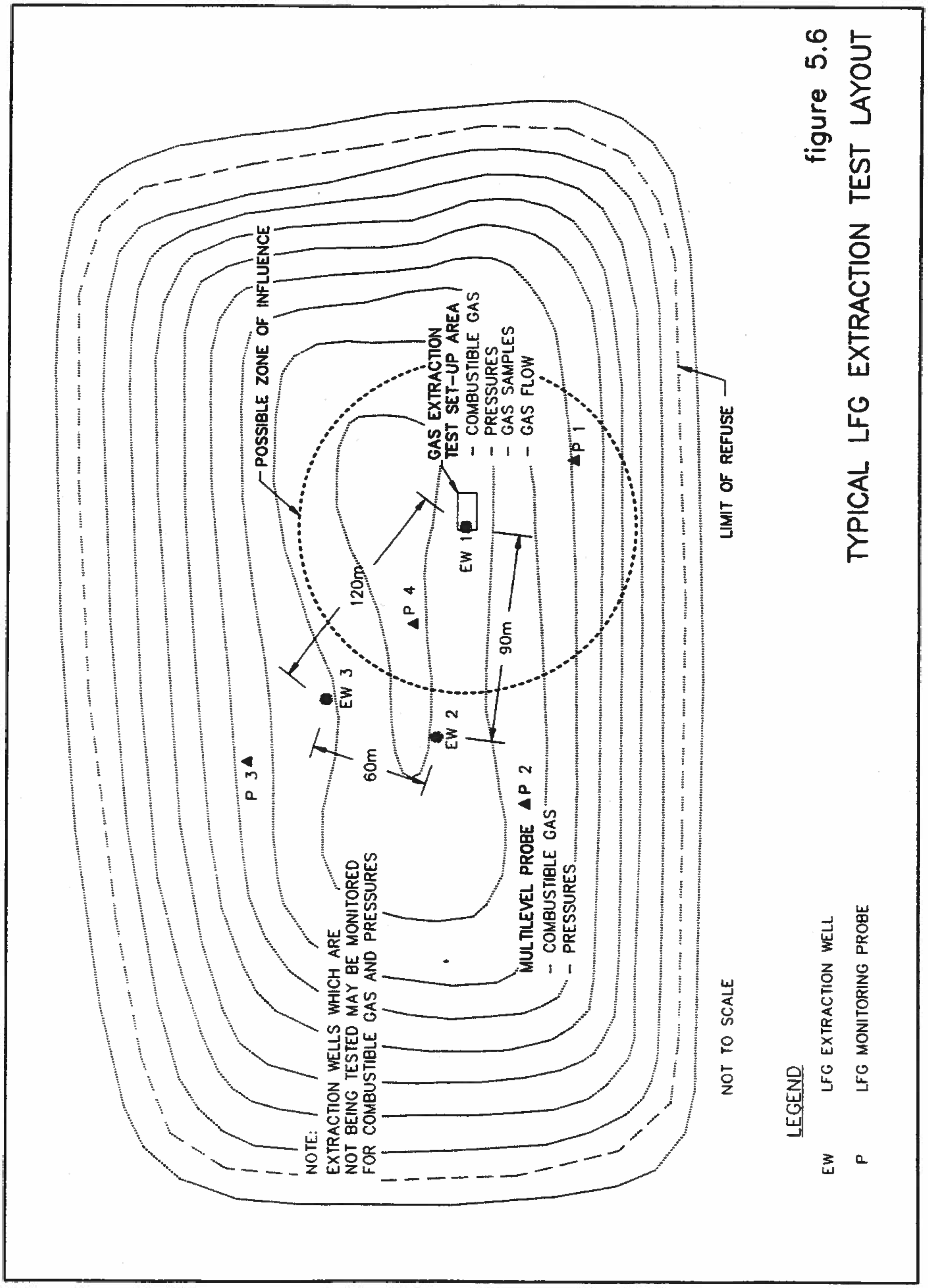


figure 5.6
TYPICAL LFG EXTRACTION TEST LAYOUT

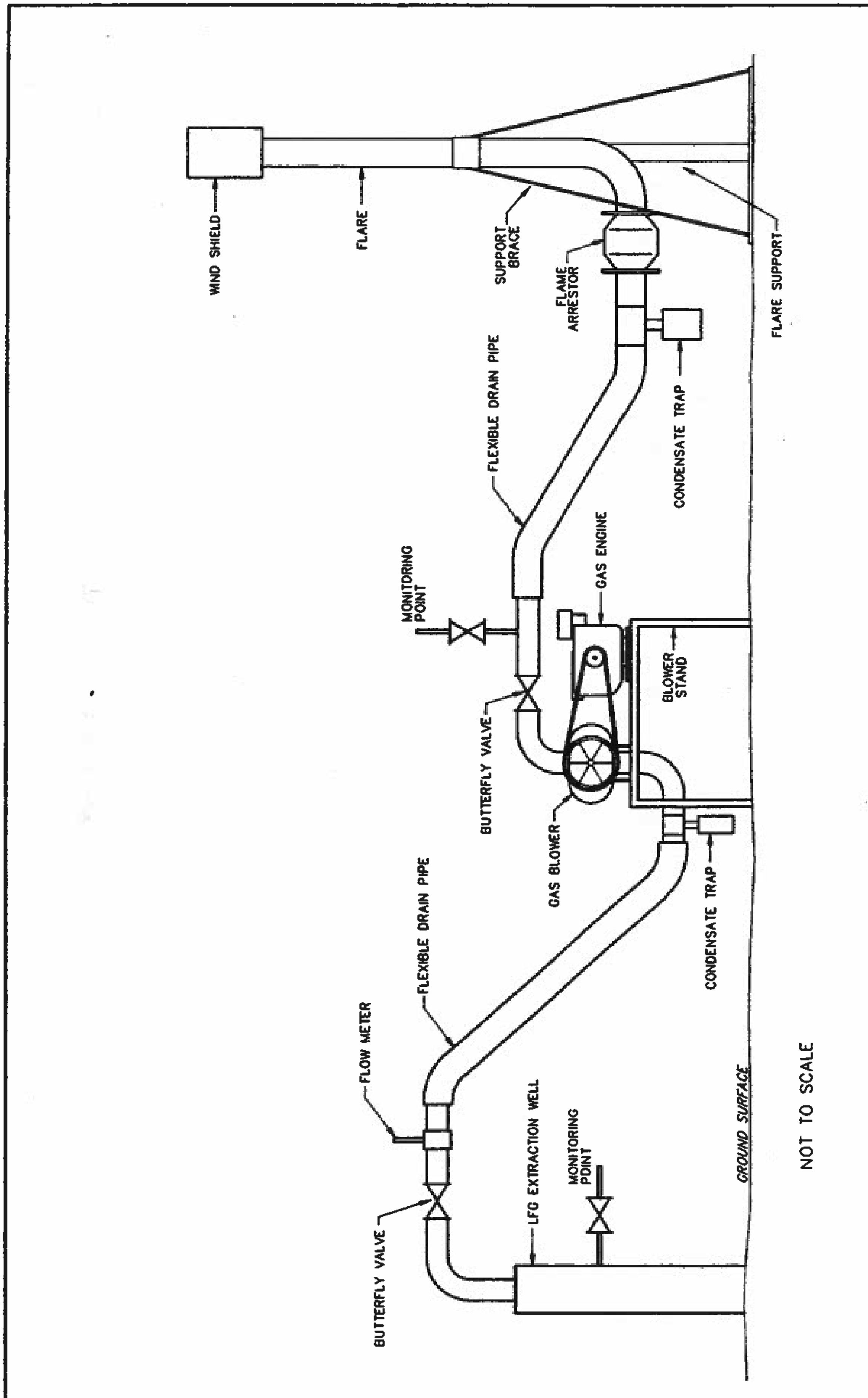


figure 5.7
TYPICAL LFG EXTRACTION TEST SET-UP

A portable gas blower and flare system as shown in Figure 5.7 is set up at the extraction well. Prior to starting the blower, static measurements of the well vacuum (i.e. pressure), and concentrations of combustible gas and oxygen should be recorded at the extraction well. The well vacuum, flow rate, and concentrations of combustible gas and oxygen should be recorded several times per day over the test period. Monitoring probes should be monitored a few times per day throughout the duration of the extraction test to record pressures and the concentrations of combustible gas and oxygen. Probes located within the zone of influence of the extraction well being tested should be monitored more frequently.

Large-scale extraction tests are costly to perform (see Table 6.5) and may yield results that are difficult to interpret. Due to the heterogeneous nature of landfills, the results of extraction tests may not reflect average or overall conditions at a site. For larger sites, extraction tests are recommended to be performed at three different locations on the site.

The decision to perform extraction testing should consider the value of the additional information or confidence that may be obtained. It is recommended that flexibility to adapt to a range of gas production rates be included in the design of any gas collection system. The costs of incorporating this flexibility should be weighed against the costs of additional testing to reduce uncertainty associated with LFG production estimates.

Due to the inherent difficulties associated with extraction testing and the nature of the information that is generated, it is recommended that extraction tests be performed only at large sites. For smaller sites, the additional information to refine well spacing and the sizing of plant and equipment does not justify the costs of extraction tests.

5.5 Flux Chambers

Flux chambers are used to estimate gaseous emission from landfills. This non-intrusive methodology uses a chamber to isolate a known surface area for emission measurement. Clean, dry sweep air, added to the chamber at a metered rate, combines with gases emanating from the surface and transports these gases through an exit port. The concentration of the exhaust gas is measured at the outlet for specific VOCs or selected parameters by real-time instrumentation or collected as a sample for laboratory analysis. The measured concentrations are then used to calculate the emission rate. Assuming that the chamber behaves as a completely mixed reactor, an emission rate can be developed using the measured concentrations, sweep air flows and chamber volume.

One disadvantage of this method is that the measurement is made over a small area (typically less than 1 m^2) while landfills usually encompass a much greater area. Statistical methods can be used to determine the number of measurements and locations required to characterize the emission from an area source. Emission rates through the surface are generally subject to influences such as solar heating and cover moisture content. Other concerns include equipment contamination and cross contamination between sample locations, primarily due to the low concentrations of some compounds analyzed. Emission rates measured are also greatly influenced by the condition of the cover (i.e. surface cracks and vegetation) within the flux chamber sample area.

Flux chamber operation can greatly influence results. At higher flow rates, increased chamber pressure leads to negative biasing of the emission rate measured. Chamber design is critical to ensure proper mixing of flows and effective sweep air velocities that can significantly affect measured emission rates. Accordingly, care should be taken in using the data collected from flux chamber testing. However, recent studies indicate that flux chambers can be operated to provide accurate measurement of gas emission rates (Reinhart and Cooper 1992) and may minimize some errors noted above.

5.6 LFG Sampling and Analyses

Gas sampling is used to identify the presence and extent of LFG migration at a site, and to define gas composition within the refuse mass. Gas samples can be obtained from permanent gas probes, monitoring wells, surface cracks in soil, shallow barhole probes, standpipes, flux boxes or any adjacent confined spaces. Gas sampling may be conducted using the following equipment:

- evacuated canisters
- adsorbent tubes
- sample bags

Samples of LFG may be analyzed for methane, carbon dioxide, nitrogen, oxygen, carbon monoxide, and sulfurous compounds consisting of hydrogen sulfide, methyl mercaptan, and ethyl mercaptan. Samples may also be analyzed for a target list of volatile organic compounds (VOCs) and with an open scan of VOCs to identify additional VOCs not included in the target list.

Trace gas sampling determines the presence, above detection limits, of compounds that are most commonly associated with odour and health impacts of LFG. Open scan and VOC target list testing are also carried out to identify trace compounds in the LFG that may have corrosive or other detrimental effects on potential gas handling equipment.

Gas analyses may be carried out using a gas chromatograph with a mass spectrometer (GC/MS). The required limits of quantification and the concentrations of other compounds that may be present may affect the analytical methods which are to be employed. Given an approximate composition of the gas, an analytical chemist can provide information on the detection limits that may be achieved. It should be noted that most analytical labs are set up to measure air quality. Samples of raw LFG which contain high concentrations of methane and carbon dioxide may adversely affect some analytical equipment. Labs should be informed of the approximate composition of LFG prior to analyses.

Direct reading instruments (DRIs) are useful for measurement of LFG in the field. The DRI most commonly used for LFG monitoring is the portable combustible gas meter, which measures the concentration of combustible gas present in air. For use in monitoring LFG, the meter should include measurement ranges for combustible gas of 0 to 100 percent by volume, and 0 to 100 percent lower explosive limit (LEL) as a minimum. DRIs that measure combustible gas to parts per million (ppm) levels are also available.

The portable combustible gas meters used for monitoring LFG should not be confused with personal air monitors, which are used for confined-space entry. Personal air monitors usually measure oxygen content and combustible gas. The combustible gas measurement range of personal air monitors is usually limited to 0 to 100 percent LEL. It is important to note that portable combustible gas meters and personal air monitors should not be used interchangeably. Personal air monitors do not provide all the information required for LFG monitoring and are not suited to exposure to high concentrations of raw LFG. Portable combustible gas meters do not perform all the functions necessary for health and safety monitoring.

Photoionization detectors (PIDs) are often used to measure VOCs. It should be noted that many PIDs do not operate properly in the presence of methane. As a result, PIDs are not recommended for monitoring at landfill sites.

5.7 Air Quality Modelling

Dispersion modelling techniques are available to predict the effect that emissions of LFG to the atmosphere will have on the quality of the air surrounding a site. Dispersion modelling is a component of the Ontario Ministry of Environment and Energy (OMOEE) publication " Interim Guide to Estimate and Assess Landfill Air Impacts, October 1992". In this document, comparison between the following three accepted dispersion models is recommended:

- OMOEE Air Resources Branch CAP Model
- Industrial Source Complex Model
- Fugitive Dust Model

Alternative modelling techniques are also available and may be technically justified. Dispersion models generally require the following information as input:

- LFG production and emission rates
- concentration of compounds of concern in the LFG
- meteorological data
- physical site setting information, (i.e. topography, site configuration, location of receptors, etc.)

From this data, the models are able to calculate the predicted concentration of compounds of concern at given locations for specific meteorological conditions.

Performance of air quality modelling is a regulatory requirement in some jurisdictions (i.e. Ontario). Comparison of the results of air quality models with appropriate exposure criteria will indicate the need for LFG controls.

The results of air quality modelling are very sensitive to the emission rate input and the type of dispersion model used. Air quality modelling should be performed by qualified persons who are fully versed in the modelling techniques and their inherent limitations.

5.8 Ambient Air Monitoring

Ambient air monitoring measures air quality in the vicinity of the landfill. Sample locations should be selected to account for wind direction. Monitoring should also account for the range of meteorological conditions that can reasonably be expected. Background samples should be collected in urban areas where there is potential for impacts from other sources on air quality in the vicinity of the landfill. Samples may be collected using multi-sorbent tubes through which a measured volume of air is drawn over a fixed period. The tubes trap the compounds of interest which are subsequently analyzed in a laboratory. The samples should be delivered, within 48 hours of collection, to a local laboratory for analysis.

The program should include initial characterization of the LFG, which involves the analysis of gas samples taken from the landfill using Tedlar bags or evacuated canisters. Results of analyses of the LFG may then be compared with the air sample results to identify possible LFG-sourced compounds of concern.

6.0 Landfill Gas Management Options

Control of landfill gas (LFG) may be required to mitigate the potential impacts discussed in Section 2.4 of this document. Management of LFG includes the use of natural characteristics of the site and its setting, engineered systems, and where possible, utilization of the LFG as a resource.

The method for controlling LFG depends upon which of the potential impacts is identified as the primary control objective. For the purpose of selecting appropriate control technologies, the potential impacts of LFG may be grouped into those related to migration of LFG through soils surrounding the site, and those related to the release of LFG into the atmosphere (i.e. odour, air quality, atmospheric loading). A landfill site is a complex grouping of natural processes and engineered systems, each of which is related to some degree to the others. The design of engineered control systems must take into consideration influencing factors created by and applied to other elements of the landfill system. The design of LFG controls must be integrated into the overall philosophy for design and operation of the site.

The following subsections discuss design considerations which may affect potential LFG impacts and options for control of LFG.

6.1 Site Design Considerations

Factors related to site design which may affect the potential for LFG-related impacts include the following:

- site configuration
- cover system design
- liner system design
- moisture addition/leachate recirculation
- operational constraints

6.1.1 Site Configuration

The configuration of the site may factor into the potential for LFG-related impacts. Sites which are filled predominantly above the surrounding grade may have an increased potential for release of LFG into the atmosphere due to the greater surface area of the landfill. Conversely, sites which are located predominantly below the surrounding grade have a greater potential for impacts related to migration of gas into the surrounding soil.

There are a number of factors related to the angle of slopes on a landfill that may affect the release of LFG to the atmosphere. Gentle landfill slopes (i.e. 4H:1V or less) may result in less gas being released to the atmosphere as a result of the following factors:

- ease of construction and maintenance of final cover, and therefore improved cover integrity;
- increased ability to influence a larger portion of the refuse mass with gas collection wells or trenches, while reducing the potential for drawing air into the site; and
- reduced ratio of landfill surface area to volume of refuse.

The possible benefits of gentle slopes are limited by the following considerations:

- Very gentle slopes may result in ponding of water on the landfill. This will increase infiltration into the site and thereby increase the site moisture content and gas production rates.
- Use of exclusively gentle side slopes is an inefficient use of landfill space.

6.1.2 Cover System Design

The primary factor pertaining to landfill cover that influences management of LFG is the permeability of the cover to moisture and gas. A permeable landfill cover such as a coarse sand promotes infiltration of precipitation into the site. It is known that the moisture content of refuse is a key parameter influencing the rate of LFG production. Within a fixed range, higher refuse moisture content generally results in increased LFG production over a shorter period. This reduced period is still likely to be greater than 20 years, however.

Permeable covers tend to allow more rapid venting of LFG to the atmosphere. This may result in lower gas pressures within the site, which could reduce subsurface migration of LFG in some soil settings. Permeable cover materials may also allow intrusion of air into the landfill while active LFG extraction is in operation. The presence of air in the landfill may result in aerobic decomposition of the wastes. Aerobic decomposition is characterized by rapid rates of landfill settlement, stronger odours, reduced methane content in LFG and elevated landfill temperatures, possibly leading to landfill fires. The drawing of air into the landfill is controlled by integrating the design of the gas collection system with the site cover, and by effectively monitoring and adjusting the gas collection system.

Low permeable covers such as clayey soils or synthetic membranes inhibit infiltration of moisture into the landfill. This can result in a lower rate, and extended duration of, LFG production. Low permeable covers tend to inhibit venting of LFG to the atmosphere. This may result in increased gas pressures within the landfill which could lead to increased subsurface migration of LFG in some soil settings.

Low permeable covers limit the drawing of air into the landfill while active LFG extraction is in operation. In the absence of active LFG collection, low permeable covers restrict the venting of gas to the atmosphere. This results in an increased buildup of gas pressure within the site. This may create point sources of gas release from cracks or fissures in the cover and/or increased subsurface migration of LFG. Where active LFG collection is not in effect, it is recommended that low permeable cover systems be equipped with passive gas vents. Passive venting systems are discussed in Section 6.2.2.1.

Soil covers may have some mitigative effect in treating LFG. It is thought that microbial communities present in soils may consume some components of LFG, thereby reducing the level of contaminants. This phenomenon has been studied at a number of landfills but is still not well understood. There are also unanswered questions regarding which specific components of LFG are affected and to what degree. It has not been determined that any significant treatment of CH_4 or odorous compounds may be achieved. It has also been questioned whether this treatment effect can be sustained in colder climates. Methods to design and ensure the effectiveness of LFG treatment soil covers are currently undefined. In cold climates, freezing would be expected to impair dramatically the effectiveness of LFG treatment soil covers during the winter. Discontinuities due to settlement or erosion of the cover would result in concentrated release of LFG from these sources with no mitigative effect from the cover soil.

The landfill cover system selected reflects the overall approach to the design of the landfill. The site designer must be cognizant of the effects that the cover design has on other components of the landfill system and must address these effects accordingly. Low permeable covers with active gas collection will maximize gas control but may be contrary to other site design objectives such as a shortened contaminating lifespan.

6.1.3 Liner System Design

Many older sites do not have liner or leachate collection systems. More modem, engineered landfills are typically equipped with soil and/or synthetic membrane liners and leachate collection systems. The effects that liner systems have on LFG management are primarily related to the moisture content of the wastes and the liner's effect on subsurface migration of LFG.

Mounding of leachate within the landfill may increase the rate of LFG production for wastes that are contained within the saturated zone. Mounding of leachate at sites that do not have a liner system may be caused by the presence of low permeable soils beneath the site or by the formation of a bio-slime layer near the interface of the refuse and the native soil. Mounding of leachate at sites which are equipped with liners and leachate collection systems is generally a result of problems with the performance of the leachate collection system. The quantity of leachate present is a function of the infiltration of precipitation into the site and the initial moisture content of the landfilled wastes. Leachate mounding may be decreased by the use of low permeable soil or synthetic covers to reduce infiltration.

Migration of LFG into the soil surrounding the site is inhibited by the presence of low permeable soils in the local stratigraphy or the use of liner systems at the site. In more permeable soils (i.e. sand, gravel), gas migration is primarily driven by pressure gradients (advection). Advective migration can be quite rapid and responds strongly to the pressure within the landfill and changes in barometric pressure. In low permeable soils (i.e. clay, clay tills), LFG migration is dominated by diffusion by concentration gradients. Diffusion is considered to be a process slower than advection. LFG will diffuse to some extent through all soils and materials. The rate of diffusion is dependent upon the properties of the material and the concentration gradient present.

Low permeable liners with leachate collection systems are recommended to optimize control of LFG migration along with their primary purpose of controlling potential groundwater impacts.

6.1.4 Moisture Addition and Leachate Recirculation

Rapid stabilization of landfills can be achieved by recirculating the leachate and/or adding moisture to the landfill using injection wells, infiltration ponds or infiltration galleries. This is carried out at some sites where engineered control systems are in place. These processes can assist natural infiltration by raising the moisture content of the site to its field capacity. Once field capacity is reached, flow-through of moisture begins. Depending on the nature of the program and the source of the moisture used, there can be an enhanced flushing action to remove contaminants from the waste. The flow-through process also helps distribute nutrients more evenly throughout the wastes and to enhance the process of biological decomposition. This type of program can compress the contaminating lifespan of the site. This is thought to enhance the control of potential impacts by concentrating the contaminating period into a timeframe that corresponds to the maximum effectiveness of the engineered control systems. In doing so, it increases the rate of LFG production, which in turn increases the need for an effective control system.

The enhanced biological decomposition resulting from rapid stabilization increases the rate of LFG production, which may be doubled. The total yield of LFG is not thought to be greatly affected and therefore the duration of LFG production is proportionally shortened by rapid landfill stabilization.

The enhanced rate of LFG production might be beneficial for some LFG utilization projects as it could supply larger, more efficient utilization plants. However, the increased rate of LFG production could also shorten the payback period for the project, adversely affecting its financial viability.

Rapid stabilization of landfills must be critically assessed during the conceptual and preliminary site design stages. The following issues have to be considered:

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

To maintain emissions of LFG at or below a given rate, a higher gas production rate means that a greater proportion of the LFG produced must be collected. As a result, the design of the collection field must be optimized. This would generally be achieved by placing wells and/or trenches closer together and using a low permeable cap. Guidelines for designing LFG collection fields are discussed in greater detail in Section 6.2.1.

The hydraulics of the collection system, including flow and head loss characteristics, must be designed to accommodate the increased LFG collection rate. The overall plant capacity, including flares, must be sized to suit the enhanced LFG production rate.

The piping system must be designed to accommodate the increased rate of landfill settlement. The design of wells and/or trenches and piping should include sufficient expansion capability for the greater-than-normal landfill settlement. Particular attention should be paid to maintaining sufficient pipeline slopes to provide for drainage of condensate. The large differential settlements associated with rapid landfill stabilization can create fissures in the site cover, which can allow air into the site. The design of wells and trenches should allow for additional separation distance from the surface of the site to minimize potential air intrusion.

The LFG system must be designed to handle and dispose of the higher-than-normal quantities of condensate that are expected. The high moisture content of the site may increase maintenance problems in LFG handling equipment. Much of the potentially corrosive nature of LFG is due to the presence of hydrogen sulphide and chlorinated compounds. These compounds tend to dissolve in water and to form weak, corrosive acids. In very moist conditions, formation of these acids will likely be more prevalent. Operators have observed that equipment generally needs more maintenance at "wet" sites than at "dry" sites.

6.1.5 Operational Constraints

Operational considerations that may affect rates of LFG emissions are primarily related to the moisture content of the refuse. Use of permeable daily cover soil such as sand will result in higher rates of infiltration and hence a higher moisture content of the site. This will increase the rate of LFG production.

The sequence and method of filling the site can affect the type of LFG collection field that is selected. Filling in relatively shallow lifts over large areas is compatible with the use of horizontal collection trenches. The arrangement of trenches is dictated largely by the direction of filling.

For large sites it is desirable to implement LFG controls during the active filling period. This is the time when odour problems can be of most concern due to incomplete construction of final cover.

Use of low permeable daily cover soil can magnify the effect of layering or stratification of the site. A highly stratified site can have much greater horizontal than vertical permeability. This can create perched water conditions within the site. Perched water and stratification of a site can increase the costs of LFG recovery by requiring closer well and/or trench spacing in some areas. Large amounts of perched water can result in increased LFG production rates in some portions of the site.

6.2 Design of LFG Management Systems

LFG management systems are constructed to suit one or more of the following purposes:

- to control subsurface migration of LFG from a landfill site
- to collect gas from the refuse to control odours and/or emissions to the air
- to collect gas from the refuse for use as a resource

LFG collection systems for odour and emissions control are similar to those for LFG utilization. Design considerations specific to utilization systems are similar to those discussed below.

6.2.1 LFG Collection System Design

Collection systems that are intended primarily to control odour and emissions are generally designed to maximize coverage of the entire site area. Such systems often also have a positive effect on controlling subsurface migration of LFG. The extent of this effect is highly dependent on the stratigraphy of the site. If controlling subsurface migration using an odour/emissions control type of system is a priority, this should be identified early in the project, since it may affect design decisions.

LFG collection systems usually include the following components:

- a collection field
- collection piping
- an LFG extraction plant
- LFG flare/treatment
- process control systems

LFG collection fields typically consist of an array of vertical wells and/or horizontal trenches that are located within the solid waste mass. A network of piping transports the collected LFG from the field to the extraction plant. LFG extraction blowers are usually located at the plant. These units generate a vacuum in the collection piping which extracts LFG from the site and transports it to the plant. LFG is discharged under positive pressure from the extraction blowers and is directed to LFG flares and/or a utilization system.

Photographs of various components of LFG collection systems are included at the end of Section 6.2.1.4.

6.2.1.1 Collection Field

Vertical wells and/or horizontal trenches are installed to collect LFG from the site. To fulfill the objectives of odour/emissions control, collection fields are generally designed to optimize LFG collection from the site. Figure 6.1, Figure 6.2, and Figure 6.3 provide typical well and trench details.

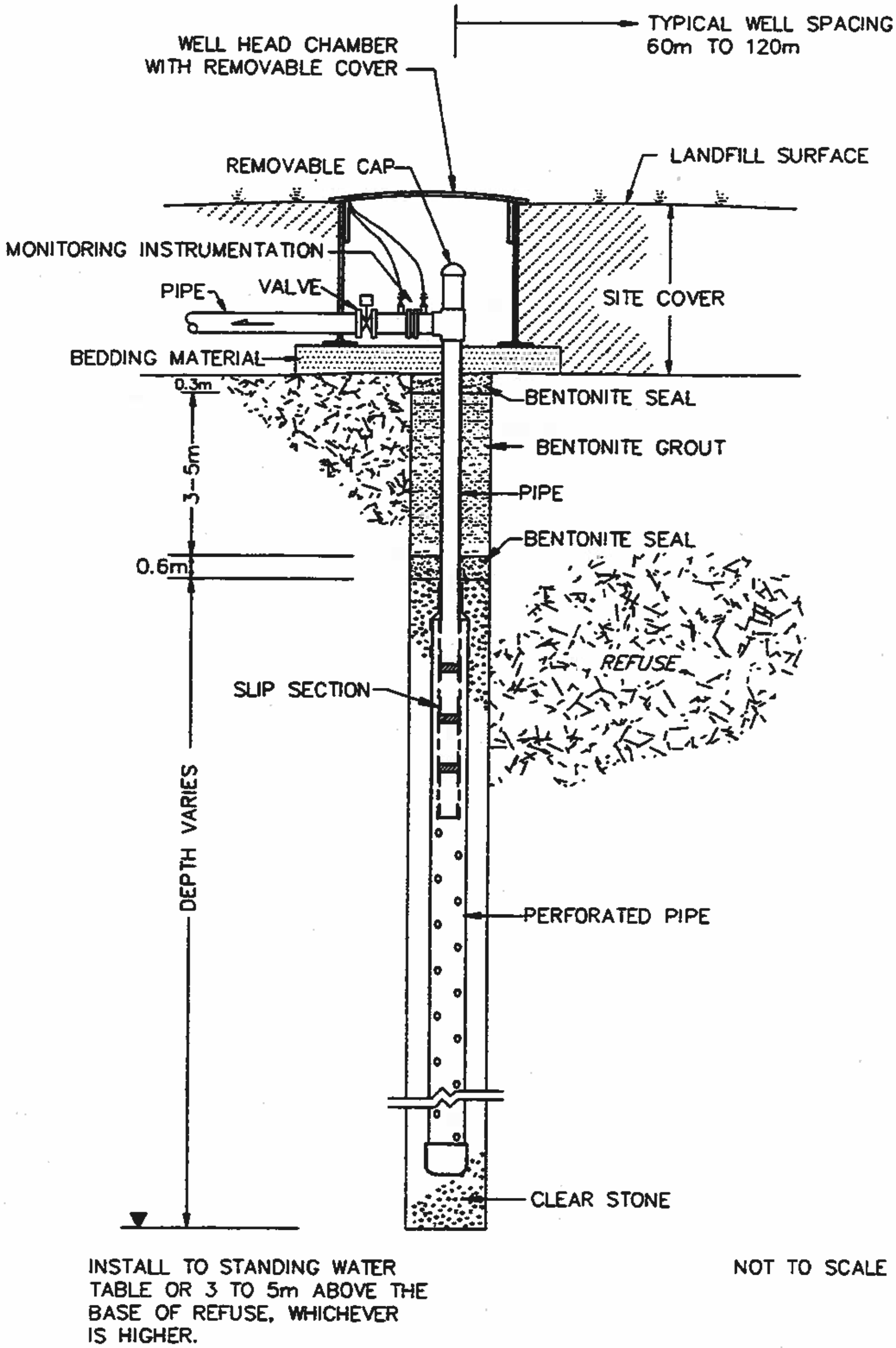


figure 6.1

RECOMMENDED DESIGN OF A LFG EXTRACTION WELL

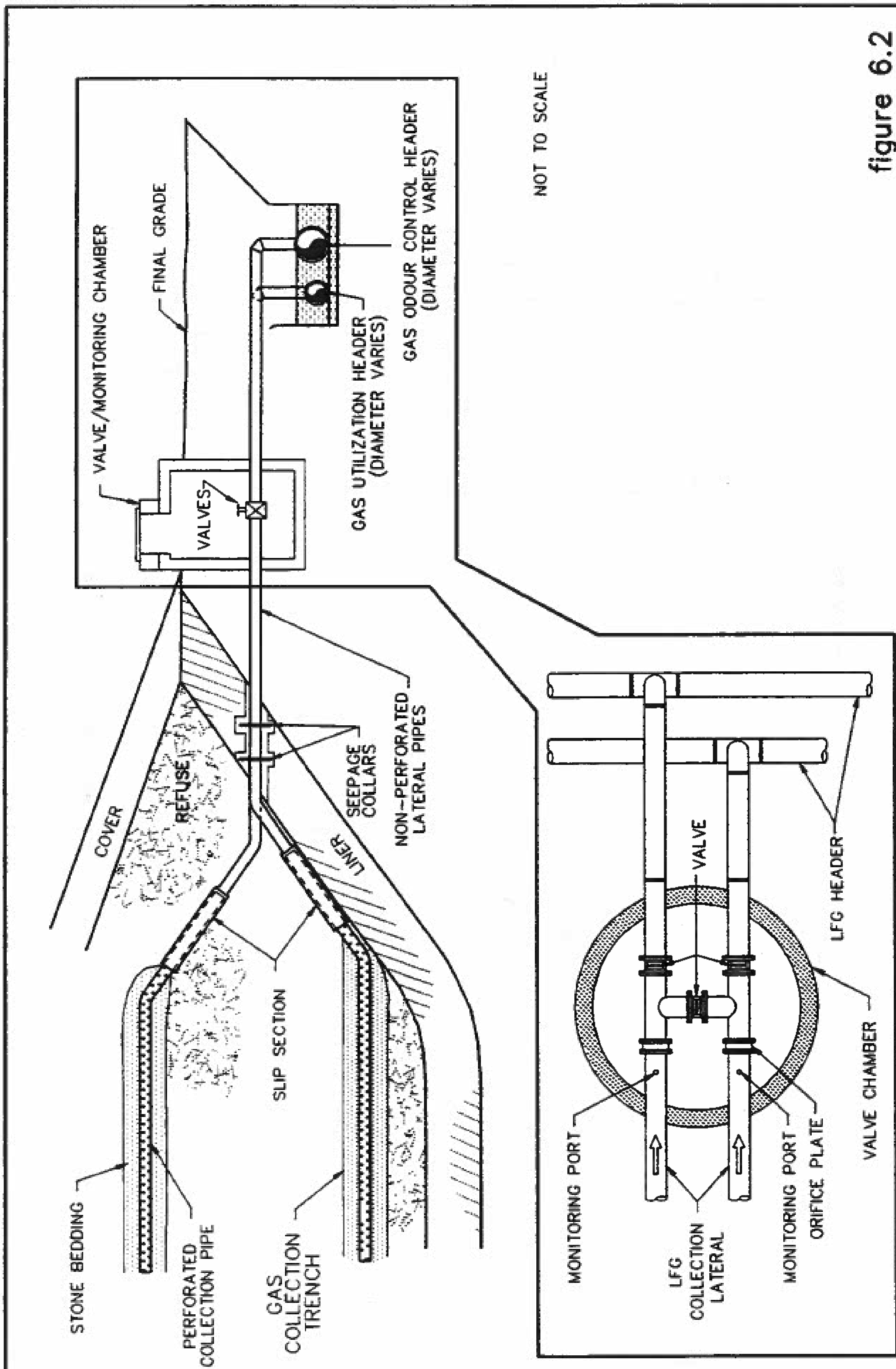
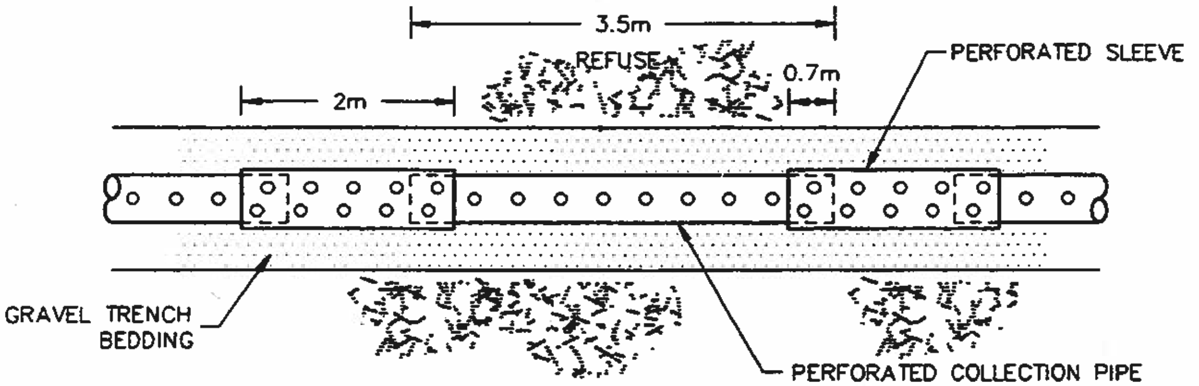
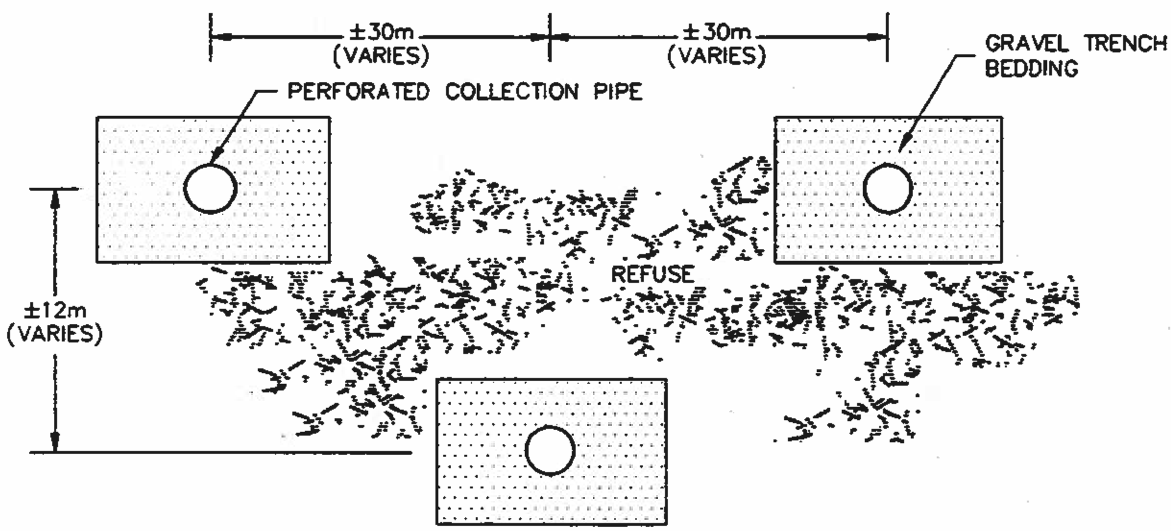


figure 6.2
HORIZONTAL COLLECTION TRENCH LAYOUT



TYPICAL HORIZONTAL COLLECTION TRENCH
PROFILE VIEW



TYPICAL HORIZONTAL COLLECTION TRENCH
CROSS-SECTION

NOT TO SCALE

figure 6.3
HORIZONTAL COLLECTION TRENCH DETAIL

The arrangement of wells or trenches on the site should be designed to include as much of the refuse as possible within their capture zones. The capture zone may be considered as that portion of the refuse in which a negative pressure may be induced by application of a vacuum at the well or trench head. This is a somewhat conservative interpretation, as a portion of the gas outside the negative pressure zone will tend to move towards the well or trench as a result of the pressure differential that develops. This conservatism is justified, however, because some component of the gas outside the negative pressure zone would be expected to vent to the atmosphere rather than to migrate into the capture zone.

The zone of negative pressure influence is highly variable from site to site and may vary from location to location within a site. There are a number of variables that affect the size of the capture zone that may be established. These include the following:

- practical limitations on vacuum that may be applied
- horizontal and vertical transmissivity of the wastes
- depth to static leachate and the presence of leachate mounds
- daily and final cover types
- site configuration

It has been found that a vacuum of 10 to 15 inches of water column (in H_2O) represents a reasonable compromise between maximizing zones of influence and minimizing air intrusion into the site, while using economical LFG extraction equipment. Capture zones that may be achieved by applying vacuum in this range are highly variable. The radius of the capture zone from the well may range from less than 30 m up to 150 m.

Vertical LFG Extraction Wells

Vertical wells are generally installed in a landfill once filling operations have been completed in a portion of the site. At some sites, methods of installing vertical wells concurrently with filling have been developed and have achieved varying degrees of success.

Use of a vertical well grid has the following advantages:

- Individual wells can be controlled and monitored to provide better areal control of gas emissions from the landfill site.
- The well field can be expanded and adjusted to reflect actual field conditions, assuming the header system has been designed with adequate flexibility and capacity.
- Some of the condensate collection problems can be minimized using the wells.

There are various vertical well designs. They range from four-inch pipes installed in boreholes less than 12 inches in diameter drilled with conventional drilling rigs, to eight-inch pipes installed in very-large-diameter (two to three feet) holes drilled with caisson-type drilling rigs. There is no significant benefit from using the much costlier large-diameter wells. Typically the limiting design factors are the maximum applied vacuum and the maximum quantity of gas that each well may have to extract. In most instances, a properly designed and installed small-diameter well provides more-than-adequate capacity with a substantial margin of safety.

Vertical collection wells are typically installed within a borehole which is augered into the solid waste. Wells should be installed to the higher of 3 to 5 m from the bottom of the waste, or the standing head of leachate. The collection well consists of a collection pipe within a gravel pack. The lower portion of the pipe is perforated to collect the LFG. The upper 4 to 6 m of the pipe is solid to limit drawing air into the waste. A bentonite, or other type of low permeable seal is usually placed in the borehole at the transition from perforated to solid pipe. This also aids in limiting the drawing of air into the site by sealing the borehole annulus.

Each vertical well should be equipped to allow monitoring of gas concentrations, temperature, flow rate, static pressure and liquid level within it. Each well should be equipped with a valve to allow individual adjustment. It is recommended that the well head, including the monitoring ports and valve, be enclosed within a lockable chamber. This will discourage tampering and vandalism, and will minimize damage due to severe weather conditions.

The well should be designed to accommodate the extreme settlement usually associated with landfills. The vertical pipe may be equipped with a telescoping section to address the change in landfill depth over time. Laterals to well heads are often equipped with a length of flexible hose. This is to allow movement in response to shear and axial forces applied to the pipe by the differential settlement of the landfill.

A well spacing of 60 m is a conservative design for a typical site with sandy daily cover. It is reasonable to assume that the actual capture zone characteristics will vary from location to location at the site. One approach to efficient well spacing is initially to install wells one-and-a-half to two times farther apart than the minimum expected for the site and then to fill in with additional wells as needed.

To maximize collection efficiency, wells should be grouped at the deeper and older portions of the site and arranged outwards from there. If there is a concern regarding subsurface migration of LFG from the site, wells placed near the edge of refuse may be grouped more tightly. This will create a greater overlap of capture zones to ensure a higher confidence in collection of LFG without the need to overdraw the wells.

There are practical limitations on the placement of vertical collection wells. It is recommended that a minimum of 4 to 6 metres of landfill depth be maintained above the top of the perforations of the well. This is required to prevent drawing air into the landfill by active extraction. The depth to perforations should be increased for wells in close proximity to side slopes. The depth to perforations should be selected to ensure that the capture zone does not fall within the required cover depth (4 to 6 metres) at the side slope of the site. This will be dependent upon the radius of influence expected, the degree of slopes on the site and the cover material. The specified depth of cover above the perforations (4 to 6 metres) may be reduced somewhat at sites with engineered low permeable or synthetic covers.

The equipment typically used for installing wells is limited in its ability to work on slopes. If a standard track-mounted soil-boring rig is used, roughly 4:1 (H:V) is the steepest slope that the machine can handle; for steeper slopes, benching at well locations will be required. If the larger crane-type caisson rig is used, access is extremely limited and stable access roads and drilling pads must be constructed. Slope stability is a concern with these types of rigs.

Horizontal LFG Collection Trenches

Horizontal collection trenches are generally used at sites where controlling LFG emissions during the site filling period is a priority. A horizontal collection system can address the one major deficiency in the use of vertical wells: it can collect LFG from beneath active areas of sites still being filled. However, the horizontal collectors are not as suitable for localized area control. These horizontal collectors will typically be installed at depth within a large landfill. The horizontal collectors will be subject to extremes of differential settlement since they extend laterally over portions of a site that may have different types, depths and age of refuse. Except for the specific items noted above, the operating principles for the vertical wells and horizontal trenches and wells are the same.

Horizontal collection trenches consist of a perforated pipe in a gravel bedding, which is placed in a trench in the refuse. The trench may be excavated into the top of a lift of refuse. Alternately, the trench may be constructed by first stripping any cover soil from the top of the refuse surface, then building a gravel berm containing the collection pipe and overfilling the trench with refuse.

The horizontal collection pipe may be a continuous run of pipe or may be segmented. The segmented approach, using two sizes of pipe with the segments overlapping, is preferred as it provides additional flexibility. Some depth of gravel should be provided below the pipe to allow for drainage of liquids from the trench. Horizontal collection trenches should be installed at a high enough elevation in the wastes to avoid flooding by mounded leachate. At sites where perched leachate conditions are prevalent, drainage of trenches may be enhanced by excavation or drilling of sumps at intermediate locations along the trench alignment.

Trench laterals should be equipped with telescoping sections of non-perforated pipe at the edge of the site to account for settlement movement. As with vertical wells, individual trenches should also be equipped with valves and monitoring ports.

Horizontal trenches are installed at various depths within the refuse as filling progresses. Trenches must be installed in a manner that is compatible with filling operations at the site. This is best achieved by aligning the trenches generally perpendicular to the direction of landfilling. One disadvantage associated with the use of horizontal collection trenches is the difficulty of arranging a trench network at sites with irregular configurations. The horizontal distance between trenches should be similar to that used for wells (30 to 60 m). The vertical distance between trenches should be less than the horizontal spacing. This is due to the fact that the horizontal permeability of refuse may be as much as ten times greater than the vertical permeability. Vertical spacing between trenches may be in the range of 10 to 20 metres. The depth of soil/refuse cover over a collection trench is an important consideration in designing the collection field layout. As with wells, 4 to 6 metres of site depth should be maintained over the expected capture zone of a trench.

Well and trench components that are in contact with LFG, condensate, refuse or leachate should be constructed of materials that are chemically resistant to the potentially aggressive compounds present. There are a number of economical plastic materials available that have proven success in landfill applications. Two of the most common are polyvinyl chloride (PVC) and high density polyethylene (HDPE).

Table 6.1 presents a summary comparison of vertical LFG collection wells with horizontal collection trenches.

Table 6.1 Summary Comparison of LFG Collection Wells and Trenches

Vertical Wells	Horizontal Trenches
• improved localized extraction control • provide extraction capabilities for full depth of waste after filling is complete • not as susceptible to moisture build-up • flexibility to add wells after site closure	• allow for collection of LFG during active filling of site • cost effective • less interference with after-use as fewer components located on site surface • requires coordination with disposal operation • arrangement may be limited by site filling plan • more common at large landfills

6.2.1.2 Collection Piping

A network of piping is constructed to transport LFG from wells and/or trenches to the LFG extraction plant. In general, LFG piping systems include the following:

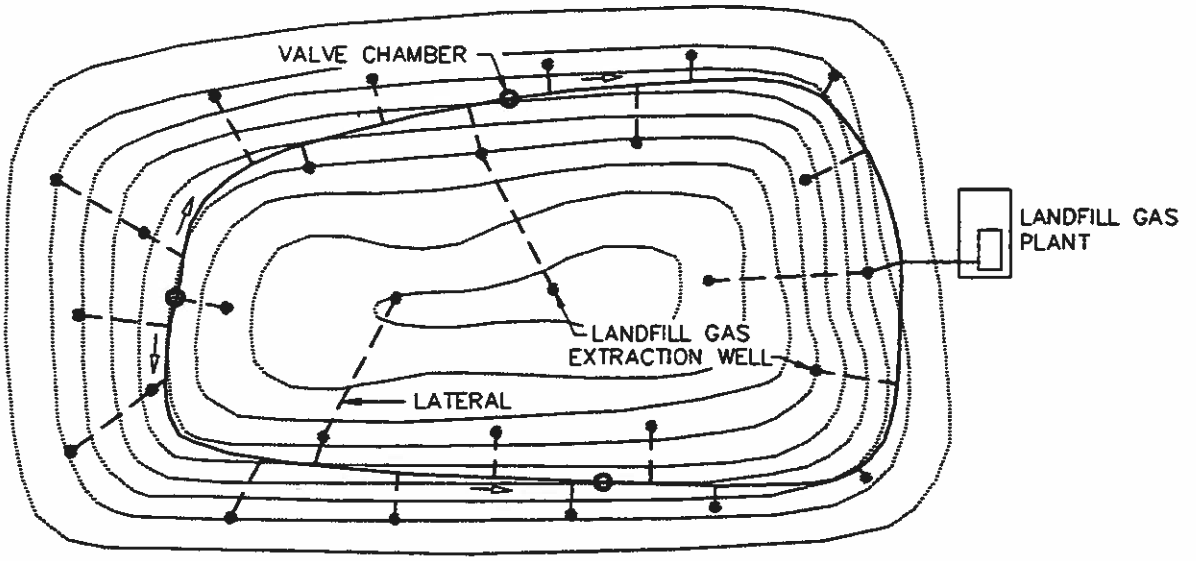
- small-diameter (minimum 100 mm), short laterals which connect to wells and/or trenches
- subheaders which connect groups of wells and/or trenches
- headers which transport LFG from the subheaders to the extraction plant

There are a number of typical patterns for arranging the LFG piping network. Piping arrangements are generally designed to facilitate drainage of liquids in the pipeline and to minimize the quantity of pipe which is required. Common arrangements of collection piping make use of either a "herringbone" or a "ring" layout as shown in Figures 6.4 and 6.5.

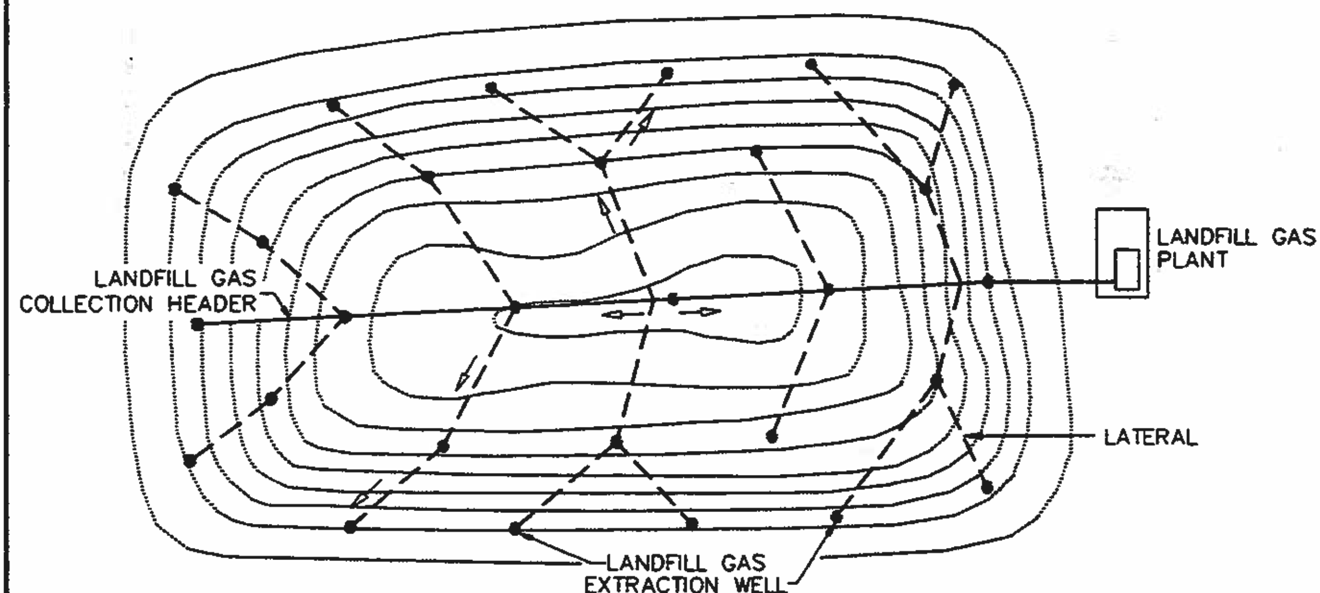
The herringbone arrangement has a single main header with subheaders and laterals branching off it. This arrangement represents the most efficient use of piping. Wells are grouped to facilitate drainage along the subheader or lateral alignment. Piping alignments should be chosen to provide the most direct routing that maximizes the slope of the pipe. Particular care should be taken to avoid creating low spots in the piping. This arrangement can be designed to minimize the quantity of condensate which is collected, by sloping the majority of the piping towards the LFG wells. Piping cleanouts can be located at the termination of subheaders as shown in Figure 6.6. The herringbone arrangement may also be used with an off-site header. This reduces the quantity of piping which must be located on refuse but may increase the quantity of condensate which is generated. Use of an off-site header system requires a reasonable grade along the alignment outside the site for gravity drainage or construction of condensate pumping stations.

The on-site ring header may be used when there is insufficient land available for construction of a header system outside the limit of refuse. The ring header offers the advantage of flexibility, allowing gas to be drawn through either side of the header. This could be useful if one portion of the header had to be shut off for maintenance. Use of a ring header (either on-site or off-site) located outside all the wells is one method of collecting all the condensate that forms in the piping. Preventing condensate drainage back into the landfill is mandated in some locales.

Use of an off-site ring header affords the operational flexibility associated with ring headers and reduces some of the problems associated with placement of piping on refuse. On-site piping is typically buried below the frost line. Some sites have clay or synthetic liners that require pipe crossings as shown on Figure 6.7.



RING LAYOUT



HERRINGBONE LAYOUT

LEGEND

—▷ DRAINAGE

figure 6.4
COLLECTION HEADER PIPING LAYOUTS (ON-SITE)

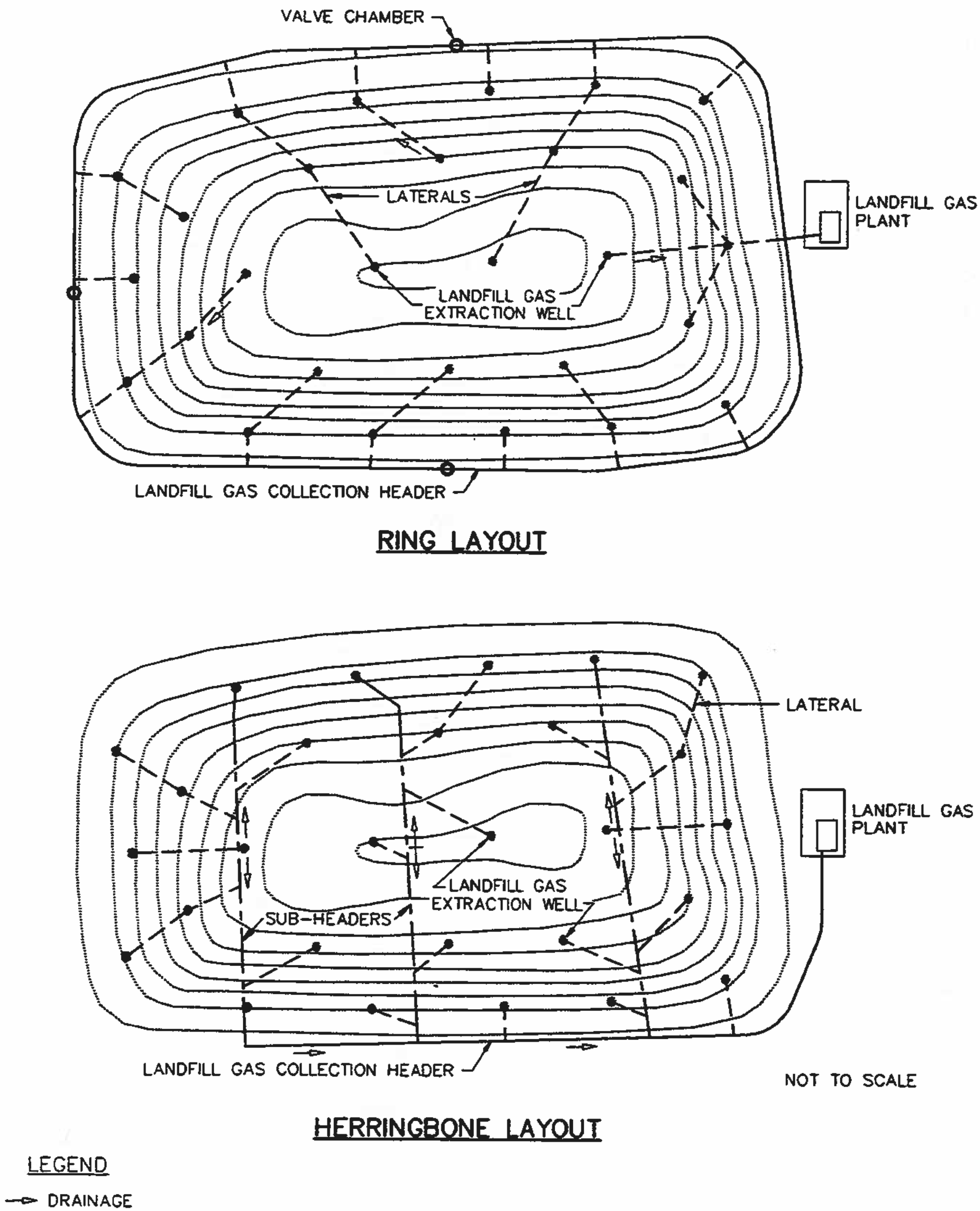


figure 6.5
COLLECTION HEADER PIPING LAYOUTS (OFF-SITE)

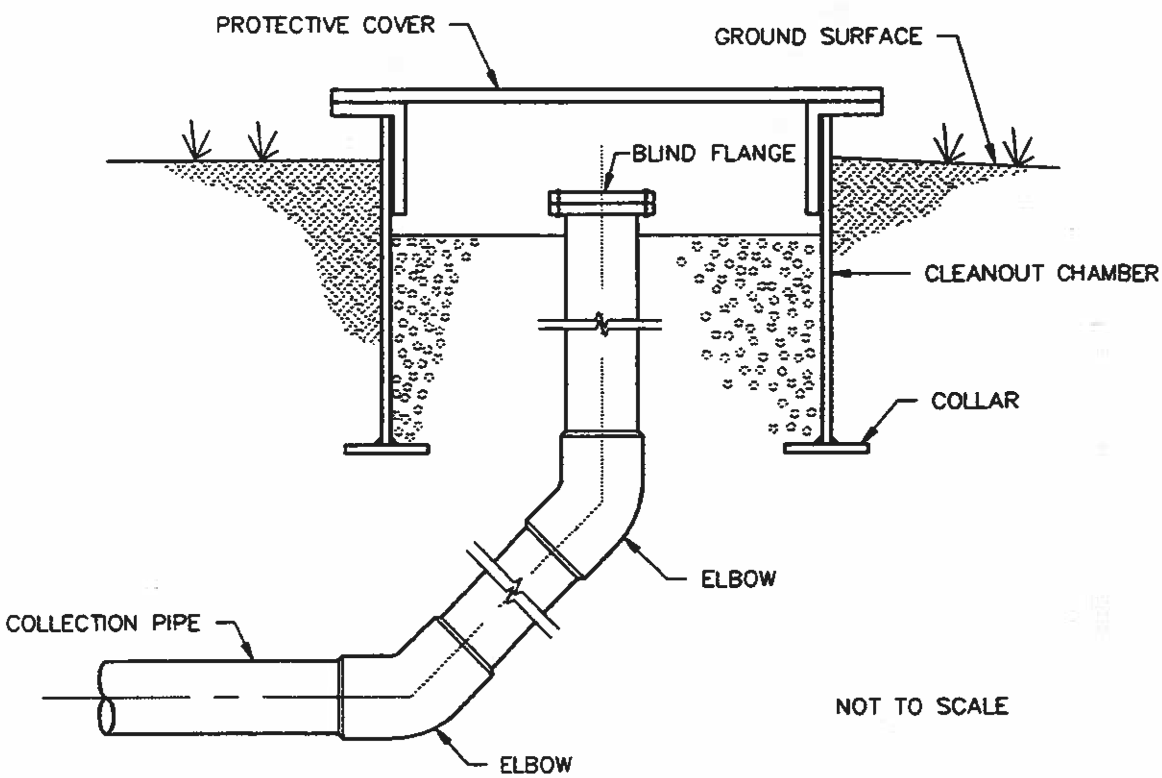


figure 6.6
COLLECTION HEADER CLEANOUT

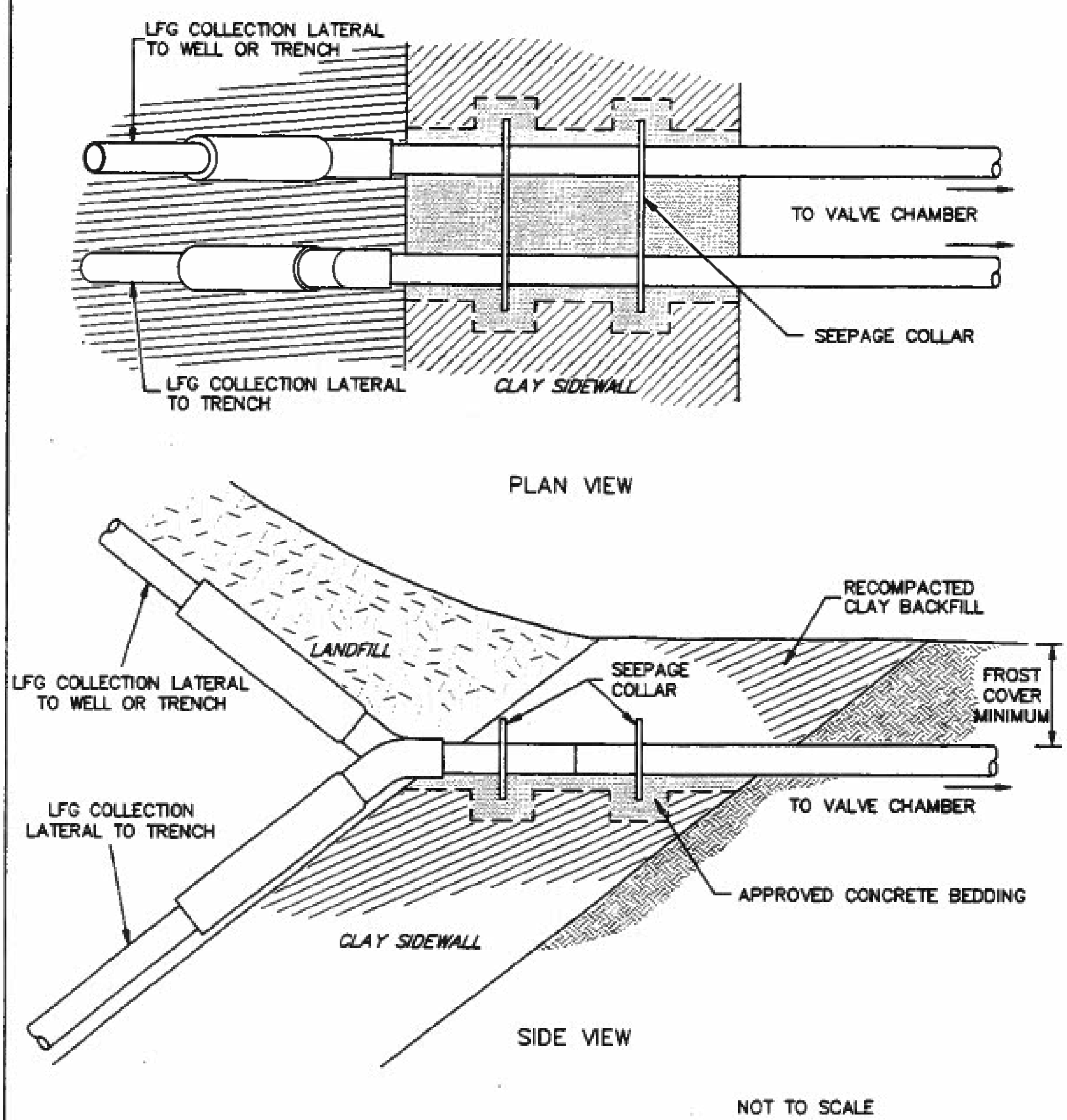


figure 6.7
CLAY SIDEWALL CROSSING

Ring headers should be equipped with a number of valves to allow isolation of portions of the site if required. Headers should be equipped with locations for monitoring of gas quality and quantity. In some applications, dual headers are employed (see Figure 6.8). A dual header system may be used at a site where control of odours and emissions and LFG utilization are both considered priorities. Dual headers allow segregation of methane-rich gas, originating in deeper portions of the site, from gas collected near the surface of the site, which may be diluted with air. Dual header systems are most applicable at large sites with long filling periods.

Table 6.2 presents a summary comparison of the major features associated with the different piping arrangements.

Table 6.2 Summary of Comparison of LFG Collection Piping Arrangements

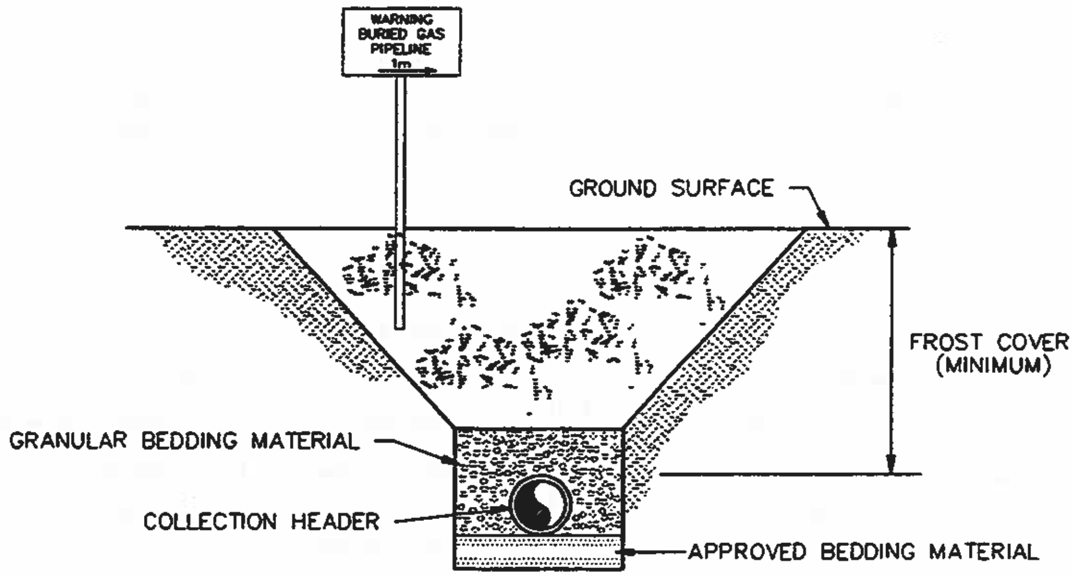
On-site Header		Off-site Header	
Ring Layout	**Herringbone Layout**	**Ring Layout**	**Herringbone Layout**
• settlement concerns • enhanced operational flexibility	• cost effective • minimize condensate removal • settlement concerns	• maximizes condensate removal • grading limitations may exist • off-site land requirements • operational flexibility • multiple liner/sidewall crossing	• cost effective • grading limitations may exist • off-site land requirements • multiple liner/sidewall crossing

It is recommended that piping placed on refuse be graded to provide a minimum 3 percent slope. This is a reasonable slope which will minimize the potential for ponding of liquids due to local differential settlement affecting the pipe slope. It should be recognized that magnitudes and rates of landfill settlement are highly variable. In some extreme cases (deep sites), settlement may occur which is greater than the 3 percent minimum grade. In such cases, repair and regrading of the area may be required.

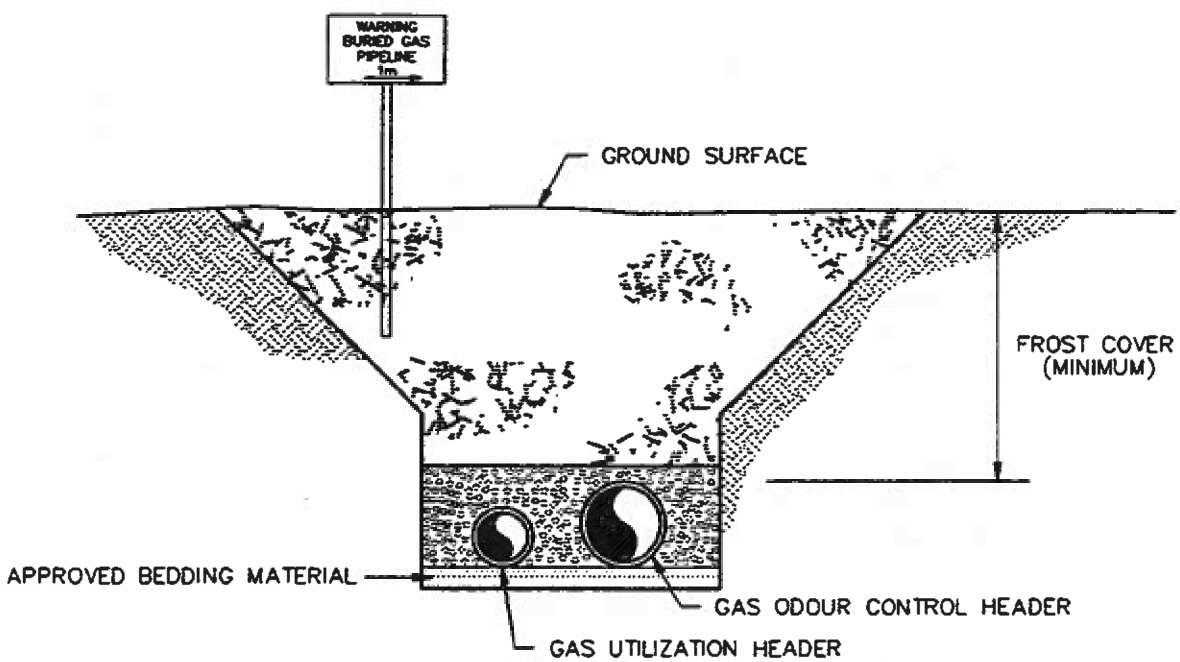
It is recommended that LFG piping be protected against exposure to freezing temperatures; otherwise, the liquid condensate and moist gas could freeze on the pipe walls and reduce or block the flow of LFG. Providing thermal insulation will reduce the quantity of liquid which will condense out of the gas. Generally the most cost effective method of insulating LFG pipelines is to bury the pipe in soil below the local depth of frost. Other methods of pipe insulation are also available such as pipe wraps or Styrofoam; however, these are generally more costly than soil cover.

Low spots in the header system will require some method of draining the piping. This can be accomplished using condensate gravity drains or pump stations. Gravity drains may be constructed which allow accumulated liquid to drain back into the landfill or into a leachate collection system connection (see Figure 6.9). At sites with perched or mounded leachate conditions, gravity drainage of condensate back into the landfill is not generally recommended. Particular care should be taken in designing condensate drains to ensure that they are able to withstand the system operation vacuum. A sufficient factor of safety should be included in the design to resist pressures applied as a result of system start-up and shut-down.

A condensate sump with pump station can be installed if a gravity drain cannot be constructed (see Figure 6.10). The condensate can be collected in a sump and pumped to a discharge point or to the next high point in the header, where it may be allowed to re-enter the LFG piping. In some cases a condensate holding tank (see Figure 6.11) may be used.



SINGLE LANDFILL GAS HEADER



DUAL LANDFILL GAS HEADERS

NOT TO SCALE

figure 6.8

SINGLE AND DUAL HEADER CROSS-SECTIONS

Pipe sizes should be selected to convey the expected quantities of LFG with manageable frictional pressure losses. A hydraulic evaluation of the system piping should be performed. The system hydraulics should be checked not only under expected operating conditions but also under the worst case scenarios. The worst case scenarios may need to include an assessment of changing LFG production characteristics in different portions of the site over time.

All buried piping should be designed to resist the dead and live leads to be applied. Particular care must be paid to ensuring that the pipe and backfill system is able to withstand heavy equipment loads.

6.2.1.3 LFG Extraction Plant

The LFG extraction plant includes the mechanical and electrical components of the system that actively collects LFG from the site. At sites where utilization may be an option, it is generally recommended to incorporate flexibility for future utilization into the plant design. Methods to achieve this are discussed in the following text. Figures 6.12 and 6.13 show a typical plant process schematic and a typical plant arrangement, respectively. Table 6.3 presents a summary of pertinent considerations for design of LFG extraction plants.

Table 6.3 Summary of LFG Extraction Plant Design Considerations

Plant Site

- Centrally located with respect to landfill
- Provide sufficient space for future expansion
- Consider zoning and proximity to adequate power supply, sewers, and water supply
- Consider proximity to fuel users, power grid interconnects, and natural gas pipelines
- Minimize visual and noise impacts

Facility

- Modular plant may offer savings
- Enclosing equipment in buildings reduces maintenance costs, enhances security, and reduces visual and noise impacts
- Buildings containing gas piping or equipment are classified as hazardous areas by electrical code
- Provide buildings with interior air monitoring and alarms, and pressure release panels
- Enclose electrical switch-gear and controls in a separate building from gas piping and equipment
- Provide space to add equipment in the future

Components

- Valves and controls as required for safe operation in accordance with applicable codes
- Provide condensate pumping or storage
- Provide LFG flow metering and recording
- Provide sufficient blowers or compressors to meet capacity requirements, plus one standby unit

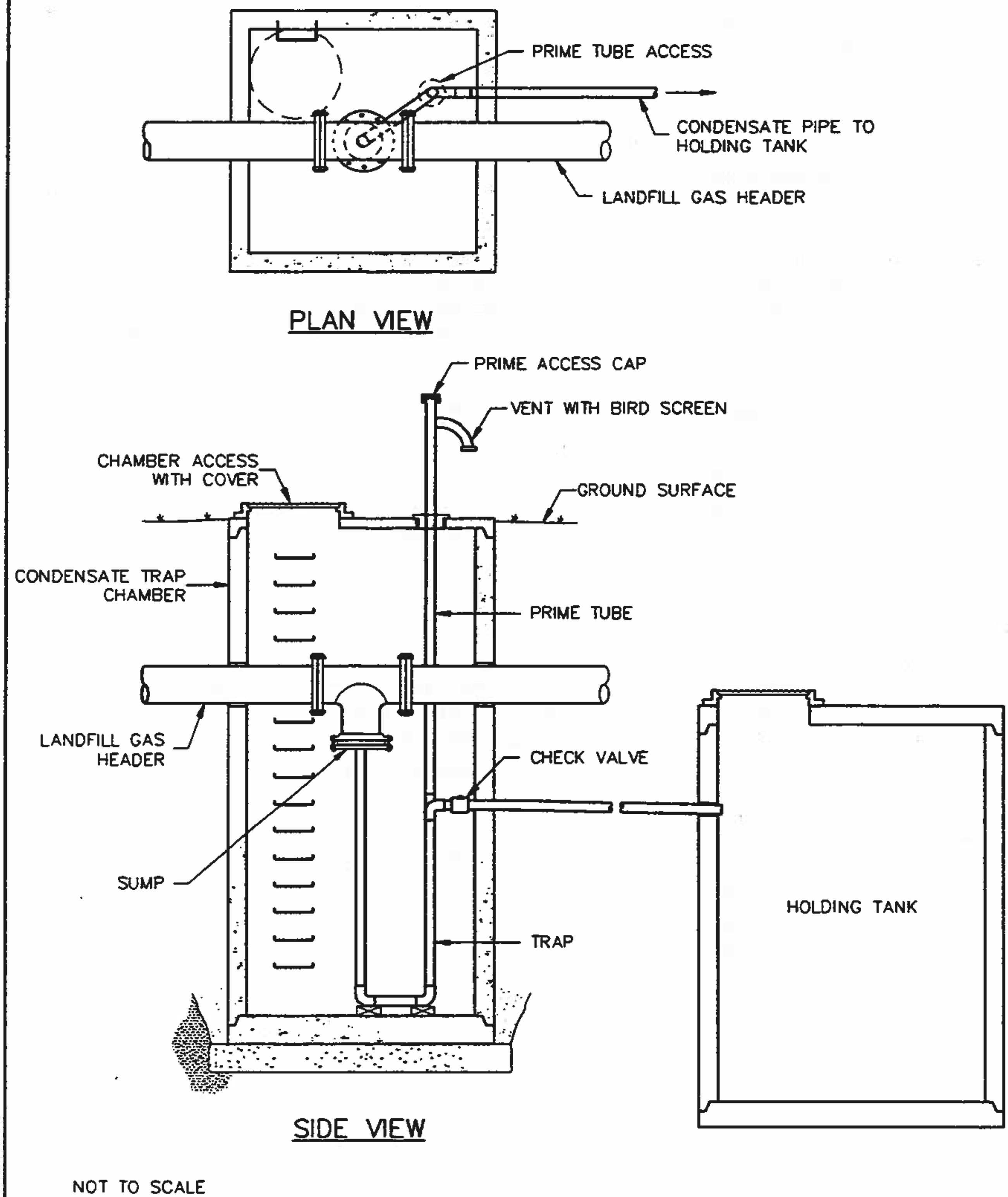


figure 6.9
CONDENSATE TRAP CHAMBER

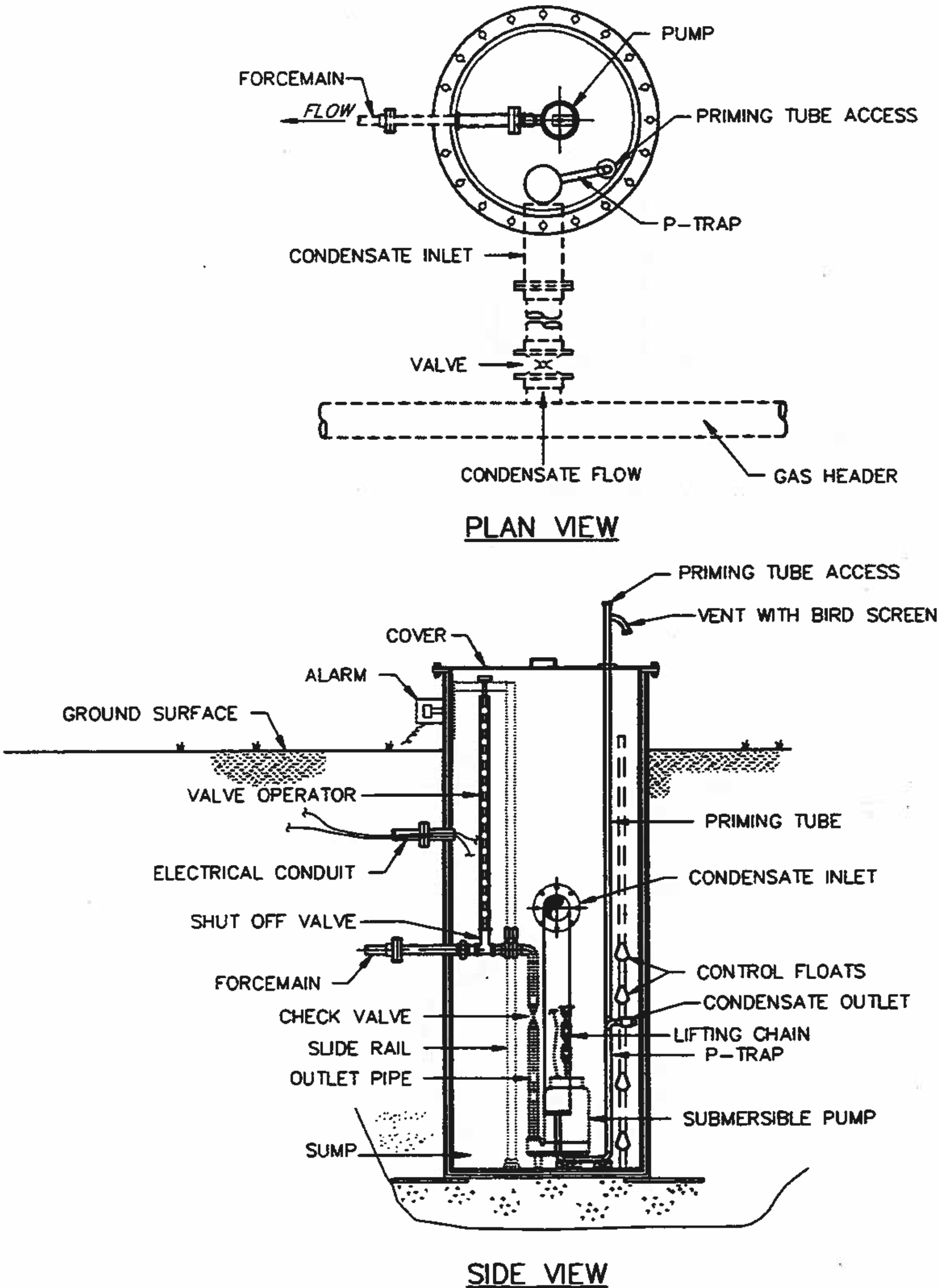


figure 6.10
CONDENSATE PUMP STATION

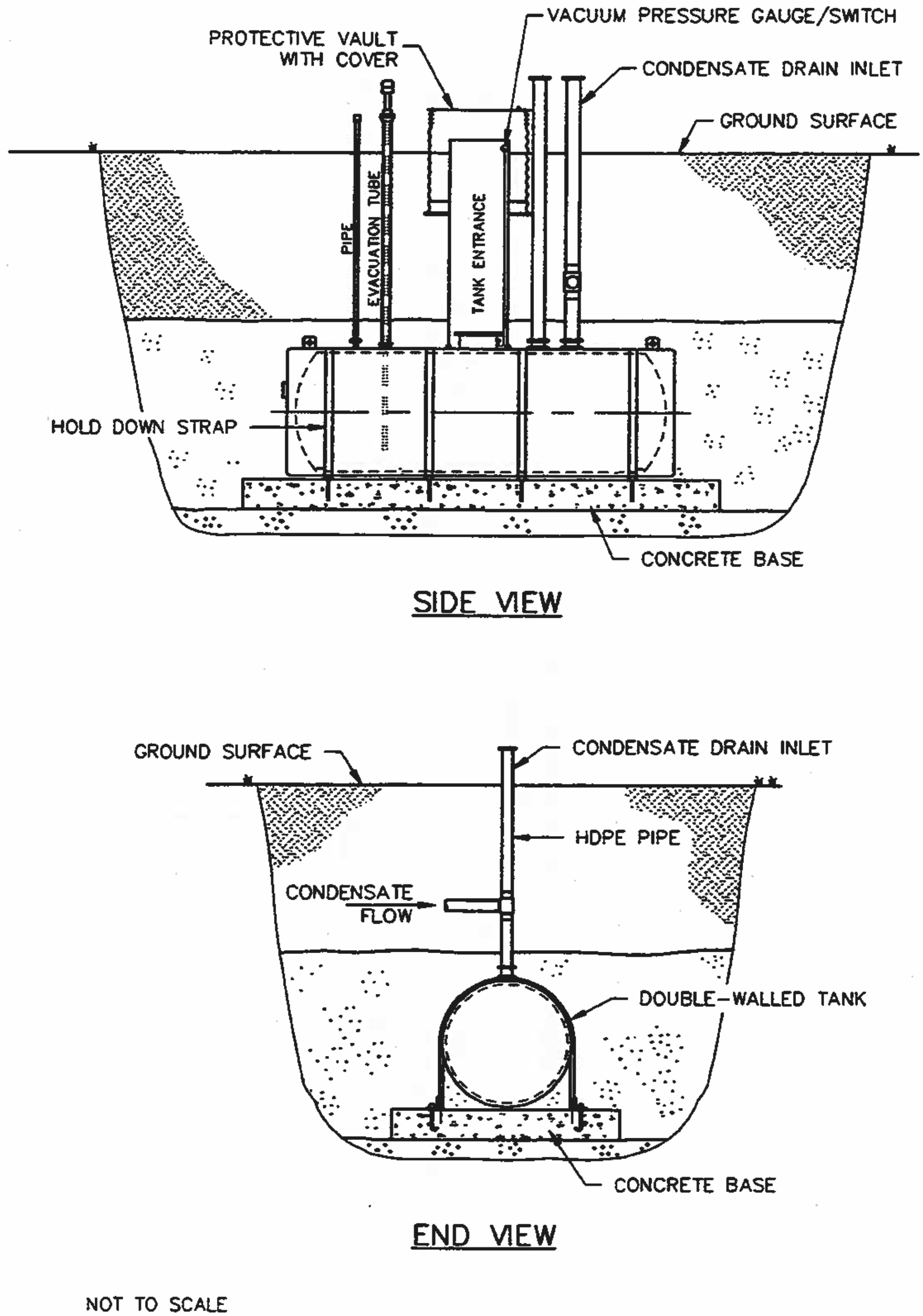


figure 6.11
CONDENSATE TANK

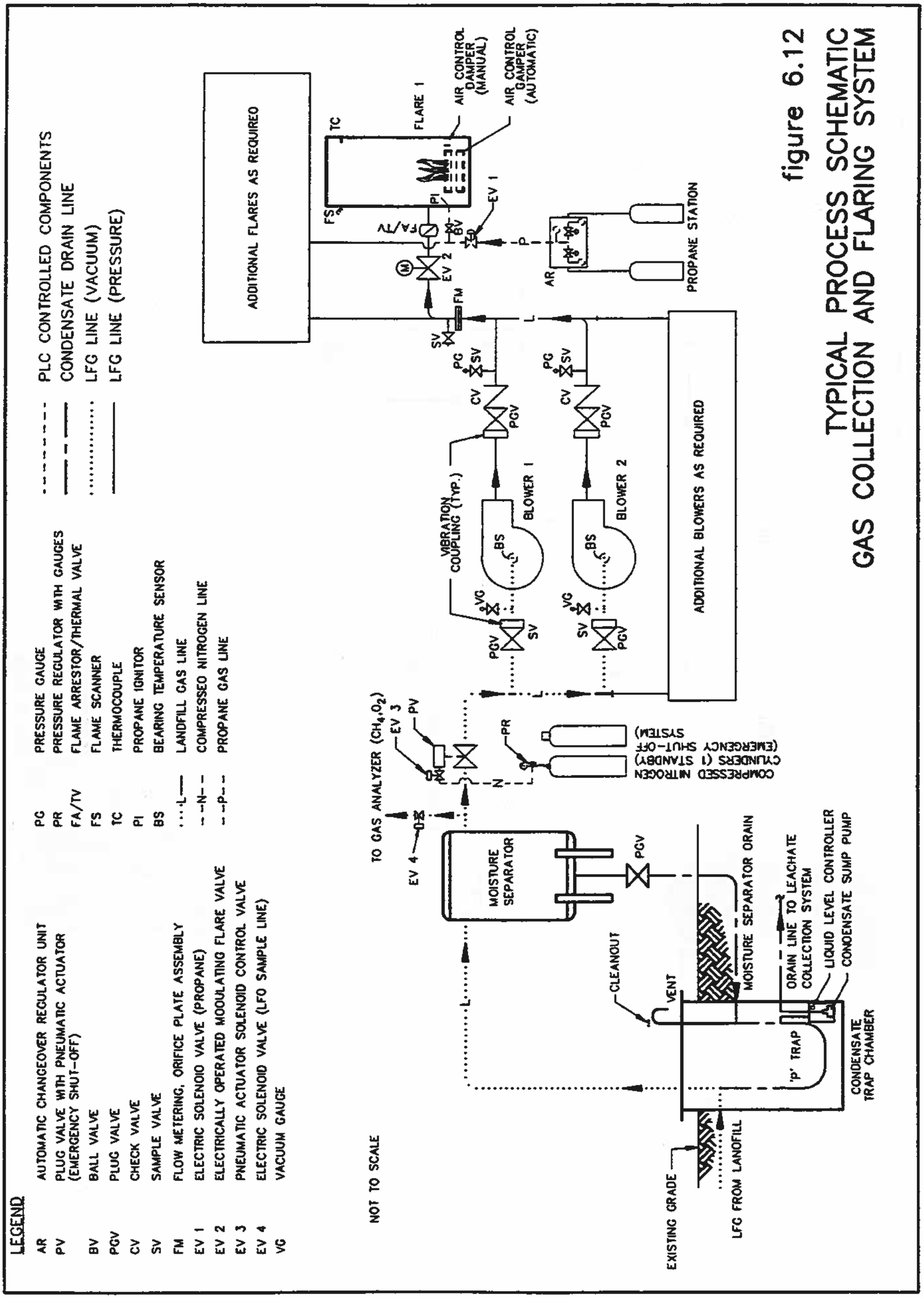


figure 6.12
TYPICAL PROCESS SCHEMATIC GAS COLLECTION AND FLARING SYSTEM

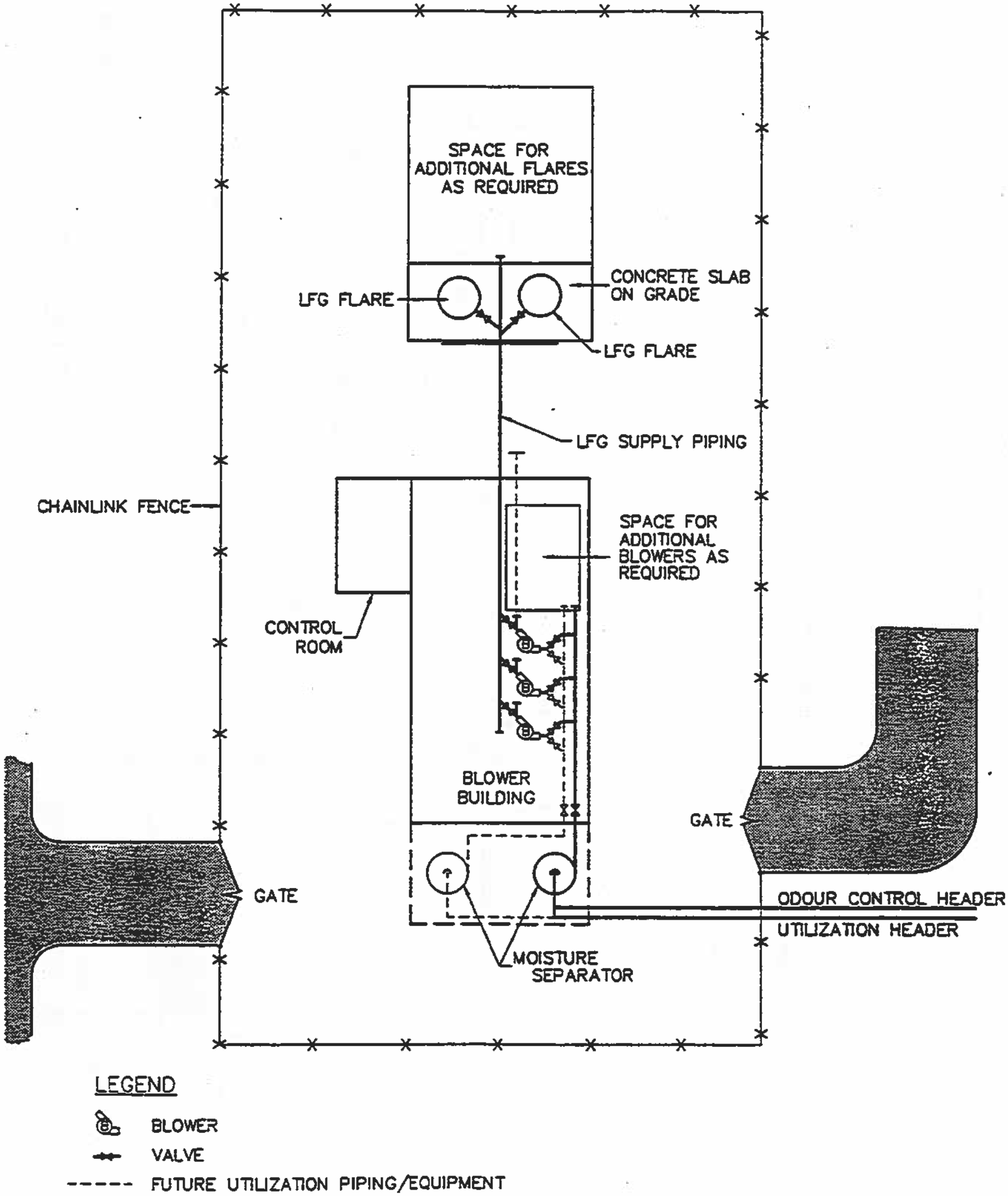


figure 6.13

LFG CONTROL PLANT COMPOUND

In general, most systems are equipped with a centrally-located control plant, which also contains the flare. Depending on the size and configuration of the site, more than one collection plant may be required. These plants may serve as pressure boost stations to deliver the collected LFG to a central location. In some cases, it may also prove beneficial to have more than one flaring station.

The ideal is a plant centrally located and at the lowest point in the land surrounding the site. This will facilitate system operation hydraulics and drainage of condensate. It is recognized, however, that it may not be practical to accomplish this at some sites. Engineered solutions are available for less than optimal conditions. These may involve selection of large pipe diameters, selection of larger blowers, construction of pump stations and construction of pressure boost stations. Such measures increase the overall cost of the system.

The following factors should also be considered in selecting the plant location:

- zoning by-laws
- site access
- proximity to power supply and sewers
- potential noise and visual impacts
- LFG utilization considerations, including proximity to electric utility interconnect, natural gas pipelines and potential fuel consumers

The primary components of a typical LFG extraction plant may include the following:

- condensate separator and storage tank with pumping system
- piping and valves
- LFG metering (quantity and quality)
- LFG extraction blowers

The LFG flare or some other treatment system is generally located at the LFG extraction plant. Overall system controls are usually also incorporated into the LFG extraction plant.

The piping system at the flare station may be designed to allow for independent operation of dual headers, allowing direction of the collected gas to the flares or to any future LFG utilization facility. If the LFG utilization plant is built, the collection plant and operating capacity should be maintained to act as a backup in the event of LFG utilization plant down-time or if the LFG utilization plant does not use all the recovered LFG.

The LFG extraction plant may be enclosed within a building or left exposed to the elements. Housing the various equipment components within a building reduces noise and visual impacts of the plant. Maintenance costs may be somewhat reduced by protecting the equipment from severe weather conditions. Enclosure of LFG pipelines and conveying equipment within a building results in the creation of an area that is typically classified as a Class I, Division D, Group 2 area according to the Canadian Electrical Code classification system. This requires that all equipment within the area be rated as explosion-proof and that special precautions be taken to seal conduits entering the area.

The buildings that house the LFG extraction plant are generally subject to hazards from LFG, which may migrate into the soil beneath the building or may leak from piping and equipment within the building. Therefore, LFG extraction plant buildings should be equipped with electronic combustible gas detection systems with alarms. The blower building should be equipped with blow-out panels to allow pressure release in the event of an explosion within the building. A separate room should be constructed to house the electrical control panels, motor control centres (MCCs) and programmable logic controller (PLC).

The plant buildings should be equipped with foundation ventilation systems or other means of protection according to the potential hazard.

Modular or "skid-mounted" LFG extraction plants are also available (see Figure 6.14). These modular systems can be configured to include all the components of a LFG extraction plant, including moisture separator, valves and piping, blowers, flare, and controls. These systems are available in a wide range of plant capacities and may offer some cost savings.

While often referred to as "skid-mounted" these modular LFG extraction plants cannot be considered readily portable. Modular systems require permanent foundations, power supply, piping connections, fenced compounds, etc. Modular components can be installed within a building.

Condensate Handling

Removal of condensate may be carried out using a sump and/or moisture separator. At 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. It is recommended that a moisture separator be included to reduce the detrimental effects that the corrosive condensate may have on gas handling equipment. Moisture separators may be very simple drum-type vessels that remove only large droplets of moisture (see Figure 6.15). If downstream equipment needs dictate, a more sophisticated moisture removal system with larger contact area and filters may be employed to provide higher removal efficiency.

At most sites where low pressure (<28 kPa or <4 psi) centrifugal blowers are used for LFG extraction, a simple drum-type moisture separator will likely be sufficient. At sites where higher pressure equipment is used for LFG extraction and/or utilization, the more complex, high efficiency moisture removal system will likely be required.

At some sites, solid particulate matter in the gas has been problematic. Fine particles of sand or grit can abrade gas handling equipment (low or high pressure) and can plug flame arrestor cores. At sites where this proves to be a problem, in-line particulate filters may be installed in the gas piping.

Once removed from the system, condensate must be disposed of in an environmentally sound manner. The chemical characteristics of condensate are highly variable from site to site. Condensate is often a somewhat more concentrated form of landfill leachate and may be considered a hazardous liquid waste. Depending on its chemical characteristics, in some localities condensate may be discharged into the sanitary sewer for subsequent treatment at an off-site sewage treatment plant. Generally, a small pumping station and forcemain will be required to deliver the condensate to the sanitary sewer. If there is no nearby sanitary sewer connection or the condensate cannot be discharged to the sanitary sewer, temporary on-site storage of condensate may be required. A holding chamber or underground storage tank may be used for this purpose. When full, the storage vessel may then be pumped out and the condensate delivered by truck to the sanitary sewer or an approved liquid waste treatment facility.

One method of estimating condensate flow is to assume that the LFG is saturated and that all the moisture condenses out of the gas. A typical condensate quantity would be in the range of 30 to 50 ml/m^3 of collected LFG. Depending on the design of the LFG collection system, it may be appropriate to include an allowance for direct contribution of liquids from the site into the system via LFG collection trenches.

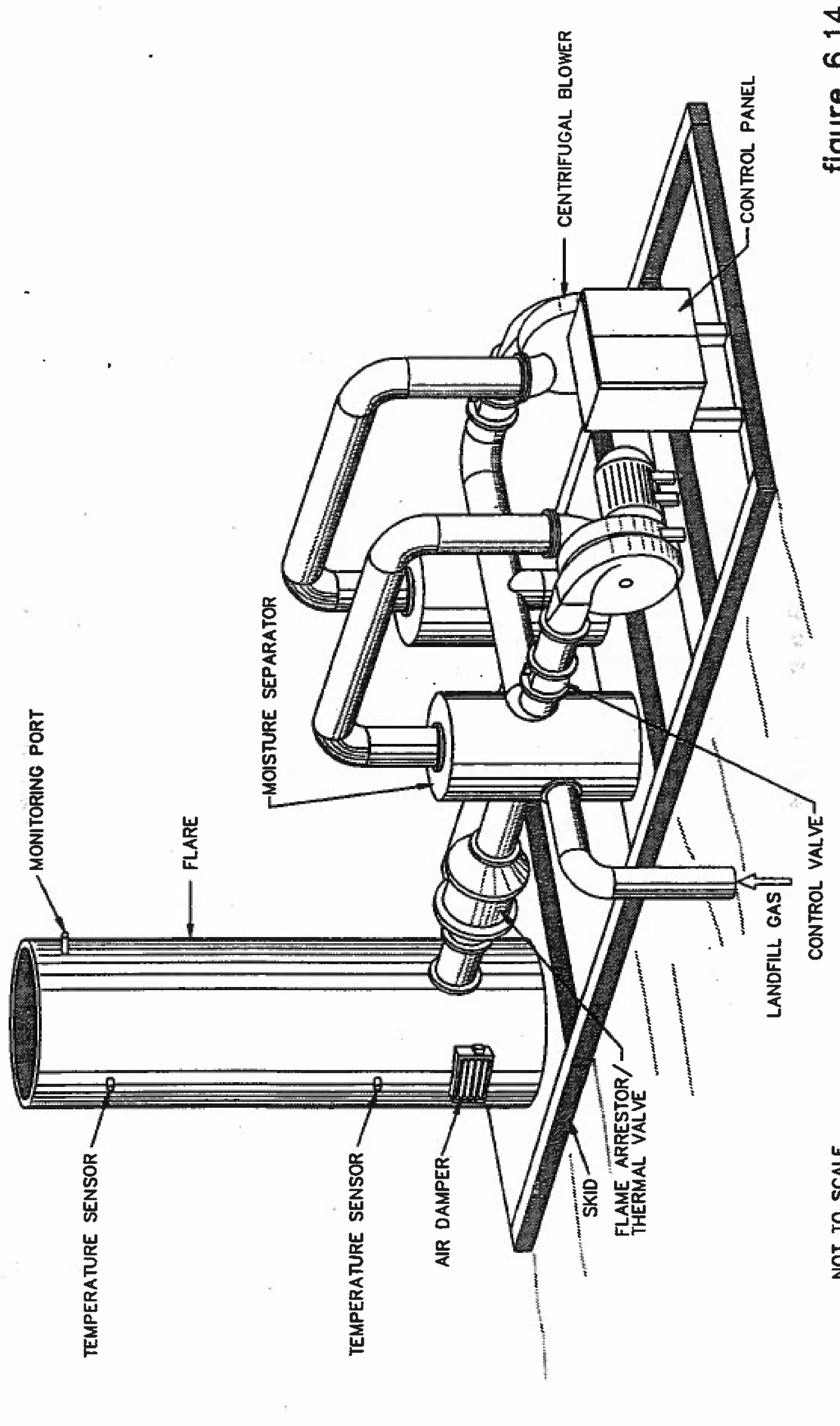


figure 6.14
MODULAR LFG COLLECTION AND FLARING STATION

SOURCE: SUR-LITE CORPORATION, 1991

Valves and Piping

It is recommended that the following components, as a minimum, be included in the LFG extraction plant piping system:

- power outage fail-safe isolation valve
- LFG extraction blower throttling and shut-off valve
- LFG extraction blower check valve
- flare flow control and shut-off valve
- flame arrestor with thermal valve

Additional components may be required depending upon the level of automation desired.

The Canadian Gas Association (CGA) has published the "Code for Digester Gas and Landfill Gas Installations, CAN/CGA-B105-M93". The CGA code presents standards for construction of LFG systems.

Metering

It is recommended that a LFG flow meter be installed to provide a continuous record of the quantity of LFG which is extracted from the site. In some jurisdictions this would be a condition of approval for the system. Quantification of extracted LFG would be useful information at any site where LFG utilization is being considered. There are numerous gas flow metering devices which may be utilized for this application. One reliable method that is commonly used is the orifice plate. The flow metering device must provide an acceptable level of accuracy throughout its expected measuring range and be able to withstand exposure to the potentially corrosive compounds in the moist LFG.

The quality of the LFG extracted may also be measured and recorded. While not generally a regulatory requirement, measurement of the methane and oxygen content of the extracted gas is useful in considering utilization and as a system diagnostic tool. There are numerous devices available for this application. As with the flow metering device, any gas analysis system must be suitable for exposure to the potentially corrosive compounds in the moist LFG.

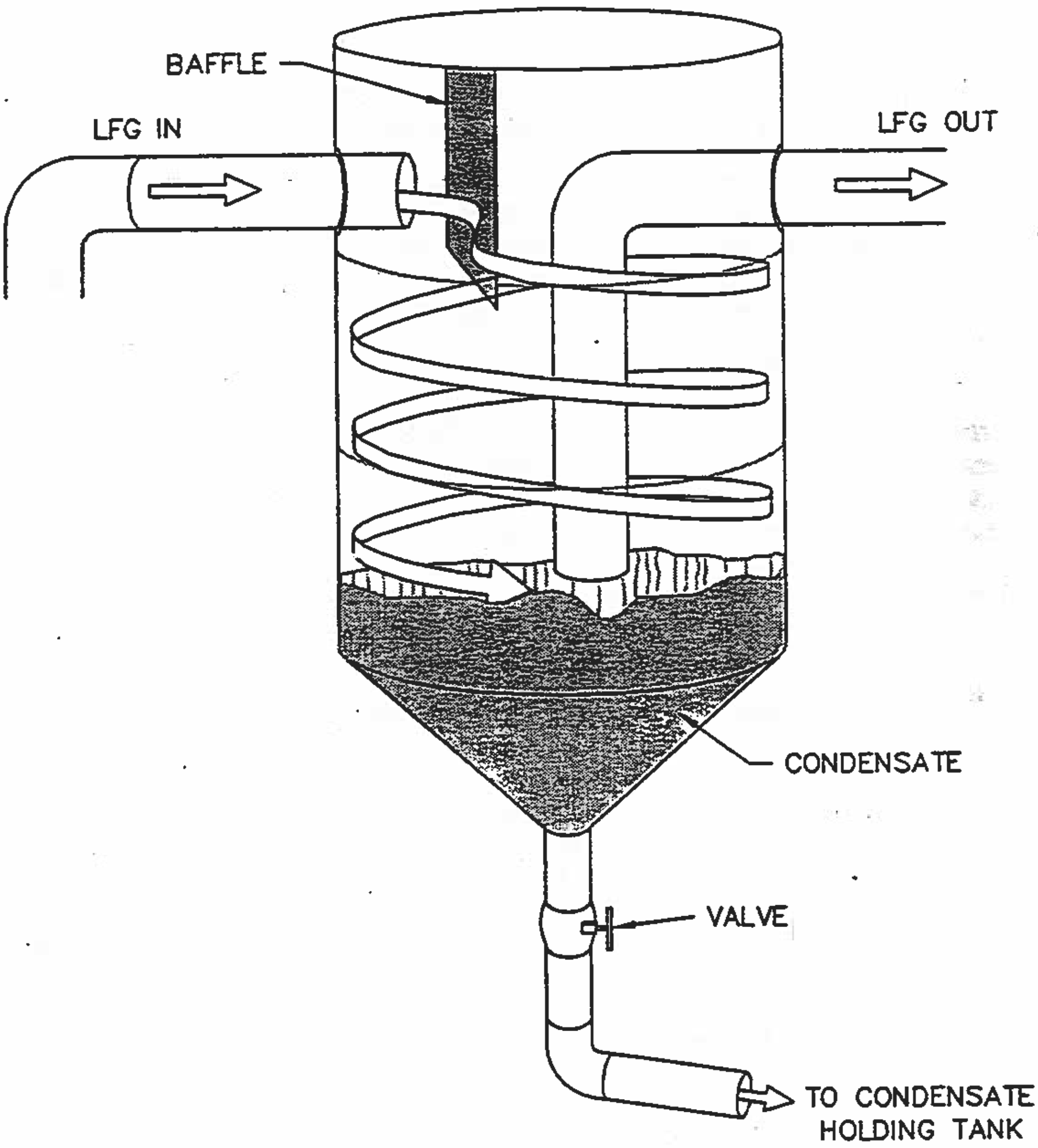


figure 6.15
MOISTURE SEPARATOR (CONDENSATE KNOCKOUT DRUM)

LFG Extraction Equipment

For many LFG systems, single-stage centrifugal blowers have proven to be suitable and economical. These types of LFG extraction blowers have low capital and operation costs, and minimal maintenance requirements. The style of construction of most single-stage centrifugal blowers is fairly simple. When constructed with appropriate materials, this type of blower stands up well to the "dirty" and potentially corrosive LFG. Depending on the model and manufacturer, single-stage centrifugal blowers typically can provide flows in the range of 85 to 8500 m^3/hr (50 to 5000 cfm) within a total pressure range of 1 to 17.4 kPa (0.15 to 2.5 psi) at horsepowers in the range of 0.25 to 100.

There are a number of options available for pressure or flow requirements that exceed those of an economical single-stage blower. Pressure performance may be increased by connecting blowers in series. Flow performance may be increased by adding blowers in parallel. Capital and operating cost considerations define the limits to adding on single-stage centrifugal blowers in series and in parallel.

Multi-stage centrifugal blowers have enhanced pressure characteristics over single-stage units. Multi-stage centrifugal blowers are available with up to five stages. These types of units can provide flows in the range of 170 to 10,200 m^3/hr (100 to 6,000 cfm) with total pressures of 20 to 90 kPa (3 to 13 psi) at horsepowers ranging from 2 to 225 Hp. Multi-stage blowers are more costly and tend to have more demanding maintenance routines than single-stage centrifugal blowers.

In some cases, where greater pressure requirements must be met, compressors may be used. Compressors are available to suit a wide range of flow requirements at pressures greater than 34.5 kPa (5 psi). Compressor systems are not commonly selected for LFG collection systems, but may be necessary if very long pipelines are required. Compressors are more common in LFG utilization applications where the equipment to be supplied, such as an engine, requires higher feed pressure than would a flare. Compressors are more costly than single- and multi-stage blowers. Compressor components are generally machined to very fine tolerances and make use of a wide variety of construction materials. Maintenance of compressors that are exposed to LFG is generally more costly and time consuming than maintenance of centrifugal blowers.

Regardless of the type of LFG extraction equipment selected, it is recommended that equipment redundancy be built into the system. One extra blower or compressor should be available as a standby. This is recommended due to the inevitable downtime that results from performing maintenance and repairs on this type of equipment. The LFG control plant should have a design capacity capable of handling 100 percent of the peak rate of LFG production estimated for the landfill plus some allowance for additional extraction for migration control. A phased approach to constructing a LFG control plant may prove to be beneficial if a gradual increase in LFG production at the landfill is anticipated. In addition, due to the uncertainty of predicting LFG production, it is recommended to provide additional capacity as a contingency measure. This may include setting aside sufficient space to add blowers and flares over and above the design capacity.

It is preferable to match blower and flare flow capacities to simplify system operations. Selection of larger blower and flare capacities may limit the ability to operate a flare at lower flow rates (turn-down ratio). Selection of small flares and blowers to obtain the required total capacity would result in higher capital costs to the project without significantly benefitting the operating flexibility of the system.

6.2.1.4 LFG Disposal Systems

The LFG which is collected from the site must be disposed of in an environmentally sound manner. Collected LFG is typically flared off and/or utilized. High temperature flaring of LFG results in conversion of the methane component of the gas to carbon dioxide and water. The trace compounds in the LFG are largely destroyed. With high temperature-controlled combustion, emissions from LFG flares have been found to meet stringent criteria and provide destruction efficiency greater than 99 percent

(Environment Canada, 1995). Utilization of collected LFG is discussed in Section 7. In most cases, collected LFG that is not utilized is flared.

There are two types of LFG flares that are commonly used. These are the open candle-type flare and the enclosed high temperature flare (as shown on Figures 6.16 and 6.17, respectively). A candle flare typically consists of a vertical pipe with a flare nozzle. Candle flares are sometimes installed on passive vents to control odours associated with the venting gases. There is some hazard associated with the system due to the potential for the flare to burn back into the passive venting collection pipes.

Candle flares should be equipped with a flame arrestor, ignition pilot, and thermal and check valves. Candle flares offer a low-cost method of disposing of LFG, which does not generally result in creation of odours. However, as the combustion temperature of a candle flare cannot be readily controlled, the destruction efficiency and emissions from candle flares may be of concern. As a result of this concern, and difficulties with measuring emissions from this type of flare, approval for candle flares may be difficult to obtain in some jurisdictions.

Enclosed flares consist primarily of a vertical stack with burner nozzles and combustion air inlets located at the base. The shell of the stack is typically steel and is lined with refractory insulating material. The flare is designed to achieve a specified combustion temperature and to retain exhaust gases at that temperature for a specified time. This ensures that a minimum degree of destruction of contaminants is achieved. Typical values for temperature and retention time are in the range of 760 to 1000°C for a period of 0.5 to 1.0 seconds. The South Coast Air Quality Management District (SCAQMD) in California specifies that MSW LFG flares attain a temperature of 815°C (1500F) for a 0.5 second retention time.

Determination of suitable destruction efficiency is based on the energy content and trace contaminants in the gas. Emissions tests performed at Metro Toronto's Keele Valley and Brock West Landfill Sites and at numerous American sites (Mostardi *et al.*, 1991) have demonstrated effective control of emissions from enclosed flares that meet the temperature specifications noted above.

Enclosed flares should be equipped with automated temperature controls that modulate the combustion air-inlet dampers to attain a specified temperature within the flare. This type of flare is equipped with an ignition pilot, which can be of continuous or intermittent operation. Enclosed LFG flares should be equipped with the following features to ensure safe operation:

- flame arrestor
- electronic ignition system
- flame sensors
- automated modulation and shut-off valves
- temperature sensors
- electronic interlocks to shut the system down under fault conditions

Provision of a standby LFG flare is not required in all cases as flares have been found to be quite reliable. In some cases, where there may be particular sensitivity to downtime of the flare, a redundant unit may be needed.

The modular LFG extraction plants discussed earlier can be configured to include a LFG flare.

In all Canadian jurisdictions, LFG flares will require specific environmental approvals. In some cases, small quantities of collected LFG are vented to the atmosphere. Such cases are limited to situations where the collected gas may be treated effectively and the concentration of the combustible component of the collected gas is too low to burn (less than 25 to 30 percent by volume). In general, this is not a preferred option for disposal of anything but small quantities of gas.

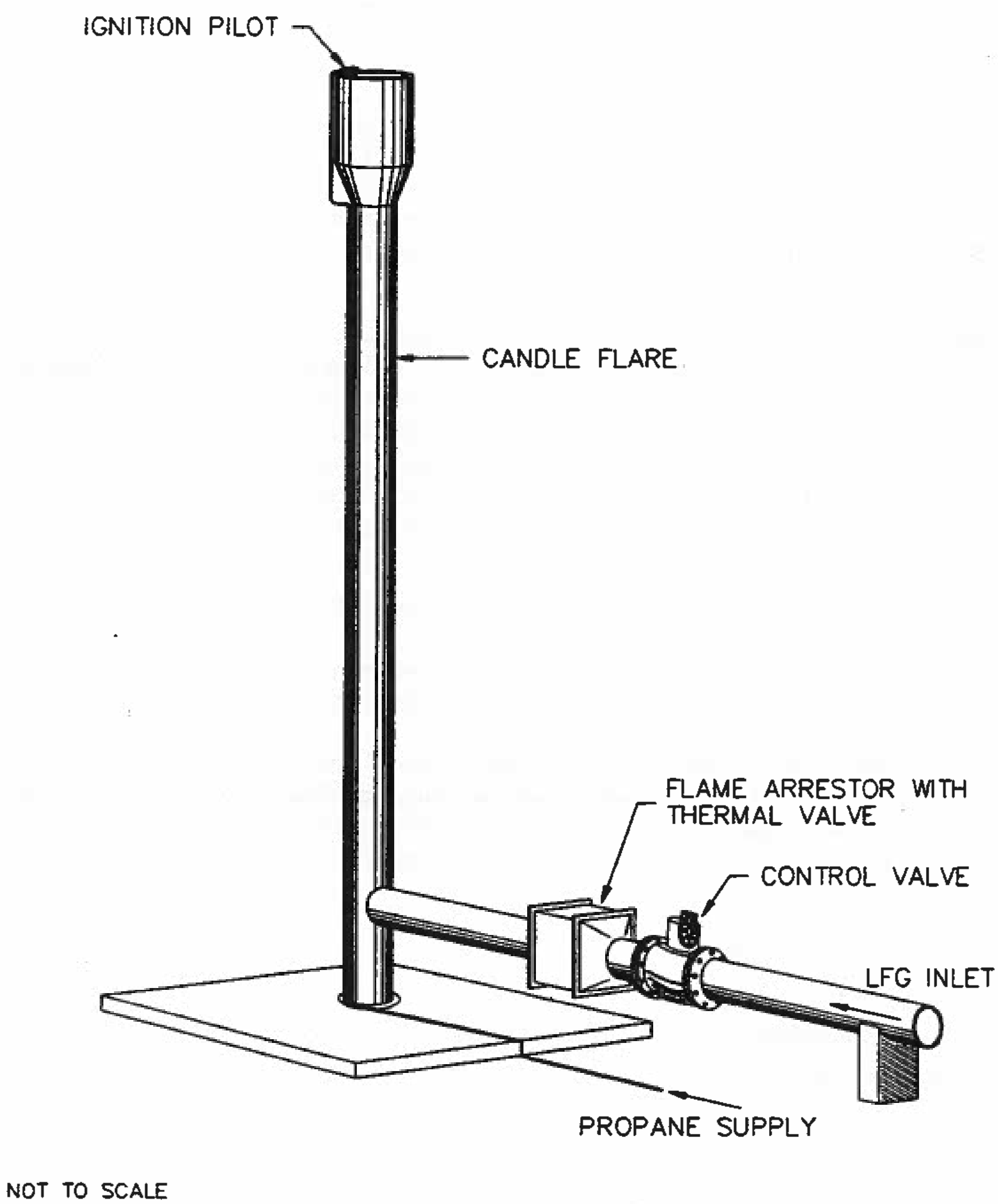


figure 6.16
LANDFILL GAS CANDLE FLARE

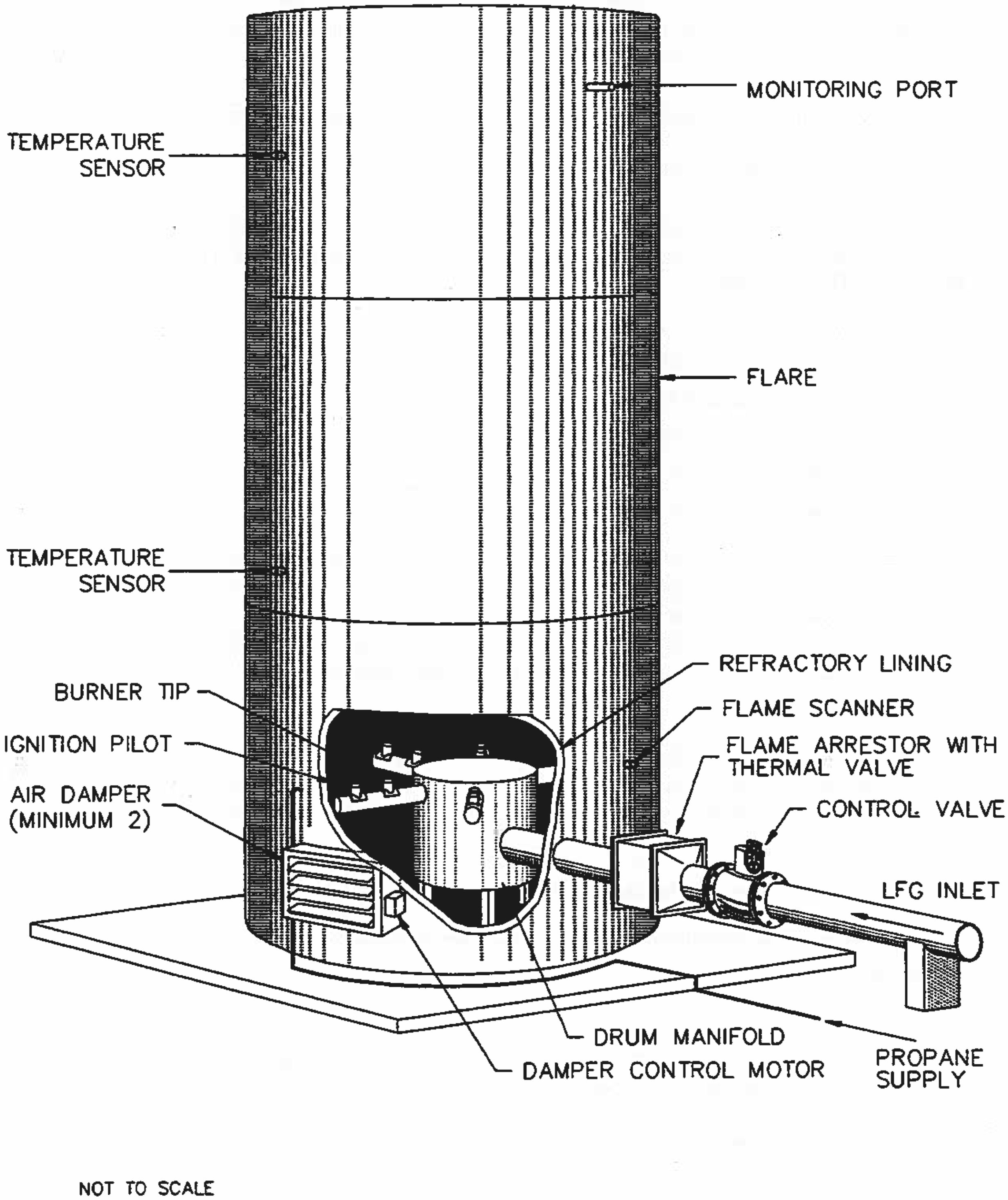


figure 6.17
ENCLOSED LANDFILL GAS FLARE

Methods of treating low-calorific-value LFG that cannot be flared include special burners, fuel augmentation, granular activated carbon and biological treatment (Groenestijn and Hesselink, 1993). Low-calorific-value fuel can be disposed of using catalytic oxidation, thermal incineration and burners designed to use this type of fuel (Eden, 1994). Augmentation of the gas would be required if the combustible concentration of the collected gas was too low to support combustion (i.e. less than 25 to 30 percent by volume). Augmentation fuel requirements may be reduced or eliminated by using heat exchangers or preheating the combustion air. Treatment methods involving the use of carbon filtration or biological treatment are limited to removal of mercaptans and volatile organic compounds.

6.2.1.5 Process Control Systems

Systems for controlling the operation of the overall LFG system can be highly automated or primarily manual. At minimum, basic functions to ensure the safe and proper operation of the system should be automated. These include:

- automatic flare temperature controls
- automatic pilot ignition confirmation interlocked with blower operation
- flare and blower operation interlocks
- main flare confirmation interlocked with blower operation
- high-temperature shutdown
- automated fail-safe valve to isolate the plant piping on power outage

These process controls may be implemented using electronic relays, programmable logic controllers (PLC); or computer-based supervisory control and data acquisition systems (SCADAs). Any of these systems can adequately perform the control functions necessary for operating a LFG collection and flaring system. PLC- and SCADA-based systems are somewhat more flexible for customizing automatic controls and automated recording of data. These features can prove useful if LFG utilization is under consideration.

The primary function of the control system is to ensure that the various system components are operated in a safe and efficient manner, and to shut the system down and activate alarms under fault conditions. The degree to which operation and data recording functions are automated is a matter of owner or operator preference.

Security and safety systems that should be included in the plant design include:

- interior ambient air monitoring for combustible gas interlocked to the ventilation system
- heat and flame detection
- building security

The plant should be equipped with warning lights and buzzers activated by the above. As most LFG control systems are monitored only part-time, if at all, it is recommended to install either a telephone service and auto-dialer or an automatic radio transmitter unit in the plant. This will provide remote notification of fault conditions or alarms to a staffed location on a 24-hour basis.

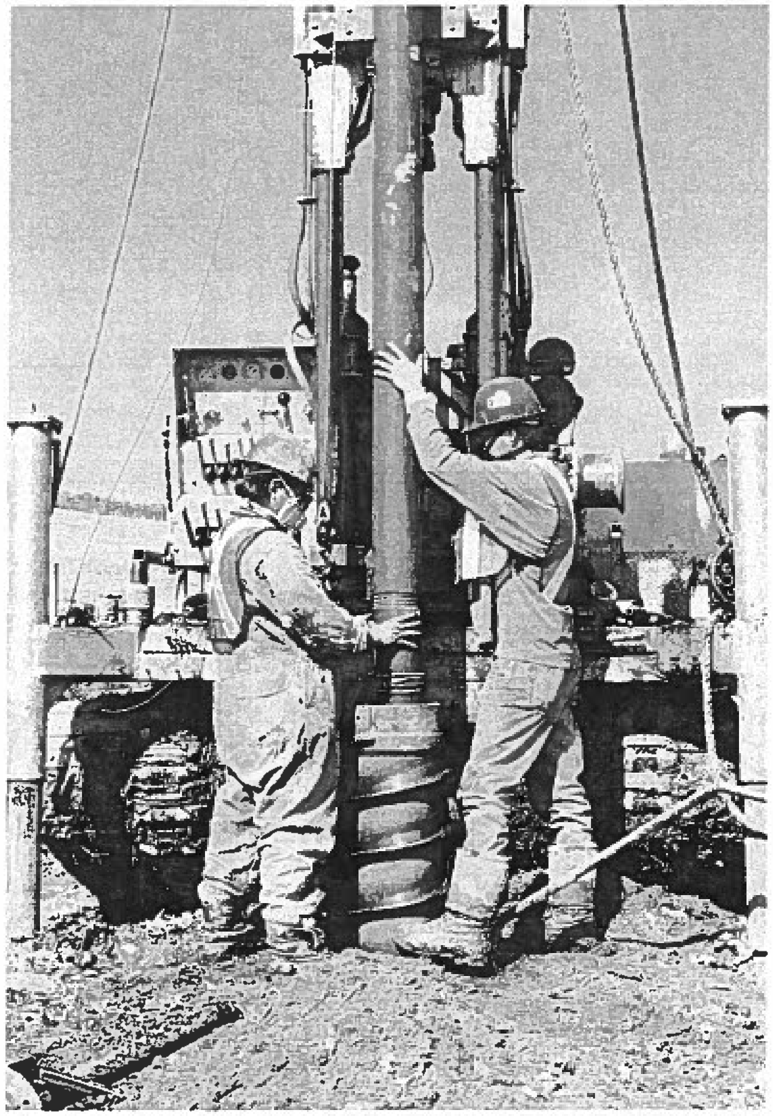


PLATE 1
INSTALLATION OF LFG EXTRACTION WELL

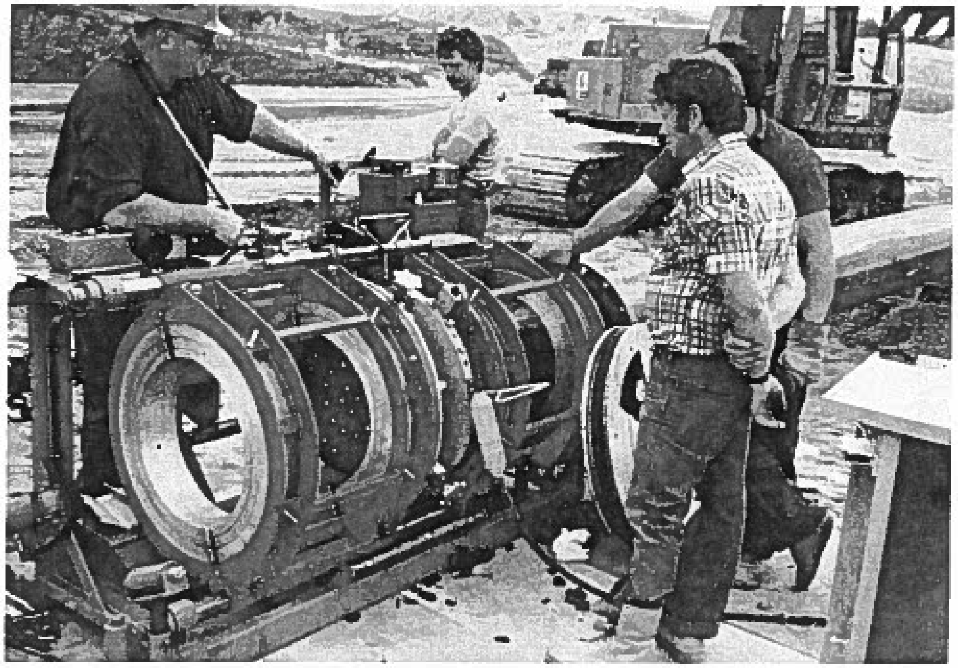


PLATE 2
HDPE BUTT FUSION MACHINE

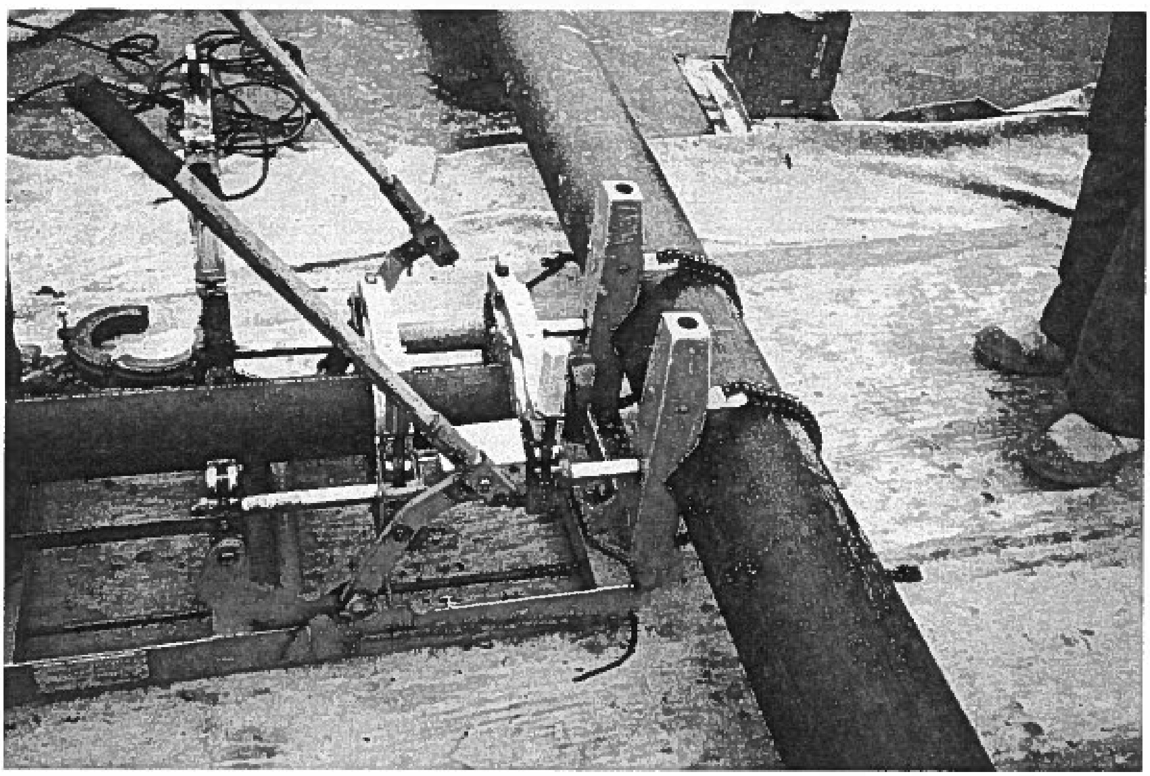


PLATE 3
HDPE SADDLE FUSION MACHINE

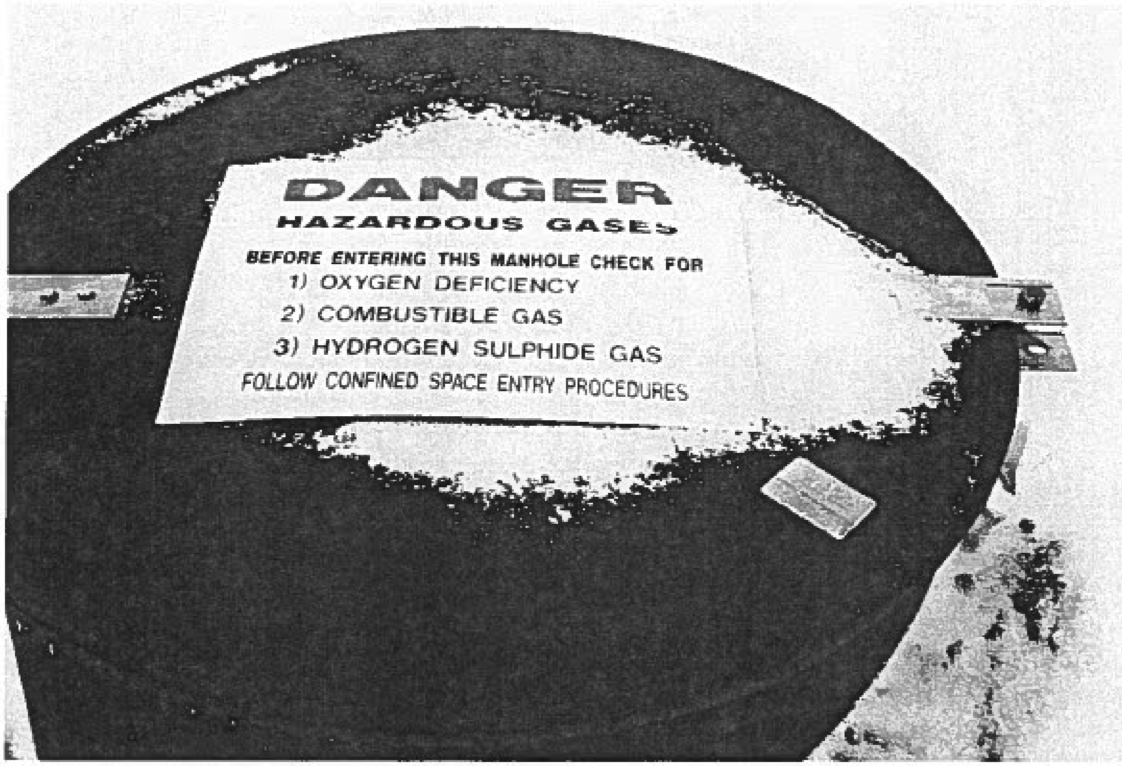


PLATE 4
VALVE/MONITORING CHAMBER

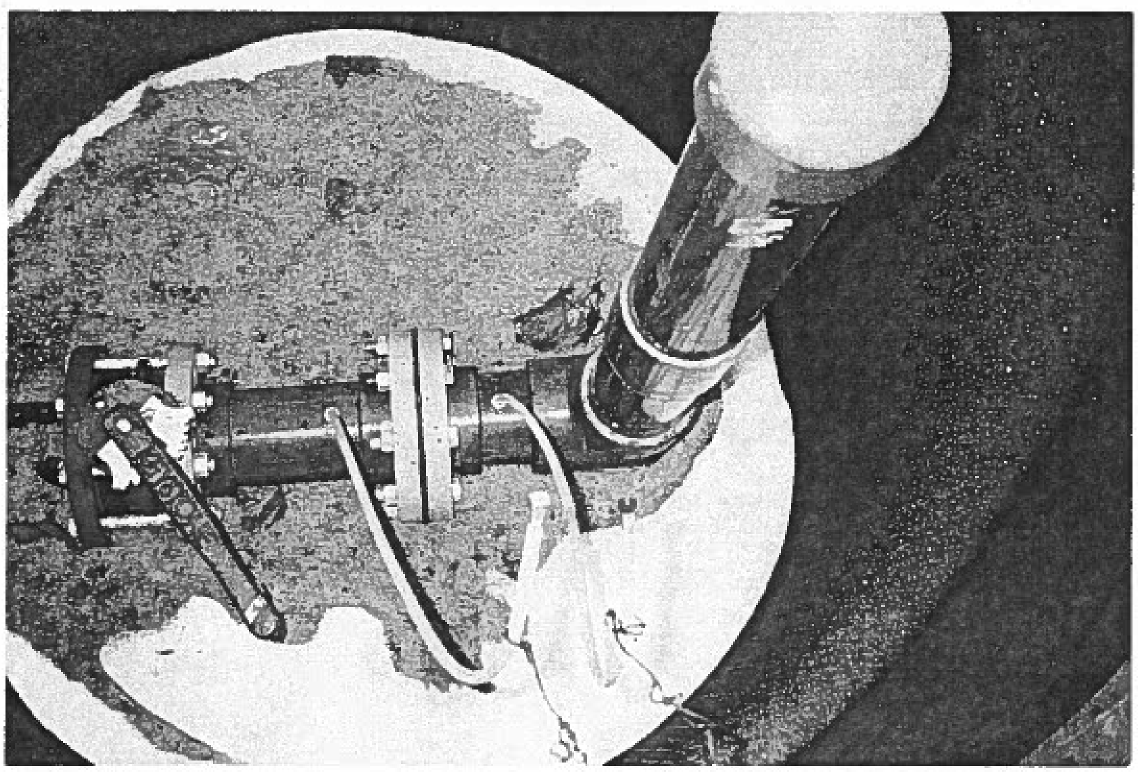


PLATE 5
WELL HEAD ARRANGEMENT

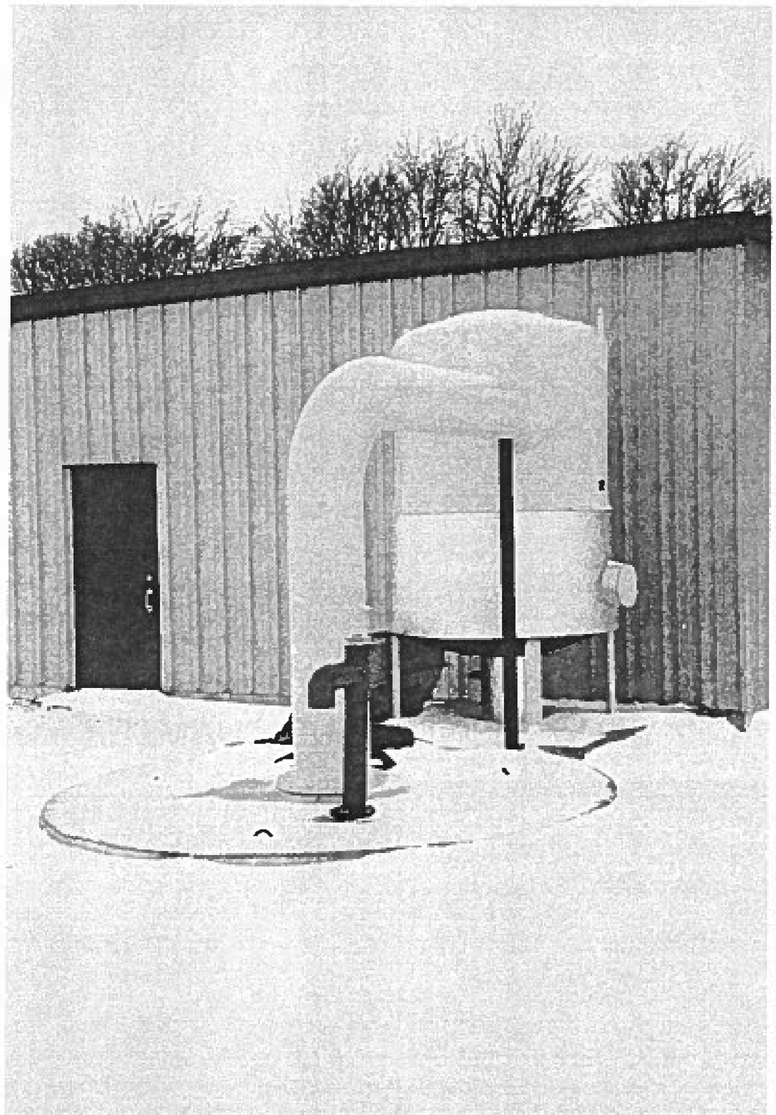


PLATE 6
MOISTURE SEPARATOR

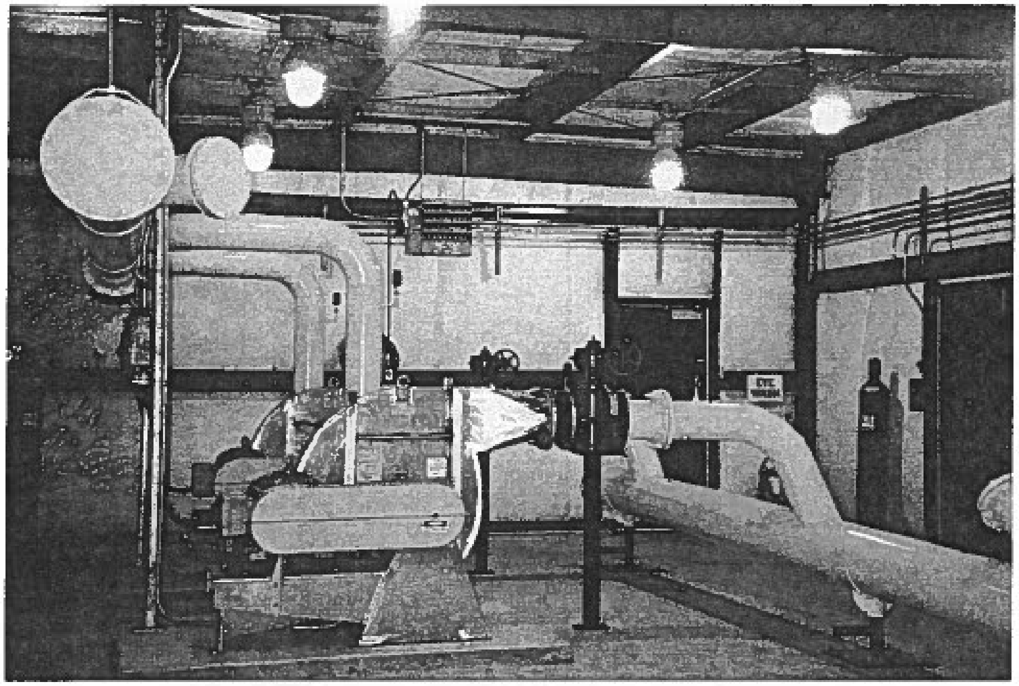
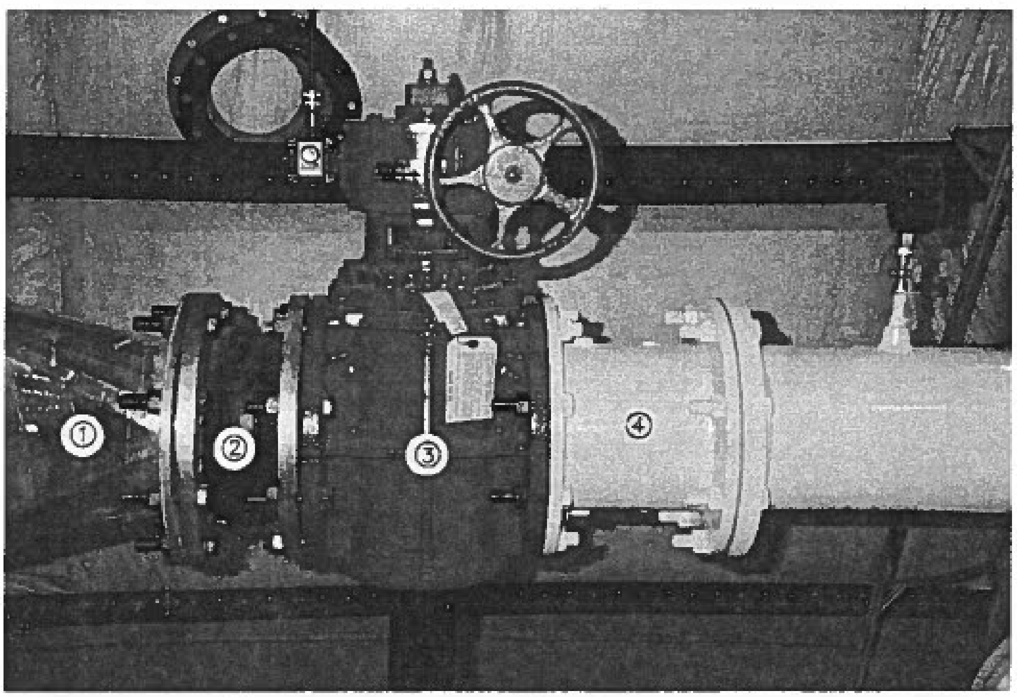


PLATE 7
LFG BLOWERS AND PIPING



LATE 8
LFG BLOWER DISCHARGE FITTING

1 LFG BLOWER DISCHARGE TRANSITION
2 VIBRATION ISOLATOR
3 MANUAL ISOLATION VALVE
4 CHECKVALVE

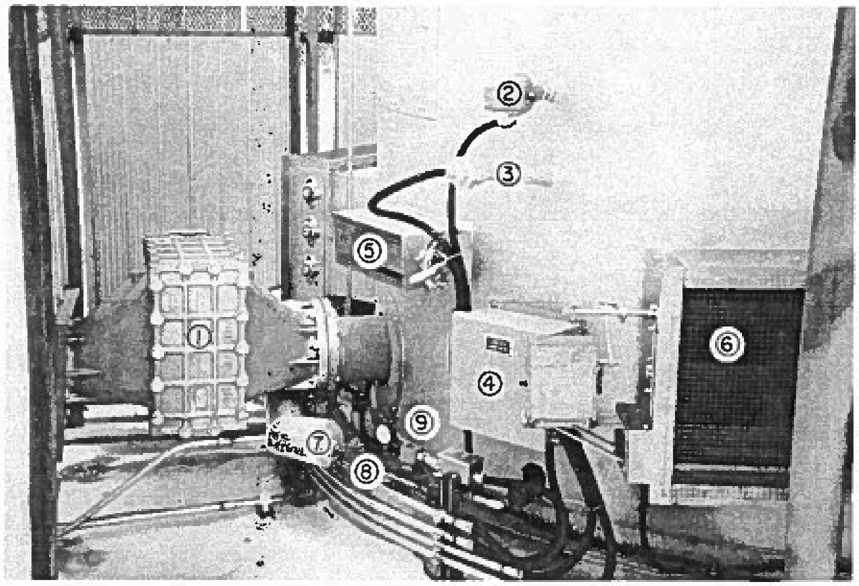


PLATE 9
LFG FLARE CONTROL EQUIPMENT

1	FLAME ARRESTOR	5	MANUAL DAMPER
2	U.V. FLAME SCANNER	6	AUTOMATIC DAMPER
3	PROPANE PILOT	7	PROPANE SHUT-OFF
4	6000 VOLT IGNITION TRANSFORMER	8	PROPANE GAUGE
		9	PROPANE SOLENOID

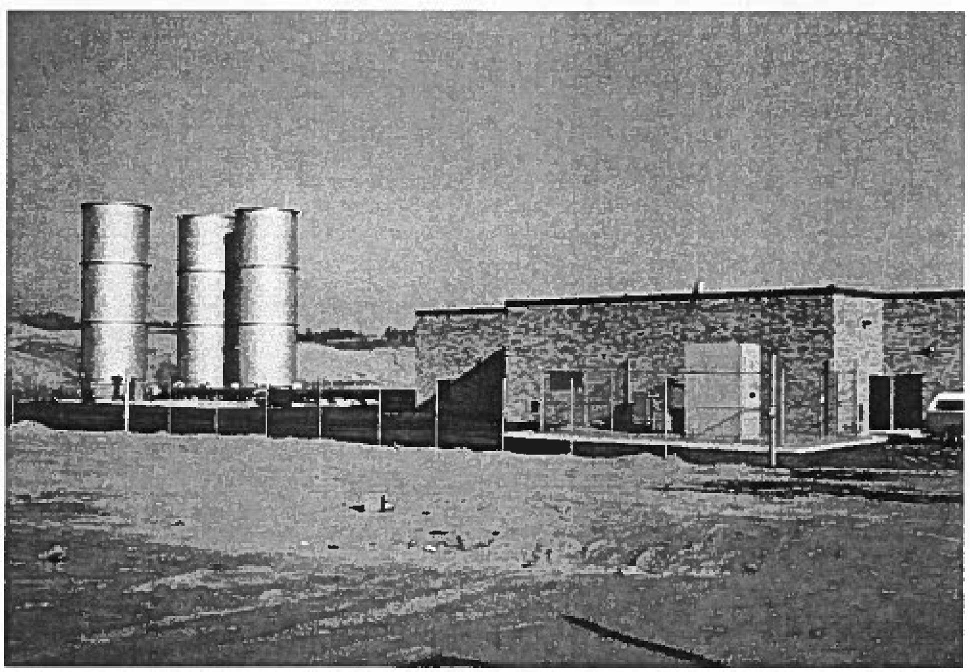


PLATE 10
LFG COLLECTION AND FLARING FACILITY
(KEELE VALLEY LANDFILL SITE)

6.2.2 LFG Migration Control System Design

Control of lateral migration of LFG in the soil may be required to prevent potentially hazardous conditions from developing in structures on or near the landfill site and to prevent off-site migration of LFG. Where natural barriers to LFG migration exist, gas migration controls may not be required. Such natural barriers may include a high water table or steep embankment such as a ravine.

It is recommended that migration control systems be designed to cover the entire migration "window" surrounding the site. The migration window is defined as the zone in the soil surrounding the landfill extending from the ground surface down to a natural migration boundary, i.e. water table or low permeable soil.

There are a number of LFG migration control technologies available. These include passive venting systems, barrier systems and active LFG extraction systems. Table 6.4 presents a summary and comparison of migration control systems.

Table 6.4 Summary of LFG Migration Control Systems

Passive Systems	Barrier Systems	Extraction Systems
• Design to provide coverage for entire migration "window", except for cap-venting systems • Odour and air quality concerns due to venting of LFG to the atmosphere • Low cost • Minimal maintenance • Applicability and/or effectiveness may be limited by geology	• Design to provide coverage for entire migration "window" • Should incorporate a passive venting system • Increased cost over passive systems • Minimal maintenance except for air curtains • Applicability and/or effectiveness may be limited by geology	• Design to provide coverage for entire migration "window" • Generally requires treatment or flaring of extracted gases and permits • Increased cost over passive systems • Requires maintenance • Broadly applicable and generally effective • Design must incorporate drainage and disposal of condensate • Collected gas may require fuel augmentation for combustion

6.2.2.1 Passive Systems

Passive systems provide a controlled method of allowing migrating LFG to escape from the soil without active mechanical systems. This effectively intercepts migrating LFG and limits the potential range of migration.

Passive venting involves the installation of horizontal trenches filled with coarse granular fill/composite geogrid, and/or the installation of vertical augered wells equipped with riser pipes surrounded by a gravel pack (see Figure 6.18 a). Passive venting systems are generally located in the soil surrounding the landfill near the edge of the refuse. Passive vents are installed to the shallower of either the depth of low permeable soils or the seasonally low water table. Horizontal collector pipes with vent risers may be installed within venting trenches to provide a conduit to exhaust LFG to the atmosphere.

Passive systems rely on the slightly positive (relative to atmospheric) pressure of gas migrating through the soil, to induce exhaust of gas to the atmosphere. The effectiveness of passive vent systems may be enhanced somewhat if the risers are equipped with wind turbines.

Due to the very low gas pressures and flows expected, passive vent systems located outside the perimeter of the landfill are not generally capable of self-supporting and safe combustion of the vent gas. As such, these systems generally discharge the gas directly to the atmosphere without flaring.

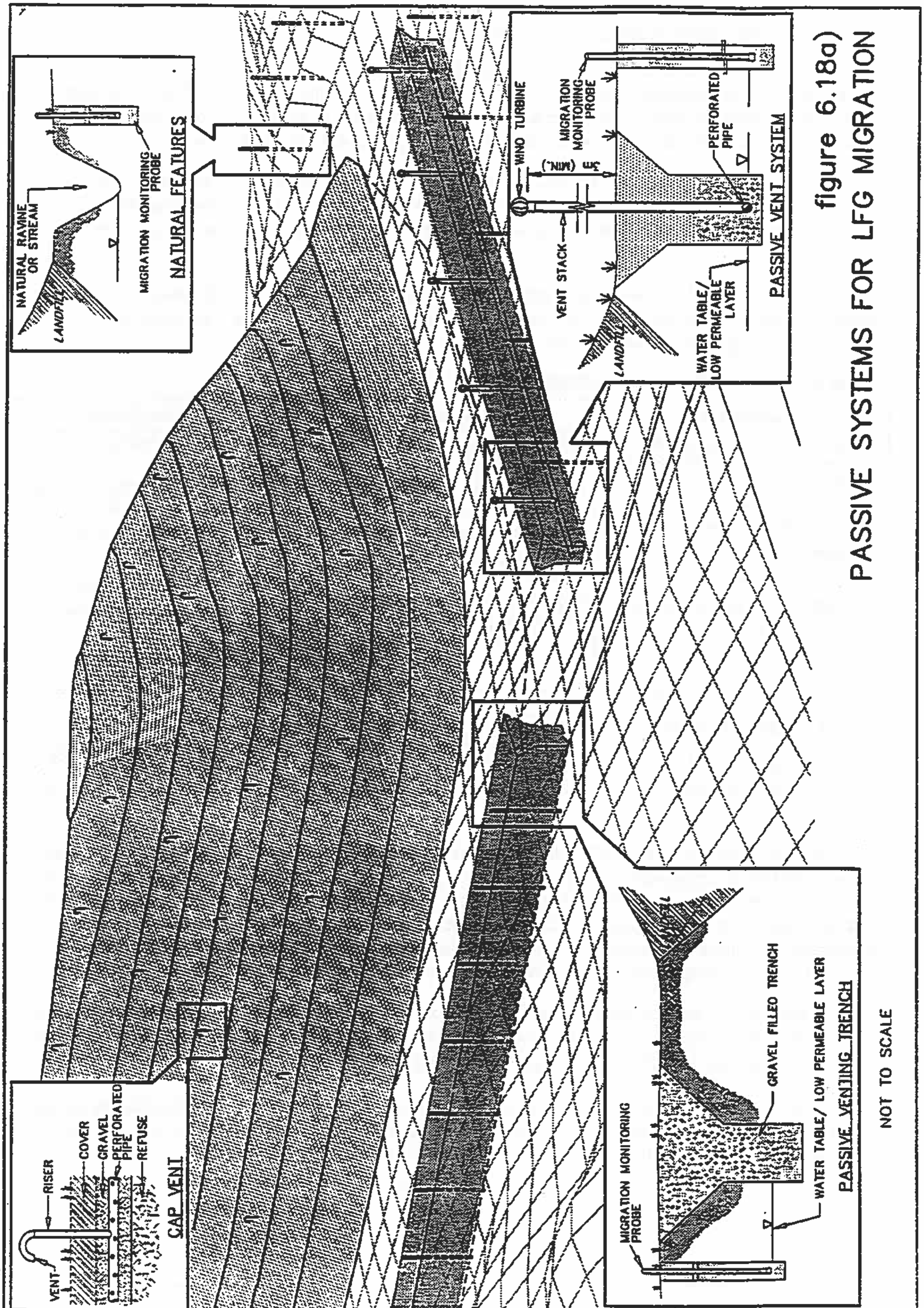


figure 6.18a)
PASSIVE SYSTEMS FOR LFG MIGRATION

The primary advantages of passive venting are lower capital costs, simplicity of construction, and minimal operating costs other than for periodic monitoring. The disadvantages of passive venting are that its effectiveness and applicability may be limited by soil conditions, and the LFG is released directly to the atmosphere from point sources. As discussed in Section 2, release of LFG to the atmosphere may result in odours and degradation of air quality, and contribute to greenhouse gases. Environmental approvals for passive vents may be required.

One method to indirectly reduce migration from a site is to allow release of gas pressure from beneath the site cover through cap vents. Cap venting systems help prevent vegetation stress on the landfill cover. The effectiveness of cap venting for migration control may be limited due to its inability to release gas pressures at depth in the refuse. Cap venting itself does not create any barrier to diffusion of LFG.

6.2.2.2 Barrier Systems

A physical or pressure barrier may be constructed in the soil adjacent to the edge of the landfill to prevent lateral movement of LFG from the landfill.

Barrier systems include bentonite and soil slurry walls, cement slurry walls, curtains of concrete grout, sheet pile walls, synthetic membranes and air pressure curtains. These systems have increased applicability and effectiveness over passive vents. These systems have virtually no operating costs (with the exception of air pressure curtains) other than periodic monitoring.

Barrier systems should include a passive venting system on the landfill side of the barrier to release LFG pressure that builds up in the soil (see Figure 6.18 b). This is necessary to ensure the effectiveness of these systems in preventing lateral movement of gas rather than simply uncontrolled redirection of the gas around or beneath the barrier.

Bentonite and soil slurry walls are constructed by excavating a trench to a desired depth while concurrently backfilling with a relatively impermeable material such as a bentonite and slurry mixture to form a barrier.

Installation of a cement slurry wall may be achieved by utilizing vibrated-beam technology. The vibrated-beam installation method utilizes a crane-mounted driver/extractor. The steel wide-flange beam (approximately 1 metre wide) is equipped with jets for injection of slurry. The beam is vibrated into the soil to the desired depth. Extraction of the beam creates a 150 mm to 200 mm wide void in the soil. As the beam is withdrawn, the cement and bentonite slurry is injected into the resulting void. The rate of slurry injection is controlled to match the rate of beam extraction to ensure a continuous cement slurry wall. The process is repeated along the alignment with each beam insertion overlapping the previous segment. This method may be combined with the insertion of high-density polyethylene (HDPE) panels into the cement slurry to further reduce the permeability of the barrier. The in-place thickness of the wall typically is less than with the excavated bentonite and soil slurry trench method.

Construction of a sheet piling barrier involves installation of steel panels into the soil. Adjacent panels connect together with specialized interlocking joints to form a low permeable barrier to gas and water flow. One method of using sheet pile walls as a low permeable barrier has been developed at the University of Waterloo and consists of slotted interlock connectors at the edges of the steel sheets that are grouted to provide a low permeable connection.

Jet grouting is a process of injecting a liquid slurry under pressure into the soil, with the slurry occupying the available pore spaces. As time passes, the injected fluid will solidify, thus resulting in a decrease in soil permeability.

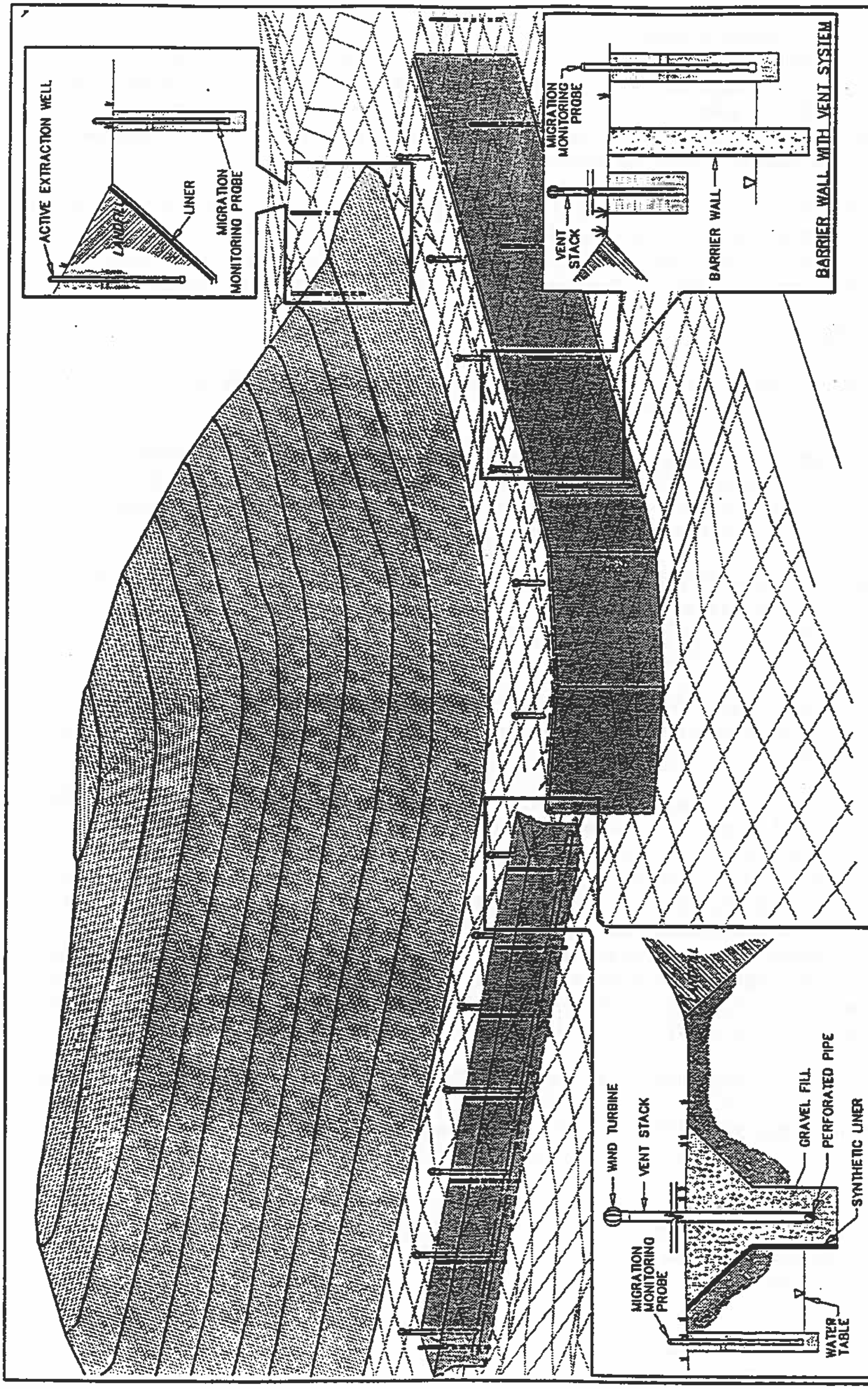


figure 6.18b)
BARRIER SYSTEMS FOR LFG MIGRATION

Synthetic membranes are similar to the HDPE panels noted above, except installation is via trenching and the membrane material is installed in sheets and seamed in the trench. Membrane material for this type of application is typically HDPE or PVC, with the material thickness ranging between 0.75 mm to 2 mm (30-80 mils). This method is most applicable to shallow depths and locations where sufficient land area for the excavation is available.

Air curtains use the positive pressure of air continuously injected into the soil to counter-balance the pressures that cause migration of LFG. A blower or compressor is used to inject air into a series of wells or trenches located in the soil outside the limit of refuse. Air curtain systems alone do not require air emission approvals, gas flaring, or condensate collection and disposal. Air curtains are active mechanical systems and hence require long-term expenditures for operation and maintenance. The applicability of air curtains is generally limited to localized protection of buildings.

6.2.2.3 Gas Extraction Systems

Active systems may be used to extract LFG from the site or surrounding soil to control migration. These systems utilize a blower system combined with wells or trenches to extract gas from the refuse or the soil. The quantity of LFG that is collected by active extraction from refuse often warrants flaring to avoid creation of odours or air quality impacts. The primary equipment of a LFG extraction plant includes a gas blower, gas flare and associated piping, valves, and electrical controls.

In general, active gas extraction systems are highly effective for mitigation of on-site and off-site LFG impacts in most situations. Active gas extraction systems may be constructed to provide gas collection capabilities over the entire surface of the landfill or around the perimeter of the site.

Systems covering the entire site are generally installed to control air quality and/or odour impacts, (see Section 6.2.1) or for utilization of the gas. Systems which cover the entire site usually have a secondary benefit of reducing gas migration into the soil. However, the extent of this benefit is dependent upon subsurface conditions on the site and in the surrounding soils.

A properly designed, constructed and maintained perimeter gas extraction system will be effective in preventing off-site migration of LFG. These types of control systems are often referred to as interceptor systems. Perimeter extraction systems do not control air and odour impacts and typically do not allow for utilization of collected LFG.

Many of the components of an active perimeter extraction system are similar to those previously described in this chapter. Such systems may include the following (see Figure 6.19):

- LFG collection wells/trenches
- LFG collection piping
- LFG extraction plant
- LFG flare/treatment
- mechanical/electrical control systems

The design of perimeter LFG extraction systems is very similar to the design of active LFG collection systems that cover the entire site. The major differences that should be considered in the design are:

- Collection wells/trenches are located at, or in, the soil just outside the limits of the refuse.
- The combustible concentration of the collected gas may be low.

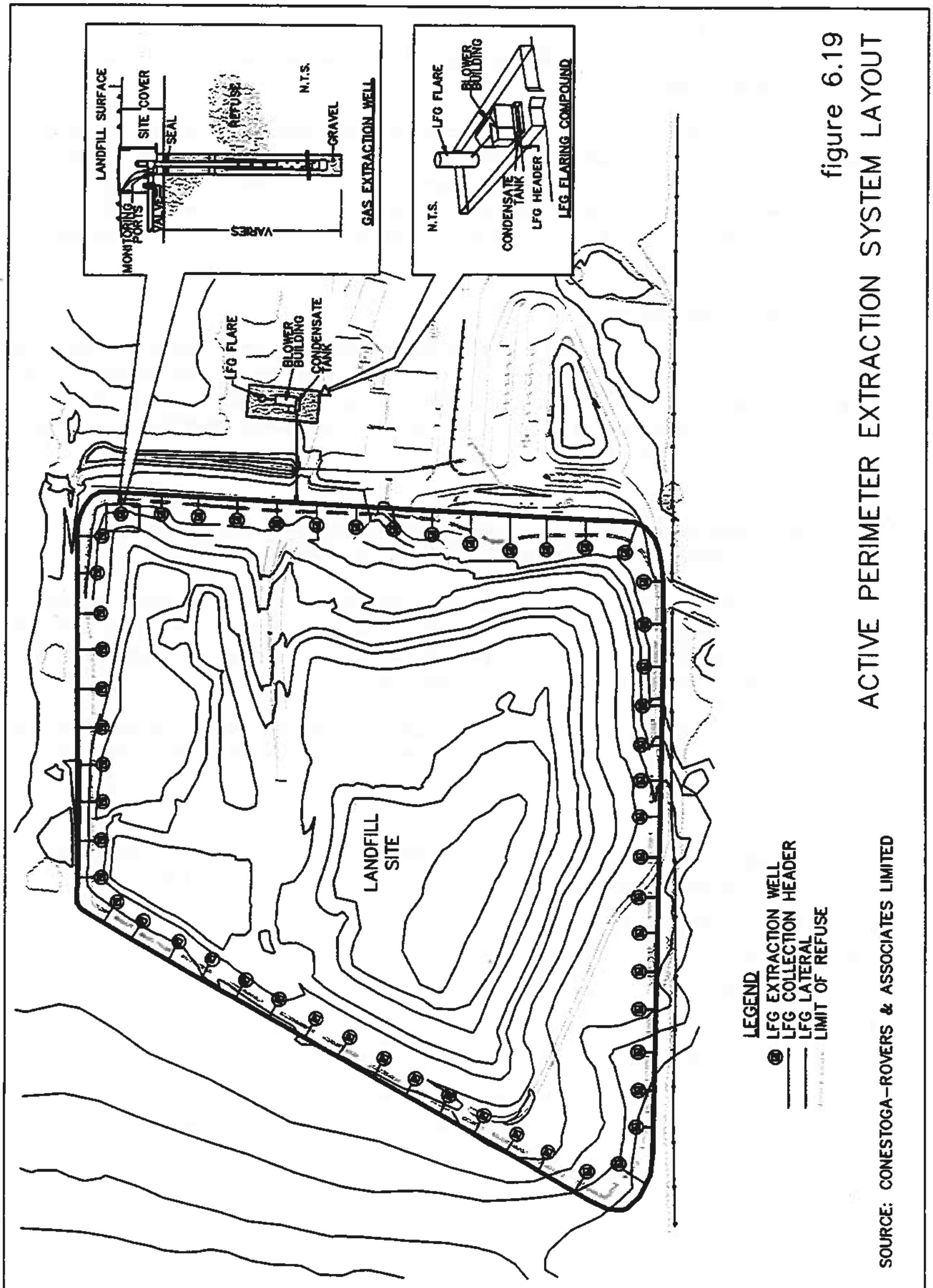


figure 6.19
ACTIVE PERIMETER EXTRACTION SYSTEM LAYOUT

SOURCE: CONESTOGA-ROVERS & ASSOCIATES LIMITED

The spacing of wells is defined by permeability of the soil or refuse. In general, perimeter migration control wells are spaced more tightly together than wells covering the entire site. A single line of wells is usually installed for migration control. Use of trench systems for perimeter LFG migration control generally does not require a network of trenches. A single-trench alignment is usually required. Trenches may be equipped with a synthetic membrane to enhance LFG collection effectiveness. As in passive venting systems, wells and trenches for perimeter extraction systems should be installed to a depth sufficient to close the migration "window". This is defined as the depth to the low permeable soils or the seasonally low water table, whichever is higher.

Concerns for settlement are reduced if the extraction system is installed in soil outside the refuse. In this case, telescoping slip-sections and flex connections are not required in the design. Drainage of liquids remains a primary consideration in the design of perimeter extraction systems. Failure of these types of systems to perform effectively is often attributed to poor drainage. Condensate handling measures are similar to those described in Section 6.2.1.3.

Requirements for the LFG extraction plant are the same as those for collection systems described in Section 6.2.1. It is likely that the character of the LFG collected and the system hydraulics may be quite different than for a plant designed to extract gas from the refuse mass. An evaluation of the system hydraulics should be performed.

The LFG collected from a perimeter LFG extraction system would be expected to have a low combustible gas content. Augmentation of the collected gas with a combustible fuel (i.e. natural gas or propane) may be required to allow flaring. This would be required if the combustible concentration of the collected gas were too low to support combustion (i.e. less than 25 to 30 percent by volume) but there were concerns regarding emissions to the atmosphere. One alternative to fuel augmentation would be treatment of the collected gases prior to release (see Section 6.2.1.4). Utilization of LFG collected from a perimeter extraction system would not likely be considered economical, due to the expected low combustible gas content.

6.3 LFG Control System Costs

Table 6.5 presents budget yardsticks for estimating the costs associated with specific components of LFG control systems. Table 6.6 shows similar costing yardsticks for complete LFG collection systems. The capital costs shown are expressed in ranges of dollars per tonne of landfill wastes. As a result, there is a broad range of variability due to variations in landfill densities, gas production rates, plant sizing limitations and economies of scale. For comparison purposes, tipping fees at municipal solid waste (MSW) landfill sites are currently in the range of \$40 to \$60 per tonne of waste. Operation and maintenance costs are expressed in ranges of dollars per year.

Table 6.5 Budget Yardsticks for LFG Control System Components

Item	Typical Installed Cost
Gas extraction wells	\$185–\$375 per vertical metre
Horizontal gas collection trenches	\$90–\$160 per horizontal metre
Blowers (500–8500 m^3/hr)	\$4–\$9 per cubic metre/hour capacity
Compressors (>20 psi) (1)	\$110–\$160 per cubic metre/hour capacity
Compressors (<20 psi)	\$20–\$50 per cubic metre/hour capacity
Candle type flares (30–400 m^3/hr)	\$25–\$50 per cubic metre/hour capacity
Enclosed flares (350–8500 m^3/hr)	\$50–\$150 per cubic metre/hour capacity

Notes:
(1) Generally only used for medium- and high-grade fuel utilization projects.

Table 6.7 presents budget yardsticks for estimating the costs associated with LFG migration control systems. As capital costs for migration control systems do not relate directly to the size of the site, these costs are appropriately expressed in dollars per square metre of the migration "window" (length of barrier and depth to water table or till) that is to be controlled. Operation and maintenance costs are expressed in ranges of dollars per year.

Table 6.6 Budget Yardsticks for LFG Collection Systems (1)

	Small sites		Medium sites		Large sites
Item Description	**less than 1 million tonnes**	**between 1 million and 2.5 million tonnes**	**between 2.5 million and 3.5 million tonnes**	**between 3.5 million and 5 million tonnes**	**greater than 5 million tonnes**
Capital Costs ($ per tonne of waste) (2)					
Collection field – wells	$0.80 – $1.50	$0.45 – $0.90	$0.40 – $0.50	$0.35 – $0.45	$0.25 – $0.40
Collection field – trenches	$1.10 – $2.10	$0.55 – $1.20	$0.40 – $0.60	$0.40 – $0.50	$0.20 – $0.40
Gas plant (3)	$0.25 – $0.50	$0.20 – $0.30	$0.15 – $0.25	$0.15 – $0.20	$0.10 – $0.20
Blowers	$0.20 – $0.35	$0.10 – $0.20	$0.10 – $0.15	$0.10 – $0.15	$0.05 – $0.10
Flaring	$0.40 – $0.75	$0.30 – $0.40	$0.15 – $0.35	$0.20 – $0.25	$0.15 – $0.20
Total Collection System – wells	$1.65 – $3.10	$1.05 – $1.80	$0.80 – $1.25	$0.80 – $1.00	$0.55 – $0.90
Total Collection System – trenches	$1.95 – $3.70	$1.15 – $2.10	$0.80 – $1.35	$0.85 – $1.05	$0.50 – $0.90
Monitoring ($ per year)	$25,000 – $35,000	$30,000 – $50,000	$40,000 – $60,000	$50,000 – $100,000	$60,000 – $120,000
Operations and Maintenance ($ per year)	$60,000 – $95,000	$70,000 – $110,000	$90,000 – $170,000	$140,000 – $250,000	$160,000 – $275,000
Extraction Test Programs ($)/ (see Section 5.4)	$40,000 – $60,000	$50,000 – $90,000	$60,000 – $100,000	$70,000 – $110,000	$100,000 – $125,000

Notes:
1. All costs are in 1995 dollars and exclude taxes.
2. Per tonne costs based on the site's waste capacity.
3. Includes building, compound, mechanical and electrical.

Table 6.7 Budget Yardsticks for LFG Migration Control Systems (1)

Item Description	Cost range
Capital Costs ($ per square metre of barrier) (2)	
Passive venting	$18 – $32
Gravel trenching	$110 – $160
Synthetic barrier with passive vents	$190 – $290
Perimeter collection system – wells	$110 – $400
Sheet steel piling (3)	$210 – $320
Perimeter Monitoring Network ($ per multi-level probe nest) (4)	$2,000 – $5,000
Monitoring ($ per year)	$25,000 – $65,000
Operations & Maintenance ($ per year)	
Passive barrier	N.A.
Perimeter Collection System	$20,000 – $120,000
Performance Tests ($)	$30,000 – $150,000

Notes:
1. All costs are in 1995 dollars and exclude taxes.
2. Per square metre wall costs based on length, depth to water table/till.
3. Specialized sealable joints required.
4. Recommended maximum multi-level probe nest spacing of 100 m.

Note that the ranges of costs shown correspond to ranges of site sizes. The lower unit capital costs and the high annual operation and maintenance costs should be applied only to tonnages at the high end of the range of applicable site sizes. Conversely, smaller projects have higher capital unit costs and lower annual operation and maintenance costs associated with them. Due to the possible variations in factors that may affect these costs, the figures shown in Tables 6.5 and 6.6 are intended to be used only as guidelines. The cost yardsticks in Tables 6.5 and 6.6 are derived from implementation of a number of LFG control projects.

6.4 Operation and Maintenance Considerations

Regular operation of LFG collection and flaring systems may be grouped into two related major tasks:

- plant operation
- collection field monitoring and adjustment

Plant operations may include start-up and shut-down of the system, flow adjustments, flare adjustments, monitoring and record keeping. Plant operations will vary from site to site and therefore cannot be described in detail in a general reference document.

The following describes equipment and procedures for carrying out regular collection field monitoring and adjustment.

6.4.1 Field Monitoring and Adjustment

Periodic monitoring and adjustment of the LFG collection field is required to optimize the effectiveness of the collection system in response to varying LFG production rates. The adjustment of valve settings to reduce or increase flows of gas from low- or high-production areas of the landfill is required to maximize LFG collection without overdrawing from those areas of the site that may be susceptible to air intrusion.

Introduction into the refuse mass of ambient air, with its 21 percent oxygen content, can have a negative impact on the natural decomposition process. At the advanced stages of methanogenic decomposition, the microbes that carry out this process survive and thrive in an oxygen-free (anaerobic) environment. Introduction of oxygen into this process will kill the anaerobic microbes, forcing the process to become aerobic. This may result in a reduction in methane production with an associated decline in potential energy recovery, greatly increased rates of differential settlement, high subsurface temperatures and increased odour problems. In some cases, it is thought that this leads to landfill fires. It is for these reasons that overdrawing and associated intrusion of air into the refuse should be avoided.

A continuous record of all monitoring data should be kept. The field monitoring records at each collection point should include the following:

1. measurement of vacuum
2. measurement of differential pressure across orifice plate (flow)
3. measurement of temperature of the LFG
4. LFG methane (CH_4) concentration
5. valve position

Monitoring at each collection point should begin with the measurement of vacuum pressure, followed by measurement of differential pressure for gas flow. LFG temperatures (typically 15°C to 40°C) are then recorded at each location. To avoid erroneous readings, care should be taken to ensure that the temperature probe is not in contact with the pipe wall or immersed in liquid. A portable gas meter is then used to measure combustible gas concentrations. As good monitoring practice, combustible gas readings should not be taken until after the pressure measurements, due to the possibility of interference with pressures by the action of extracting the gas sample.

As part of the regular monitoring of the collection field, periodic adjustments to the well head valve position should be carried out to optimize system effectiveness. It should be noted that collection field adjustments must be made based upon a review of historic well or trench performance considered within the context of the overall field operation. Even relatively minor changes to a particular collection point will influence flow and vacuum at other locations within the collection system. A certain amount of judgement gained from experience is required when making adjustments to the collection field. If combustible gas readings at a specific well or trench are found to be substantially below the plant gas concentration, then the flow from that well or trench should be reduced.

During system commissioning, the gas concentrations should be monitored regularly (weekly or biweekly) and adjustments to the collection field should be performed as necessary. The frequency of this monitoring will vary. During stable operations, monitoring rounds should be carried out monthly to verify the collection field performance.

It should be recognized that seasonal changes affect the performance of the collection system. Changes in soil permeability due to variations in subsurface moisture and frost affect venting of gas to the atmosphere. Barometric pressure fluctuations change pressures in the site which can affect gas collection. Long term variations in precipitation and infiltration may affect the site moisture content and gas production rate.

During field monitoring, all personnel should exercise caution due to the potentially hazardous nature of LFG. When entering a gas utility chamber, they must follow the confined space entry protocols of the applicable Occupational Health and Safety Regulations.

6.4.2 Maintenance

The following provides a general description of the types of maintenance activities that are associated with LFG collection systems. System maintenance requirements include routine inspection, scheduled and unscheduled maintenance of system components, and keeping records of the inspection and maintenance activities. Maintenance requirements for collection fields are expected to be minimal. General observations of any unusual conditions in the field should be made during monitoring and adjustment rounds. Actions to be taken must be determined in response to specific problems that arise. Scheduled maintenance and operation requirements may be grouped into weekly, monthly and annual activities.

A weekly plant operation and maintenance inspection should be performed. This consists primarily of a plant inspection with recording of observations and readings of a number of items such as gas flow, flare temperature, combustible and oxygen concentration in the LFG, bearing temperatures, motor run times, etc. In addition to the detailed weekly plant inspection, it is advisable to perform a brief visual plant check on a daily basis. The daily check would include observation of any unusual conditions. Correction of irregularities or adjustments to the system operation should be carried out only by personnel familiar with the operation of the LFG collection system.

More involved maintenance procedures may be carried out on a monthly cycle. This could include greasing bearings, changing belts, calibrating detectors, etc.

A major system shut-down and equipment overhaul should be carried out on an annual basis. This should include the following activities as a minimum:

- shutting down and inspecting the flare;
- making repairs and adjustments as necessary;
- overhauling blowers by cleaning and repacking bearings, replacing belts, carrying out performance tests, and making repairs and adjustments as necessary; and
- removing, cleaning and overhauling pumps.

6.5 Health and Safety

Precautions must be taken to avoid hazardous conditions which may be associated with LFG systems. In addition to the hazards posed by LFG, concerns including high temperatures, high speed equipment, high voltage equipment and noise may be encountered by personnel. All personnel involved with the LFG system must be fully aware of the potential hazards and the protocols required to work safely. The following provides an overview of the nature of the potential hazards and an introduction to some of the precautionary measures to be taken. It is recommended that individual owner/operators utilize their in-house occupational health and safety resources to develop detailed policies and practices for personnel involved with LFG systems.

LFG may be combustible, suffocating and toxic. Some trace compounds found in LFG are toxic at sufficiently high exposure concentrations. Depending upon its composition, LFG may be lighter than air, heavier than air or of a similar density. LFG is capable of venting freely from the uncapped surface of the refuse as well as migrating through the soil around the landfill. Typical methane concentrations range from 30 to approximately 60 percent by volume in LFG. Methane is explosive in concentrations ranging from 5 to 15 percent by volume in air. Five percent by volume in air is referred to as the Lower Explosive

Limit (LEL) of methane. Fifteen percent by volume in air is referred to as the Upper Explosive Limit (UEL) of methane. LFG may contain concentrations of methane within the explosive range. LFG that contains methane above the UEL may be diluted with air down into the explosive range. LFG that contains methane below the LEL may become more concentrated, until it reaches the explosive range, if it is allowed to accumulate in an enclosed space and displace available air. Because of these variable properties, extreme caution must be exercised when LFG may be present. When working in the vicinity of a landfill site, it is generally prudent to assume that LFG is present within the explosive range and act accordingly, until the atmosphere can be verified as safe.

Accumulation of LFG in enclosed or low-lying areas on or near landfills, may cause displacement of air, thereby creating an oxygen-deficient atmosphere. This oxygen deficiency may be severe enough to pose a suffocation hazard to persons in the area.

All personnel should make every effort to become fully aware of the nature and hazards of LFG, and the precautionary measures to be taken to avoid accident or injury.

6.5.1 Confined Spaces

Entry into and work in confined spaces is generally governed by provincial occupational health and safety legislation. The following information is intended to introduce personnel to the hazards of confined space entry at or near landfills. This section should be considered introductory only. Any personnel required to carry out confined space entry must be fully trained and competent in the procedures detailed in the applicable Health and Safety legislation.

Accumulation of LFG may result in the displacement of oxygen by methane and the denser carbon dioxide within chambers, sewers, underground structures and low-lying ditches adjacent to landfills. LFG may also migrate through the soil surrounding the landfill. There have been reported incidents of workers without proper gas detection equipment entering confined spaces on or near landfills and being asphyxiated.

Confined spaces associated with LFG systems may include the following:

- below-grade structures or chambers on or near the landfill
- pumping stations
- buildings or rooms that contain piping conveying LFG
- low-lying areas or excavations
- other enclosed or semi-enclosed spaces that LFG may enter

6.5.2 Lockout Tagout

Procedures must be followed to ensure that equipment being worked on is isolated from all potential hazardous energy sources and is locked out or tagged out before any individual performs any servicing or maintenance activity where an unexpected energization, startup or release of energy could cause an injury. Energy sources can be electrical, mechanical, hydraulic, pneumatic, chemical, thermal or other.

Specific procedures and rules must be developed and obeyed for the following:

- lockout/tagout involving one or more than one person;
- proper use of energy isolating devices;
- release of stored energy;
- procedure for testing or positioning activities; and
- documentation and record keeping.

Applicable legislation, regulations, guidelines and standards are available that describe the specific lockout or tagout procedures to be followed.

6.5.3 Air Monitoring for Drilling and Construction Work

There is a health and safety concern due to the potential for exposure to high concentrations of LFG during drilling and construction operations at or near a landfill site. The following suggests minimum air monitoring requirements and action levels. Monitoring and personal protection equipment should be in good working order and used only by those trained in and familiar with its use and limitations.

Combustible Gas

Action levels are based on the readings from a combustible gas meter. The readings are generally given as a percentage of the lower explosive limit (percent LEL) and are collected in the general work area. An atmospheric oxygen level of less than 19.5 percent may affect the readings from a combustible gas meter and give lower-than-actual levels. Test oxygen content first.

Non-confined Space Readings, General Area

0-10% LEL	Continue working and monitoring atmosphere for combustible gases. Inform personnel working in the area whenever readings are >5% LEL.
10-20% LEL	Continue working with caution. Inform personnel working in area of readings. Be prepared to cease operations.
>20% LEL	Cease operations and move to a safe place. Reevaluate work plan. Engineering controls such as forced ventilation and use of non-sparking tools are to be implemented if operations are to continue. **DO NOT CONTINUE WORKING UNTIL CONDITIONS ARE CONSISTENTLY BELOW 20% LEL.**

HOT WORK is to be conducted only at 0 percent LEL.

For field work that is not being conducted within a waste disposal site, the following action levels can be used for combustible gas readings taken at or near the borehole rather than in the general area:

Borehole Readings

Instrument reading	Action to be taken
<20% LEL	Continue working and monitoring atmosphere for combustible gases. Inform personnel working in the area whenever readings are >10% LEL.
20-40% LEL	Continue working with caution. Inform personnel in area of readings. Be prepared to cease operations.
>40% LEL	Cease operations and move to a safe area. Reevaluate work plan. Engineering controls such as forced ventilation and use of non-sparking tools are to be implemented if operations are to continue. **DO NOT CONTINUE WORKING UNTIL CONDITIONS ARE CONSISTENTLY BELOW 40% LEL.** Supplied air or self-contained breathing apparatus (SCBA) may be necessary.

Oxygen

A direct reading oxygen meter is used to determine the percentage of oxygen in the atmosphere.

All Areas

Instrument reading	Action to be taken
<19.5 **percent** or >23.5 **percent**	Cease operations and move to a safe area. Re-evaluate work plan. Engineering controls such as forced ventilation and use of non-sparking tools are to be implemented if operations continue. **DO NOT CONTINUE WORKING UNTIL OXYGEN LEVELS ARE BETWEEN 19.5 AND 23.5 percent.** When oxygen levels are outside this range, combustible gas meter readings are not reliable. Supplied air or SCBA respiratory protection may be necessary.

Hydrogen Sulphide (H_2S)

Whenever readings approach 10 ppm on a direct reading H_2S meter, cease work immediately, move to a safe area. H_2S has a threshold limit value (TLV) of 10 ppm. Exposure to even low concentrations of H_2S can cause olfactory fatigue which impairs the ability to detect the characteristic H_2S odour. Air purifying respirators with organic vapour cartridges are not suited for exposure to H_2S.

6.5.4 General Plant Safety

All personnel should take the necessary precautions to avoid hazards at the plant. The following are recommended minimum general safety guidelines:

1. Confined space entry regulations must be followed.
2. All plant personnel must be thoroughly advised of the hazardous nature of LFG. All personnel shall exercise caution when in an area marked hazardous, by signs or symbols informing personnel of the danger from combustible gases. No open flame, matches, smoking, welding or other activity potentially capable of generating an explosion shall be allowed in any area associated with landfill gases.
3. All plant personnel must be advised of the potentially corrosive and toxic nature of LFG and its associated condensate. Rubber or latex gloves should be worn when in contact with LFG and condensate.
4. LFG system buildings are to be kept locked at all times except during monitoring and maintenance operations.
5. All compound gates are to be kept locked except during maintenance and monitoring operations.
6. Only personnel authorized by the site supervisor are permitted within the plant compound.
7. The site supervisor shall be notified prior to any entry into the plant compound and upon completion of duties within the plant.
8. Hearing protection shall be worn when working in the blower room.
9. High speed automatic start mechanical equipment may be present. Belt guards for blowers should be in place when blowers are in operation.
10. Only qualified electricians should be allowed to perform electrical duties in the gas buildings.
11. All personnel should avoid contact with the exterior surfaces of the flare stack and the blower bearing surfaces, as they can burn upon contact.
12. All personnel should be made aware of the presence of high voltage equipment at the gas plant complex.
13. Lockout and tagout procedures should be followed for work on any equipment.

7.0 Landfill Gas Utilization

7.1 Benefits of LFG Utilization

The collection and use of landfill gas (LFG) as an energy resource offers important environmental benefits. LFG is composed primarily of methane (CH_4) and carbon dioxide (CO_2), which are known greenhouse gases that contribute to global warming. Trace compounds present in LFG can also contribute to odour and air quality concerns at landfill sites. It is recognized that LFG migration to neighbouring properties can lead to potentially harmful (explosive) conditions. LFG control and utilization benefits the public by reducing these negative impacts. The economic return from utilizing collected LFG can defray some of the costs of operation and maintenance of a landfill.

The growing awareness of energy conservation and environmental issues has motivated municipalities as well as private developers to investigate and in some cases to harness and utilize LFG as a resource.

There have been numerous successful LFG utilization projects undertaken in Canada and the United States. Given the availability of markets for sale of energy or products, the technologies for utilizing LFG have proven economically viable for a wide variety of sites and applications.

In Canada, most of the utilization projects have been either small-scale direct use applications or large-scale electrical generation. The case studies discussed in Section 8 provide some insight into Canadian LFG utilization experience. There are many more LFG utilization projects carried out in the U.S. and Europe. The American experience indicates that the scope of viable projects is broader than those that have been undertaken in Canada. Emerging LFG utilization technologies are also expanding the range of viable projects even further.

A LFG utilization project must be economically viable to be undertaken. There are a number of Canadian sites that are large enough generators of LFG to be considered potentially viable candidates for utilization projects. Implementing a larger number of viable LFG utilization projects would generate revenue and help Canada's efforts to create a positive impact on the global environment.

7.2 Utilization Options

This section discusses utilization technologies, cost guidelines, feasibility assessments and impediments to utilization of LFG. It is hoped that by presenting this information for guidance, the list of sites where LFG utilization is considered will be expanded.

The options for utilizing LFG are defined by the degree that LFG is processed. The level of processing affects the economics of the application. LFG processing systems modify the LFG composition to suit the end-use intended for the gas. LFG treatment techniques are discussed in Section 7.3. The three general categories of LFG processing result in the following outputs:

1. low-grade LFG fuel
2. medium-grade LFG fuel
3. high-grade LFG fuel and by-products

Figure 7.1 provides a summary of LFG utilization options based on the three fuel grades.

As collected from the site, LFG is typically made up of a mixture of methane, carbon dioxide, trace sulphur and chlorinated compounds, and is saturated with water vapour. The sulphur and chlorinated compounds in the presence of moisture contribute to the corrosive nature of LFG. Depending upon the site and the collection system, LFG may also contain small quantities of oxygen and nitrogen drawn into the site by active collection.

Unprocessed LFG typically has a heating value per unit volume approximately one-half that of natural gas. This is due to the lower methane content and the presence of carbon dioxide which absorbs, rather than contributes heat energy during combustion. The lower heating value (LHV) of typical LFG (50 percent CH_4 / 50 percent CO_2) is roughly 16.8 MJ/m^3 (450 BTU/cf).

7.2.1 Low-Grade Fuel

The use of LFG as a low-grade fuel requires a minimal level of gas processing. A condensate removal chamber as part of a LFG collection system reduces the amount of moisture in the gas stream. The LFG is then delivered "as is" to an on-site or off-site user. Low-grade fuel, following the removal of free moisture, is suitable for a variety of space and process heating applications, and as boiler fuel for production of steam for heating or electrical generation using steam turbines. Most of the current and past Canadian LFG utilization projects have been small- and medium-scale low-grade fuel utilization.

Heating

Low-grade fuel, also described as raw LFG, may be typically utilized for fueling a furnace, drying kiln or boiler. Low-grade LFG can be used at industrial facilities with low- to medium-temperature process heat requirements or for space heating. Heating applications for LFG provide a more efficient conversion to energy than does generating electricity.

Due to the low heating value of raw LFG, the equipment used must be designed to operate on this fuel. The equipment must also be designed to withstand the various trace compounds in the LFG, which may be corrosive. A typical arrangement for the use of LFG as a heating fuel is shown in Figure 7.2.

Ideally, the end-user of the LFG would have a consistent and adequate demand for the fuel and be in proximity to the landfill site, preferably within 10 km. The LFG is typically transported to the end-user through a dedicated pipeline. The primary factor in determining the marketability of low-grade LFG as a heating fuel is the distance to the end-user and therefore the costs associated with transport of the fuel.

Use of the fuel to heat large structures such as on-site equipment service shops is very attractive from a cost-savings perspective. There are concerns associated with exposure of people to exhaust products; however, there are radiant heating systems which prevent such exposure. Fuel demand for space heating has daily and seasonal fluctuations. This generally dictates that space heating can be only a supplementary use at all but small sites. Space heating greenhouses is one larger-scale application that has proven successful.

Raw LFG can be used for a range of applications, from heating a greenhouse to providing supplemental fuel for heating a major plant operation (i.e. cement kiln, asphalt plant, chemical plant). This form of LFG utilization has been used in Canada and the United States and has a proven record for technical feasibility and reliability. Due to the wide range of potential end-users of LFG as a heating fuel, each candidate landfill site should be evaluated individually to determine marketability and economic feasibility.

Low-grade LFG may also be used to evaporate the leachate and condensate that is generated on site. Pilot projects in the U.S. and Europe are exploring the feasibility of treating leachate by evaporation using LFG as the fuel source (Birchler *et al.*, 1994).

Low-grade LFG as heating fuel has the potential of being the most financially attractive of the utilization options. This results from the very low costs that are typically associated with this application and the energy conversion efficiency of direct use of LFG as a fuel, which is higher than for other utilization options. Where a high-volume, non-cyclical consumer of gas energy is located in proximity to a landfill, even a very small project can prove highly profitable.

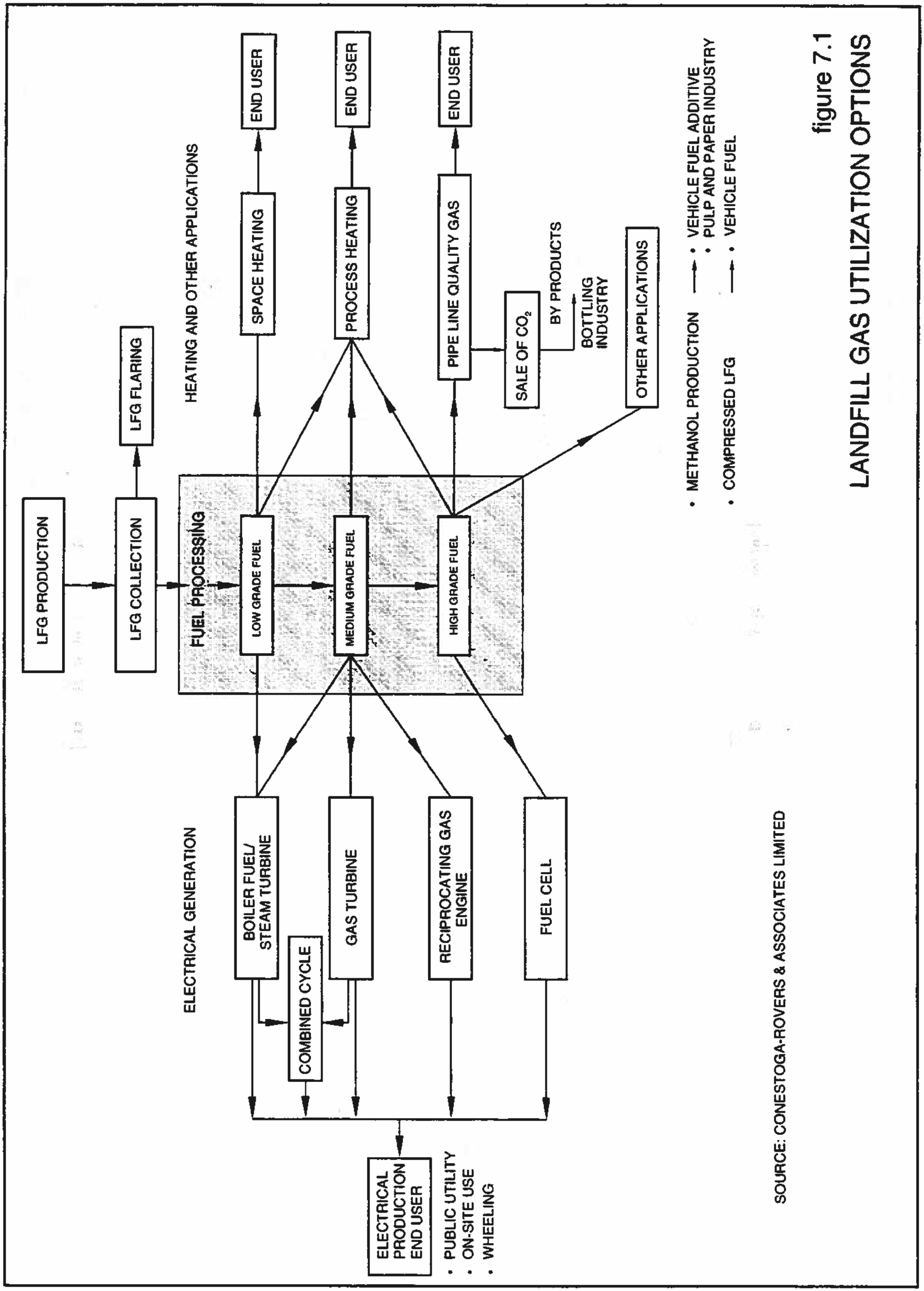
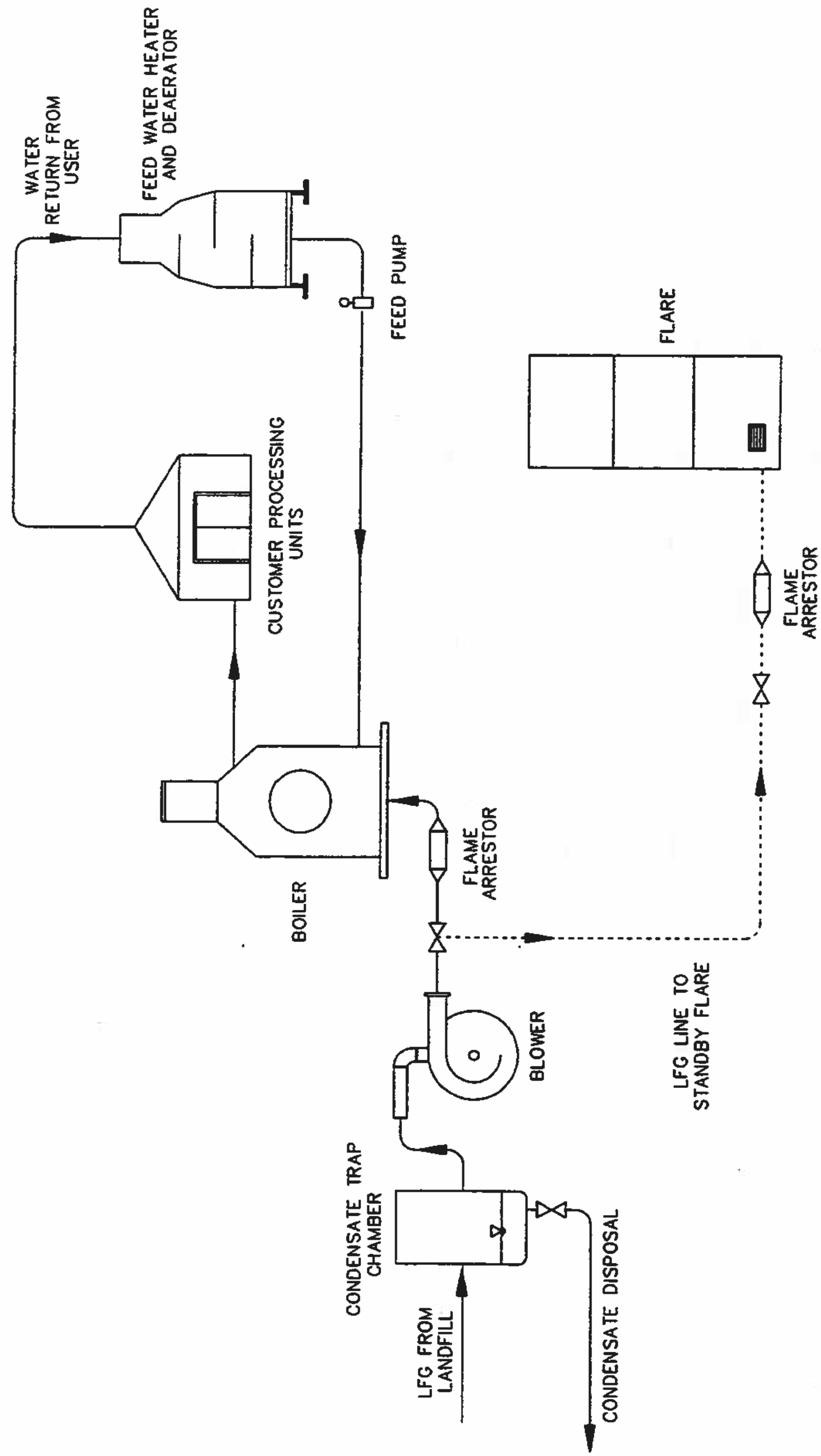


figure 7.1
LANDFILL GAS UTILIZATION OPTIONS



SOURCE: MACVIRO, 1991

figure 7.2
TYPICAL LOW-GRADE FUEL SYSTEM WITH HEAT EXPORT

Boiler Fuel

Low-grade fuel (raw LFG) may be used as fuel for boilers to produce steam for heating or electricity generation. LFG requires minimal treatment and compression for use in a gas-fired boiler producing high-pressure steam. The combusted LFG has contact with only the boiler tubes before being discharged through a stack. Any corrosion from the gas stream occurs on robust static components rather than on the precise moving parts of an engine or turbine.

The steam from the boiler may then be used for process or space-heating applications. Steam may be transported to nearby users if an on-site application is not available. Steam may also be used to produce electricity with a steam turbine. Steam turbines require extensive auxiliary equipment such as condensers, cooling towers, makeup water treatment, boiler feed pumps and other miscellaneous equipment. The high maintenance required for the operation of a steam turbine electrical generation plant makes it generally necessary for the plant size to be in the range of 10 to 50MW to ensure economic feasibility. Figure 7.3 shows a steam turbine in a typical LFG-fired steam-powered plant.

LFG-fired power boilers and steam turbines is the technology most used for large (10 to 50MW) electricity-producing plants utilizing LFG. This form of LFG utilization occurs in both North America and Europe, and has proven technically feasible and reliable.

Figure 7.4 shows the advantages and disadvantages of the various methods of electrical power production from LFG. Table 7.1 presents guidelines for selecting technology to generate electricity from LFG.

Table 7.1 Guidelines for Technology Selection — Electrical Generation from LFG

Technology	Preferred Plant Size (MW)	Fuel Grade	Minimum LFG Heating Value (Btu/cf)	Minimum Methane Content (%v/v)	Plant Efficiency Gross (%)	Plant Efficiency Net (%)*
Combined cycle	>10	medium	360 (LHV)	40	~37	~35
LFG-fired boiler with steam turbine	10 to 50	low medium	200 (HHV)	20	~33	~30
Gas turbines	3 to 18	medium	360 (LHV)	40	~27	~21
Reciprocating gas engines	0.5 to 12	medium	400 (LHV)	45	~35	~30

* Net plant efficiency varies depending upon parasitic loads.
LHV: Low Heating Value
HHV: High Heating Value
Note: Cost yardsticks are shown in Table 7.2

Source: MacViro, 1991.

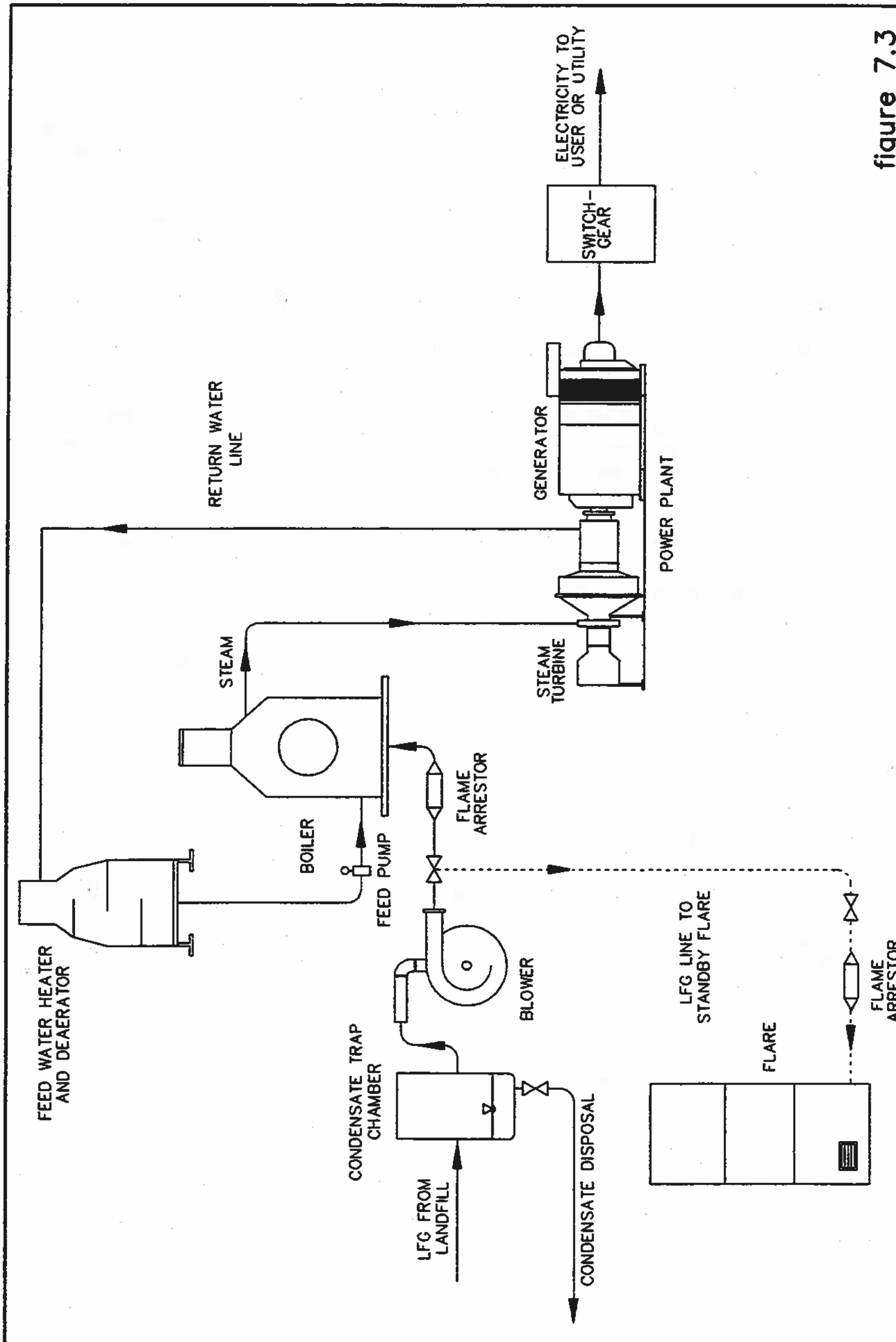
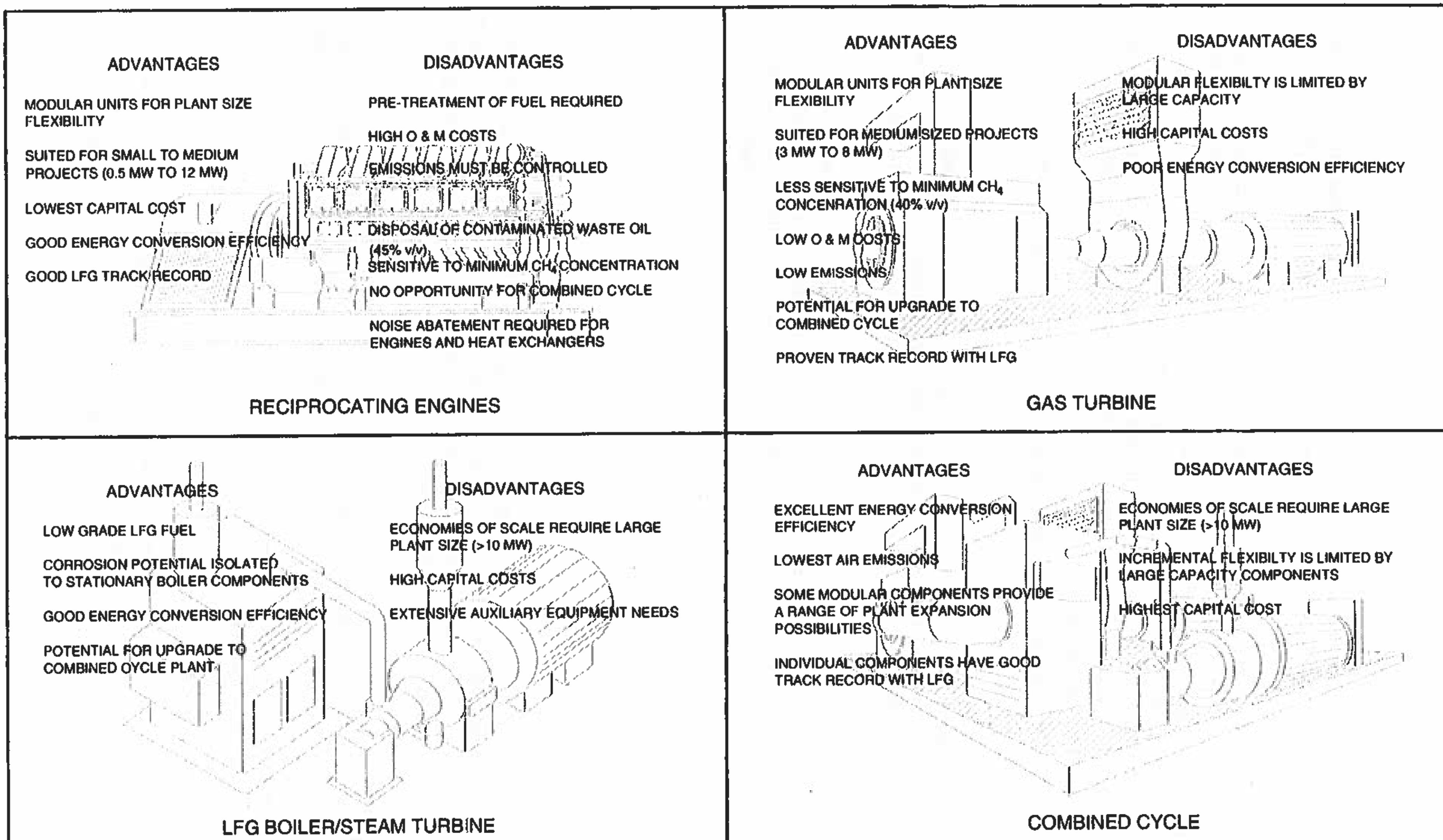


figure 7.3
TYPICAL LFG FIRED STEAM POWER PLANT

SOURCE: MACVIRO, 1991



SOURCE: CONESTOGA-ROVERS & ASSOCIATES LIMITED

figure 7.4

TECHNICAL OPTIONS
ELECTRICAL POWER FROM LANDFILL GAS

7.2.2 Medium-grade Fuel

Raw LFG may be upgraded to medium-grade fuel by further reducing its moisture content, trace contaminants and particulates. Treatment involves the removal of volatile organic compounds, mercaptans, sulfur compounds and moisture with a scrubber/filter system and a dehydration system. The cost of this level of treatment is significantly higher than for low-grade LFG but lower than for pipeline-quality gas.

When processed, medium-grade LFG has a greater potential for use as a heating fuel than does low-grade gas. Medium-grade LFG has essentially the same energy content as low-grade fuel. Processing eliminates some of the concerns regarding the corrosive potential of the gas and therefore opens the door to other possible end-uses. Medium-grade LFG can be used to fuel a wider range of industrial boilers, dryers, kilns and gas furnaces or to produce electricity through the use of reciprocating engines, gas turbines or combined-cycle (gas turbine and steam turbine) systems. Figure 7.1 shows the LFG utilization options that are available for a medium-grade fuel.

The following sections describe the various utilization options for a medium-grade LFG fuel.

Heating

As with low-grade LFG fuel, medium-grade LFG fuel may be used as a heating fuel for industrial boilers, dryers, kilns or gas furnaces. The cost and effort of upgrading raw LFG to medium-grade LFG may be advantageous since the efficiency of facilities using the fuel is increased, and the operating and maintenance costs are reduced.

Similar to the case of low-grade LFG, the ideal end-user of medium-grade LFG would have a consistent and adequate demand for the fuel and be located less than 10 km from the landfill site, if not on-site. Following processing, medium-grade LFG is transported through a dedicated pipeline to the end-user. The operational and maintenance costs for medium-grade LFG export would be greater than for low-grade (untreated) LFG but would still be relatively less than for the production of steam from a plant boiler.

The requirements for sale of medium-grade LFG fuel to an end-user are identical to those for sale of low-grade LFG fuel. The number and types of industries that can make use of the cleaner medium-grade fuel is greater than for low-grade fuel.

Reciprocating Gas Engines

Medium-grade LFG may be used as a fuel for reciprocating gas engines that in turn drive generators to produce electricity. Reciprocating gas engines using medium-grade LFG are readily available and may be obtained as modular units or within a complete parallel generator package. A typical reciprocating gas engine LFG utilization system is presented in Figure 7.5.

Reciprocating gas engines are available in various sizes with electrical outputs ranging from approximately 0.5MW to 3.3MW per unit. The modular nature of reciprocating engine systems provides flexibility for incremental expansion, should additional LFG be produced and become available for use.

Reciprocating gas engines require attention from trained personnel to ensure continued efficient operation, and they have relatively high maintenance costs. Additional disadvantages include necessity for cooling; exhaust gases that may contain products of incomplete combustion; high lubricating oil consumption; and possible classification of the waste lubricating oil as hazardous for disposal purposes.

The incremental expansion and the range of electrical outputs have made reciprocating gas engine technology suitable for the development of small (0.5MW to 12MW) electrical generating plants. This application is one of the most common and successful utilization options selected by developers.

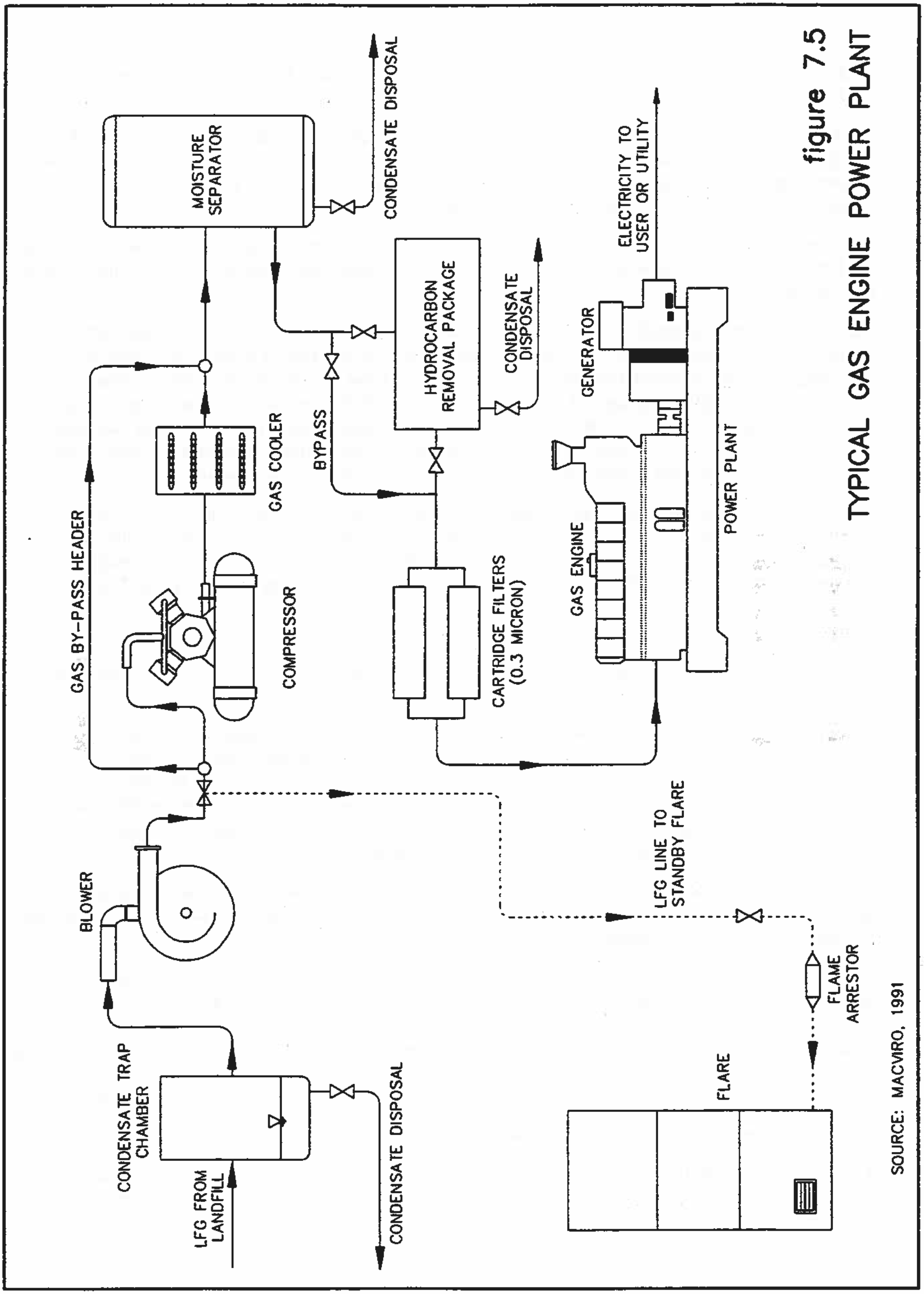


figure 7.5
TYPICAL GAS ENGINE POWER PLANT

Gas Turbines

Medium-grade LFG may be used as a fuel for gas turbines that in turn drive generators to produce electricity.

Gas turbine systems using medium-grade LFG as a fuel are available and may be obtained as modular and packaged systems. Gas turbine systems are available in various sizes but are generally larger than reciprocating engines with electrical outputs ranging from 3MW to 8MW for each unit. A typical gas turbine LFG utilization system is presented in Figure 7.6.

The modular nature of gas turbine systems provides flexibility for incremental expansion should LFG be produced and become available for use. This flexibility for expansion is controlled by the capacity of the gas turbines.

Gas turbine systems generally have cleaner air emissions and fewer operational and maintenance requirements than reciprocating gas engines of equivalent size. Gas turbine systems also offer greater operating flexibility than reciprocating gas engines. Gas turbines can operate on lower calorific values and lower-concentration methane [13.4 MJ/m^3 (360BTU/cf) @ 40 percent CH4] than reciprocating engines [14.9 MJ/m^3 (400 Btu/cf)@ 45 percent CH_4]. Gas turbine systems further offer the flexibility to modify and improve the LFG energy conversion efficiency by upgrading to a combined-cycle system to make use of the high-grade waste-heat exhaust (approximately 430°C) from the turbine.

When compared with the costs of reciprocating gas engines, capital costs associated with the initial set-up of a gas turbine system are higher. Gas turbines have lower energy conversion efficiencies than reciprocating engines. In some cases, the gas turbine's flexibility and lower operation and maintenance costs may offset the higher initial capital cost and lower energy conversion efficiency (see Table 7.1).

Combined Cycle

Medium-grade LFG may be used as a fuel for a combined-cycle system that in turn drives a generator to produce electricity.

A combined-cycle utilization system involves recovering large volumes of high-quality waste heat from gas turbines. The waste heat is redirected to a boiler which provides steam to drive a steam turbine. Recovery and reuse of the waste heat from the gas turbines reduces the volume of LFG that would be required to heat the boiler. The individual components of combined-cycle systems are readily available. The combined-cycle system components may be obtained in modular and packaged systems. A typical combined-cycle LFG utilization system is presented in Figure 7.7.

The modular nature of the gas turbine system allows LFG developers some degree of flexibility for incremental expansion of combined-cycle systems should more LFG be produced and become available for use. This is generally controlled by the size of the steam turbines.

Combined-cycle systems can be designed to accommodate various size requirements but, due to economies of scale, are generally cost effective for plants with greater than 10MW output. Due to the recovery and reuse of waste heat, combined-cycle systems have high (net) LFG energy conversion efficiencies of over 35 percent, compared to steam turbines at 30 percent (MacViro, 1991), reciprocating gas engines at 30 percent and gas turbines at 21 percent. Exhaust gases from gas turbines may contain products of incomplete combustion. Reuse of the waste heat gases improves plant air emissions.

Due to the complex nature of the combined-cycle process, continuous plant supervision is required.

Combined-cycle systems have not been extensively used in North America. This technology has been more widely used in many European countries such as Denmark. The individual components of the combined-cycle system have proven records for LFG utilization. Combined-cycle systems for the production of electricity are a successful application for large scale LFG utilization projects.

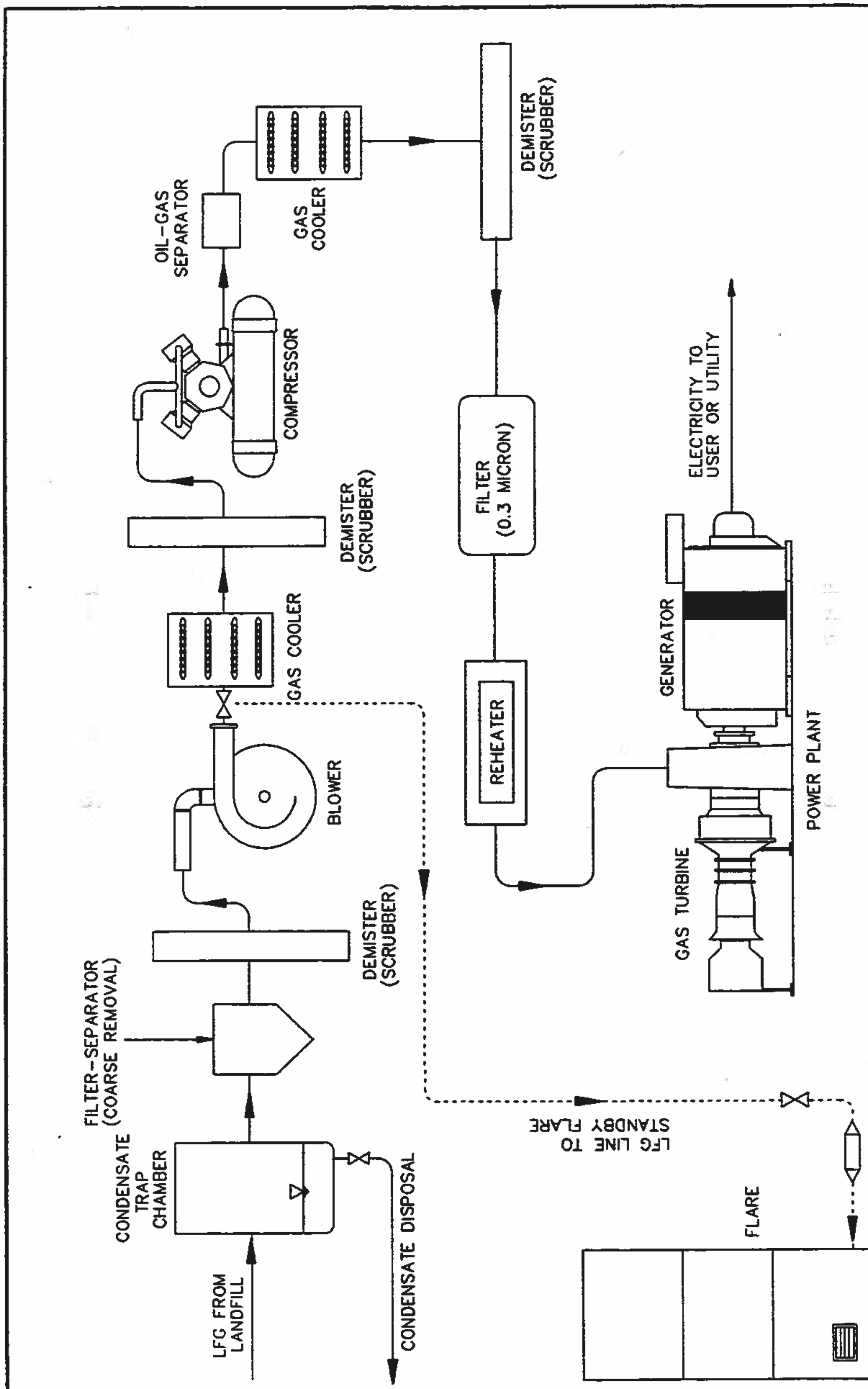


figure 7.6
GAS TURBINE POWER PLANT

SOURCE: MACVIRO, 1991

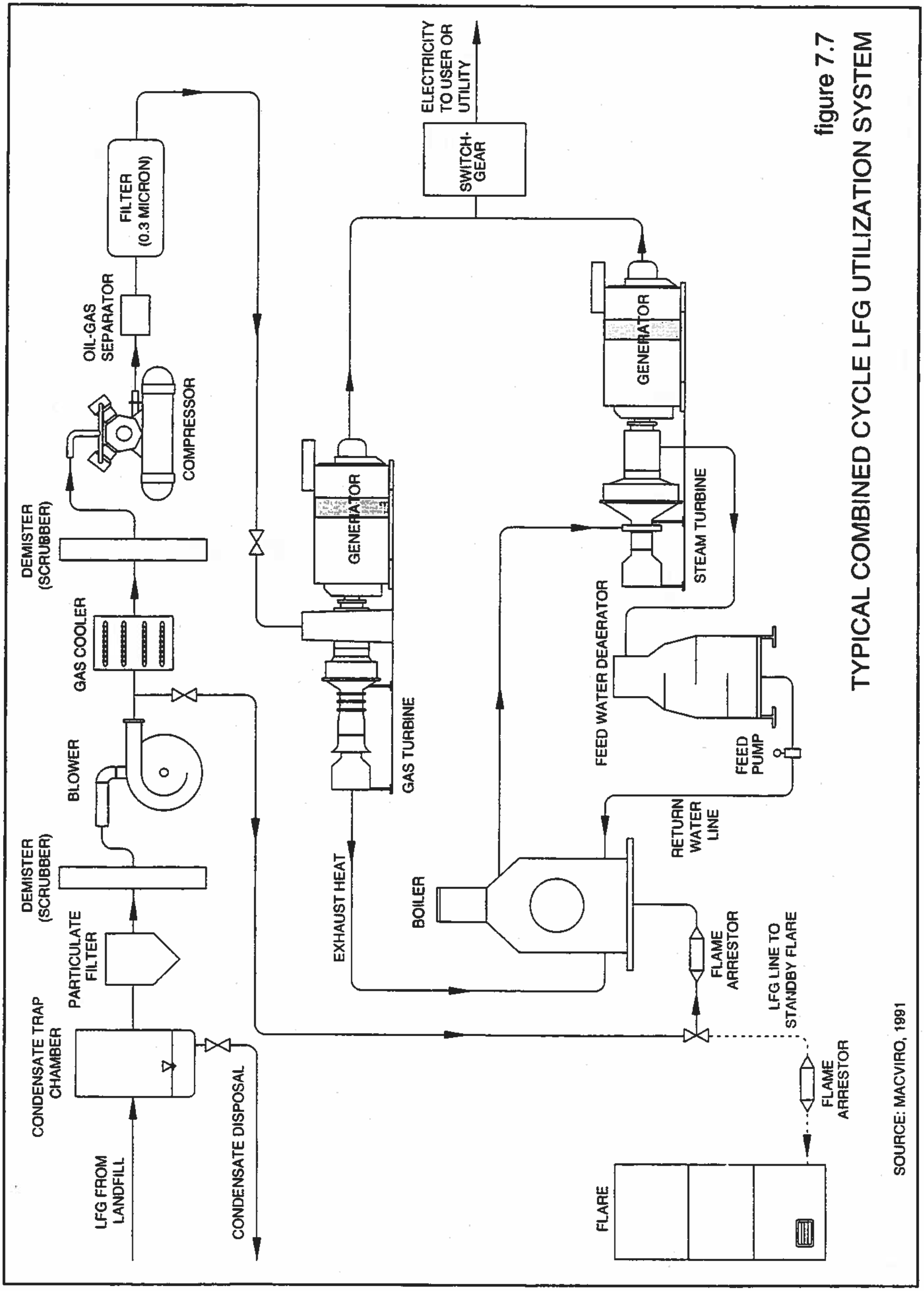


figure 7.7
TYPICAL COMBINED CYCLE LFG UTILIZATION SYSTEM

7.2.3 High-Grade Fuel

The use of LFG as a high-grade (high BTU) fuel requires upgrading the LFG and relatively more processing than for low-grade or medium-grade fuel. LFG processing includes the removal of moisture and trace contaminants such as volatile organic compounds, mercaptans, sulfur compounds and hydrogen sulfide. The LFG is further processed by the separation of the gas into its two major components, methane and carbon dioxide. There are a number of proprietary separation processes on the market.

Upgrading the LFG allows several end-uses including

1. high-calorific-value heating fuel (pipeline-quality gas)
2. electrical generation
3. commercial sale of carbon dioxide (pipeline-quality gas byproduct)
4. production of chemical products (i.e. methanol)
5. emerging LFG utilization technologies (i.e. fuel cells, vehicle fuel)

The following sections describe the various utilization options and emerging technologies.

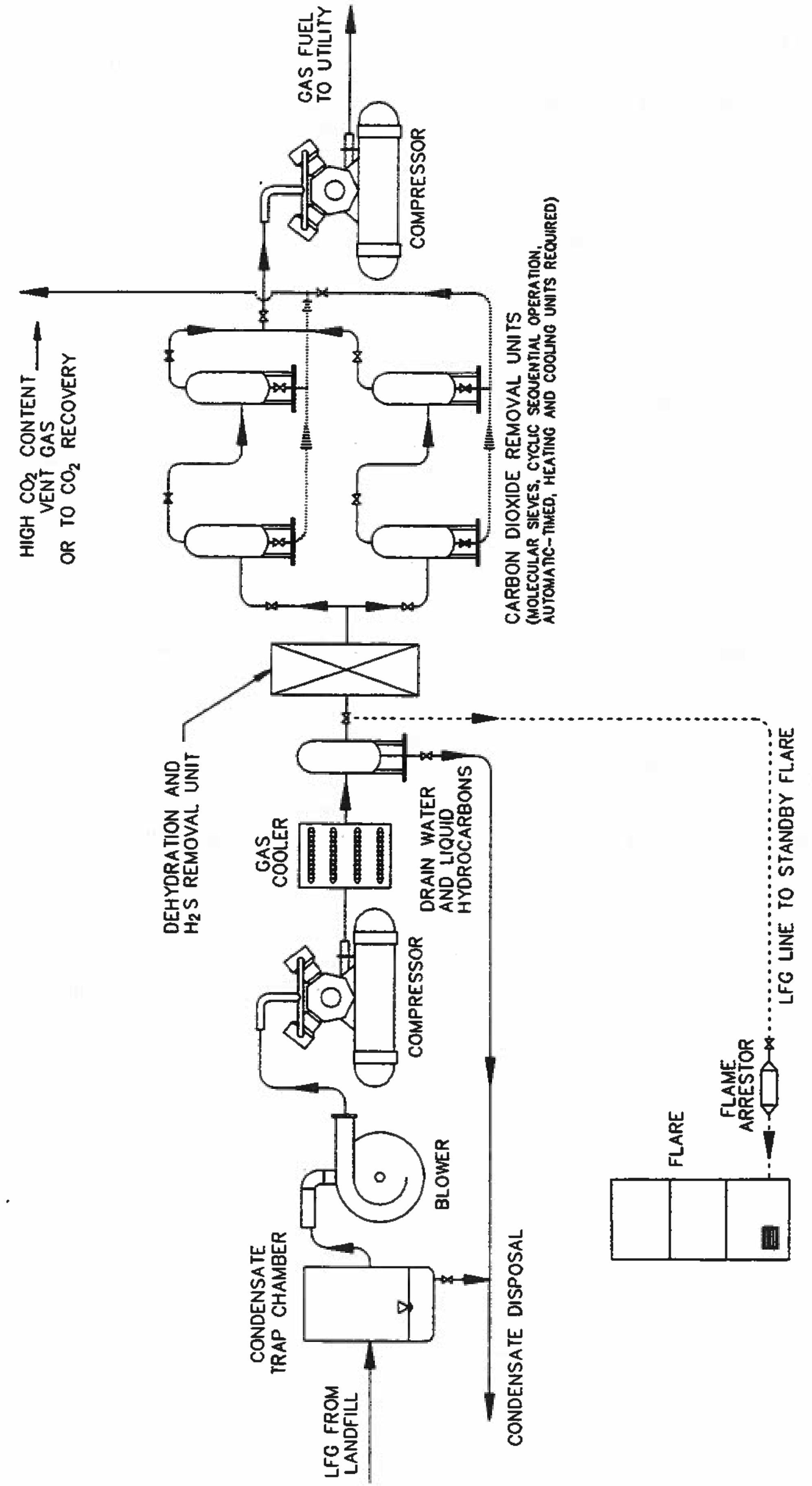
Pipeline-quality Gas

Utilization of LFG as a high-grade fuel to produce pipeline-quality gas has not yet been undertaken in Canada but has been implemented at landfills in the United States. Success with these types of projects has been limited.

The separated methane component of the LFG is generally used as a direct substitute for commercial pipeline grade natural gas and has heating value of approximately 37.3 MJ/m^3 (1000 BTU/cf). Following processing, the pipeline-quality gas is delivered under pressure to the local gas utility or directly to an off-site user. The ability to upgrade the LFG to pipeline quality allows for a wide range of potential end-users. A typical pipeline-quality gas utilization system is presented in Figure 7.8.

The production of high-calorific-value gas involves complex processes and high capital and operating costs. By upgrading the LFG to high-calorific-value gas, the mechanical and electrical complications of electrical power plant equipment are avoided. The markets for pipeline-quality gas are natural gas utilities or nearby industrial users.

A review of existing American utilization projects suggest that economic viability for a pipeline-quality gas project could occur if the gas produced can be sold in the range of $4.00 to $6.00/1000 cf (MacViro 1991). Currently the cost of natural gas is approximately $4.00/1000 cf and at these rates this utilization option does not appear economically feasible.



SOURCE: MACVIRO, 1991

figure 7.8
TYPICAL HIGH-GRADE LFG FUEL SYSTEM

Commercial Sale of Carbon Dioxide

The production of pipeline-quality gas involves the removal of carbon dioxide and other trace gases present in the LFG. Carbon dioxide can be removed from LFG by surface adsorption (molecular sieves), membrane separation, or solvent treatment systems as described in Section 7.3.

Inquiries have been made by large carbon dioxide users regarding the commercial viability of using the carbon dioxide byproduct of a LFG upgrade process. To date, there are no known existing or planned facilities that sell carbon dioxide derived from LFG. If markets could be established, the sale of carbon dioxide could contribute to the overall viability of a project to convert LFG to pipeline-quality fuel.

Production of Chemical Products

The production of methanol from LFG is a relatively new technology, with no such facilities in current operation in Canada. Processes producing methanol from LFG are generally proprietary. Methanol has historically been used in the chemical industry. Promising methanol markets include use as an alternative fuel or fuel additive for both gasoline- and diesel-powered engines, and as an alternative to chlorine in the bleaching process of the pulp and paper industry. In general, the high cost of this technology make this option worthy of consideration primarily for medium and larger sites.

Fuel Cells

The fuel cell is an emerging technology for LFG utilization that converts hydrogen directly to electricity. Use of fuel cells requires that the LFG be processed to produce high-grade fuel, which is then converted to hydrogen. While medium-grade LFG is used with this system, fuel cells are considered a high-grade LFG fuel use because the gas processing system is included as a component of the fuel cell system.

The fuel cell system involves the use of a high-grade LFG fuel processor; a fuel cell stack power transformer (direct current to alternating current); and a cooling tower for waste heat treatment. Fuel cell systems have a higher level of energy conversion efficiency (approximately 40 percent) and lower emissions (Pacey *et al.* 1994) than other methods of electrical production from LFG. A schematic of a fuel cell LFG utilization system is presented in Figure 7.9.

A fuel cell power plant is constructed using numerous individual fuel cells. The modular nature of fuel cells provides flexibility for incremental expansion should additional LFG become available. LFG-based fuel cell systems have been demonstrated as pilot projects in the United States, but never as a full-scale LFG utilization technology.

One disadvantage with fuel cells is their high capital cost compared with other LFG utilization technologies. The fuel cells required to produce electricity from LFG are not currently produced in commercial quantities. It is anticipated, however, that LFG fuel cells may become generally available in the near future. As fuel cells are developed and are brought into the marketplace, it is expected that the cost of fuel cells will decrease making the application of this technology more competitive.

Vehicle Fuel

A pilot project is underway at the Puente Hills Landfill in California to convert raw LFG to a usable vehicle fuel. Similar to the pipeline-quality gas option, LFG is treated to remove some contaminants and to increase the volumetric energy content of the gas (CO_2 removal). The treated fuel is then compressed into storage tanks. A quantity of low-BTU gas byproduct is flared.

The compressed fuel is then dispensed to specially modified vehicles. A number of cars and trucks have been converted to LFG fuel for the pilot project. While the economics of this technology remain uncertain for large-scale projects, the technical issues related to vehicle emission, vehicle performance and fuel conversion seem to be manageable. When one considers fuel consumption by vehicles that visit landfill sites, the use of LFG as a vehicle fuel holds promise (Maguin *et al.*, 1994).

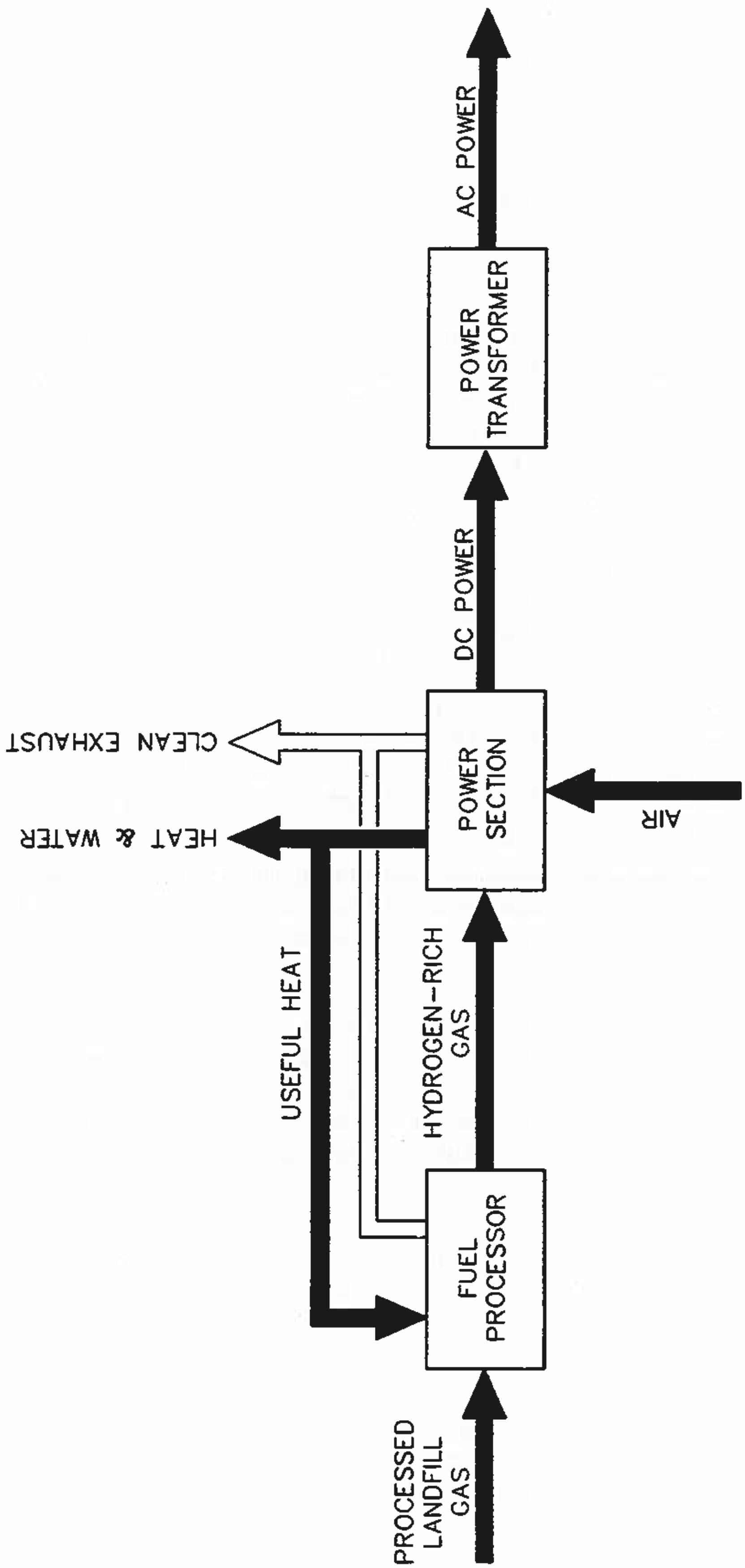


figure 7.9
FUEL CELL ELECTRICAL POWER

SOURCE: INTERNATIONAL FUEL CELL CORPORATION

7.3 LFG Treatment

Landfill gas contains methane, carbon dioxide, trace quantities of hydrogen sulfide and chlorinated hydrocarbons, and is generally saturated with water vapour. When extracted from a landfill site, LFG is warm and may also contain small quantities of nitrogen and oxygen from atmospheric air. LFG can be corrosive to some materials as a result of moisture in the presence of some of the trace compounds. As a result of this corrosive potential, and the presence of other trace compounds, LFG may require treatment for use in some processes. This treatment is usually required to reduce wear on equipment that is used to handle LFG, thereby reducing maintenance costs.

The extent of LFG treatment is primarily dependent on the end-use of the gas being processed. Treatment of LFG can be costly. Effective gas treatment is required not only for the proposed end-use of the LFG but also to minimize wear of gas handling equipment and to reduce maintenance and operation costs. The feasibility of a particular treatment process depends a great deal on the methane content, collection rate and contaminant composition of the LFG.

LFG treatment systems may include some of the following steps, depending on the level of treatment that is required:

- moisture removal } Low-grade fuel
- particulate removal
- removal of trace gases
- carbon dioxide stripping

(moisture removal: Low-grade fuel; moisture removal + particulate removal + removal of trace gases: Medium-grade fuel; all four steps: High-grade fuel)

Moisture Removal

LFG is typically saturated with water vapour when extracted from a warm landfill environment. This high moisture content, combined with contaminants including carbon dioxide (CO_2), hydrogen sulfide (H_2S), and volatile organic compounds, results in the corrosive nature of the gas.

LFG collection systems make use of some of the following moisture removal techniques including:

- moisture separators
- mist eliminators
- direct cooling
- compression followed by cooling
- absorption
- adsorption

Moisture separators, (also called condensate knockout pots, scrubbers, and free liquid knockouts) separate free liquid from the LFG stream. Moisture separators typically swirl the gas through a large drum (see Figure 6.15). This has the combined effect of reducing the gas flow velocity thereby allowing droplets to fall out of the gas stream, and increasing contact of the gas with the sides of the drum thereby allowing the liquid to collect on the walls of the vessel and draw to the bottom. This type of moisture separator removes only droplets of liquid.

A mist eliminator (also called coalescing filter, demister or extractor) is typically used downstream of the moisture separator or is sometimes incorporated on the outlet of a moisture separator. Small liquid droplets, not captured by the moisture separator, pass through the mist eliminator, which has a large surface impingement area. The liquid hits the surface of the filter and coalesces to form large droplets, which then drain to the bottom of the vessel. Mist eliminators are typically made of stainless steel woven wire mesh and, in combination with moisture separators, can remove up to 99.9 percent of the free liquids from the gas stream (Ikoku, 1984). Mist eliminators also remove particulate matter that is entrained in the liquid droplets which coalesce on the filter material.

Cooling and compression decreases the dew point of the gas, which in turn reduces its ability to contain water vapour. This temperature decrease by direct cooling of the gas stream causes moisture to condense out of the LFG. Gas cooling is typically accomplished with either air/air or air/liquid heat exchangers. Compressing the gas followed by cooling removes additional water vapour from the gas stream. Compression increases the temperature of the gas. Additional cooling of the gas may be required to suit the process conditions. Cycles of gas cooling and re-heating may be used to improve moisture removal efficiencies. Commercial gas compressors are readily available for this application.

Absorption technology uses a liquid that has a high affinity for water. With the gas stream in contact with the liquid, water vapour is removed from the gas. This process usually involves a combination of physical (dissolution) and chemical reactions of the sorbent with solute. The gas to be absorbed is introduced at the bottom of the column and allowed to rise through the absorption medium or the absorbent medium is sprayed on the gas stream requiring treatment. The treatment performance of the medium depends on the specific characteristics of the medium and the gas composition. Glycols are the most effective liquid dehydrators in current use with natural gas clean-up systems. Three types of glycol that have been successfully used to dehydrate natural gas are ethylene glycol (EG), diethylene glycol (DEG) and triethylene glycol (TEG). EG is the most common and cost-effective of the glycols in use due in part to the low-temperature operation of the process. This process has been used successfully in LFG utilization projects (USEPA, 1991).

Adsorption techniques use granular solids that have an affinity for water to remove moisture from the gas stream. In this case, where gas flows through the granular material, the water in the gas stream is retained on the surface of the particles of the solid adsorbent material. The most common solid adsorbents include silica gel, alumina and certain silicates known as molecular sieves.

Devices utilizing both absorption and adsorption include packed towers, plate columns, spray towers, and venturi scrubbers (USEPA, 1991). These moisture removal systems are regenerated after use by heating the active medium above the boiling point of water. Over time, contamination of the dehydrating materials reduces the effectiveness of the process and they must be replaced. These moisture removal processes are typically required for medium- or high-grade fuel utilization projects.

Particulate Removal

Solid particles entrained in the gas stream must be removed prior to use in medium- or high-grade fuel applications. These particles can cause significant damage or increased maintenance to utilization prime movers. Mist eliminators are a common particulate removal technology used in utilization projects. Additional treatment is accomplished using particulate filters, which are highly effective for particles of one micron and larger. Some of the moisture removal techniques described previously also remove particulates.

Filters require regular maintenance and replacement. Filters will also collect some hydrocarbon vapours found in LFG. The presence of hydrocarbon vapour on the filter medium will, over time, decrease the filter efficiency and increase the frequency of replacement.

Removal of Trace Gases

Trace gas treatment technologies for LFG utilization are typically used to remove sulphur compounds, non-methane hydrocarbons and volatile organic compounds (VOC), primarily chlorinated and halogenated compounds, found in LFG. Several treatment processes are available to remove trace gases from LFG and include:

- granular activated carbon (GAC)
- selective solvents
- iron sponge

GAC is the most common adsorbent used for hydrocarbon or VOC treatment. Typically, LFG flows through the adsorbent bed, and as the gases pass through the bed, moisture and trace contaminants are removed. GAC systems can be readily reactivated after use by replacement of the carbon or regeneration with heat or steam. A disadvantage of the GAC process for LFG treatment is the high affinity of GAC for water vapour. This can be alleviated by implementing high efficiency moisture removal prior to the GAC process step.

The selective solvent process uses various solvents to selectively absorb trace gases, such as hydrogen sulfide, carbon dioxide and others, from the LFG stream. One solvent process is the alkanolimine process which uses monoethanol amine (MEA), diethanolamine (DEA), and triethanolamine (TEA). It can effectively remove hydrogen sulfide, carbon dioxide and some hydrocarbons from the gas stream. Other solvent processes can be designed to maximize affinity for hydrocarbons, volatile organic compounds, chlorinated compounds and other contaminants as may be required. These processes are typically not selective for other compounds that may be found in LFG. This may require additional processing units or reduced intervals between regeneration and replacement of the solvents.

The iron sponge process uses hydrated iron oxide (Fe_2O_3) supported on wood shavings, where the iron reacts with the hydrogen sulfide (H_2S) in the LFG to produce iron sulfide. The iron sponge can be regenerated a limited number of times before the sponge media must be replaced.

Carbon Dioxide Stripping

Carbon dioxide in the presence of water can cause corrosion and has no heating value. High-grade fuel utilization processes remove carbon dioxide from the LFG. Removal processes include solvent extraction, adsorption and membrane separation.

The proprietary Selexol process uses a solvent to remove the carbon dioxide in the LFG at low temperatures and high pressure (USEPA, 1991). One adsorption process using a series of molecular sieves to selectively adsorb carbon dioxide produces a stream of up to 99 percent methane (USEPA, 1991).

Membrane technologies separate gases by using a membrane that is selectively permeable to one gas over another. For example, the separation of carbon dioxide from LFG is accomplished by passing a LFG stream through a membrane that is more permeable to carbon dioxide than methane. A spiral-wound type of membrane (typically composed of cellulose acetate) system has been used to upgrade LFG to pipeline-quality gas. Membrane separation technology has been used in pilot-scale high-grade fuel processes in Europe with some success (Rautenbach, 1993).

7.4 LFG Utilization Development Plan

As with any business endeavour, undertaking a LFG utilization program requires that a systematic plan for implementation be developed. This is carried out to minimize the risk involved in the venture. The steps involved in implementing a LFG utilization project may include the following:

- preliminary site characterization (see Section 3)
- feasibility assessment and decision to proceed
- LFG utilization development:
  - establish business arrangement;
  - call for proposals, tender project or select partner;
  - negotiate agreements;
  - establish financing;
  - obtain permits and approvals;
  - construction LFG plant;
  - commissioning and start-up LFG plant.

Figure 7.10 outlines the process for development of LFG utilization. The plan for implementation includes a number of points where a conscious decision must be made whether to proceed or terminate the project. Each of these decisions is made based on an increased level of knowledge gained in the preceding steps. The economic viability of the project is the primary determinant in the decision-making process.

Depending on the site owner's policies, it may be decided to issue a request for proposals (RFP) for LFG utilization. The RFP process is a method of selecting a development option that is commonly applied by municipalities. If an RFP is called, it is advisable to base the RFP on a defined and conservative scenario for LFG collection over a period. To the extent that it is possible, the proposed terms and conditions of the project should be defined in the RFP. These measures will allow for a fair comparison of base proposals. It is often advantageous to encourage proponents to include alternative plans for LFG utilization. This should be viewed as a supplement to the basic RFP scenario.

7.5 Feasibility Assessment

The following sections provide a description of the work tasks that should be completed in assessing the feasibility of LFG utilization. Figure 7.10 shows a logic diagram which outlines the components of a feasibility assessment.

7.5.1 LFG Study and Assessment

A LFG study would be required to determine the quantity and quality of LFG available at the landfill site. The gas production assessment may be modelled and/or may make use of field investigations. Details of the approach for assessment of gas production at landfill sites is provided in Section 5.2.

It should be noted that the gas production models described in Section 5.2 are commonly applied for regulatory purposes. As such these models, with the approved default values, may not represent a conservative method of predicting LFG production for utilization. Appropriate modifications to the modelling techniques should be made to ensure the results do not over-estimate the LFG production potential.

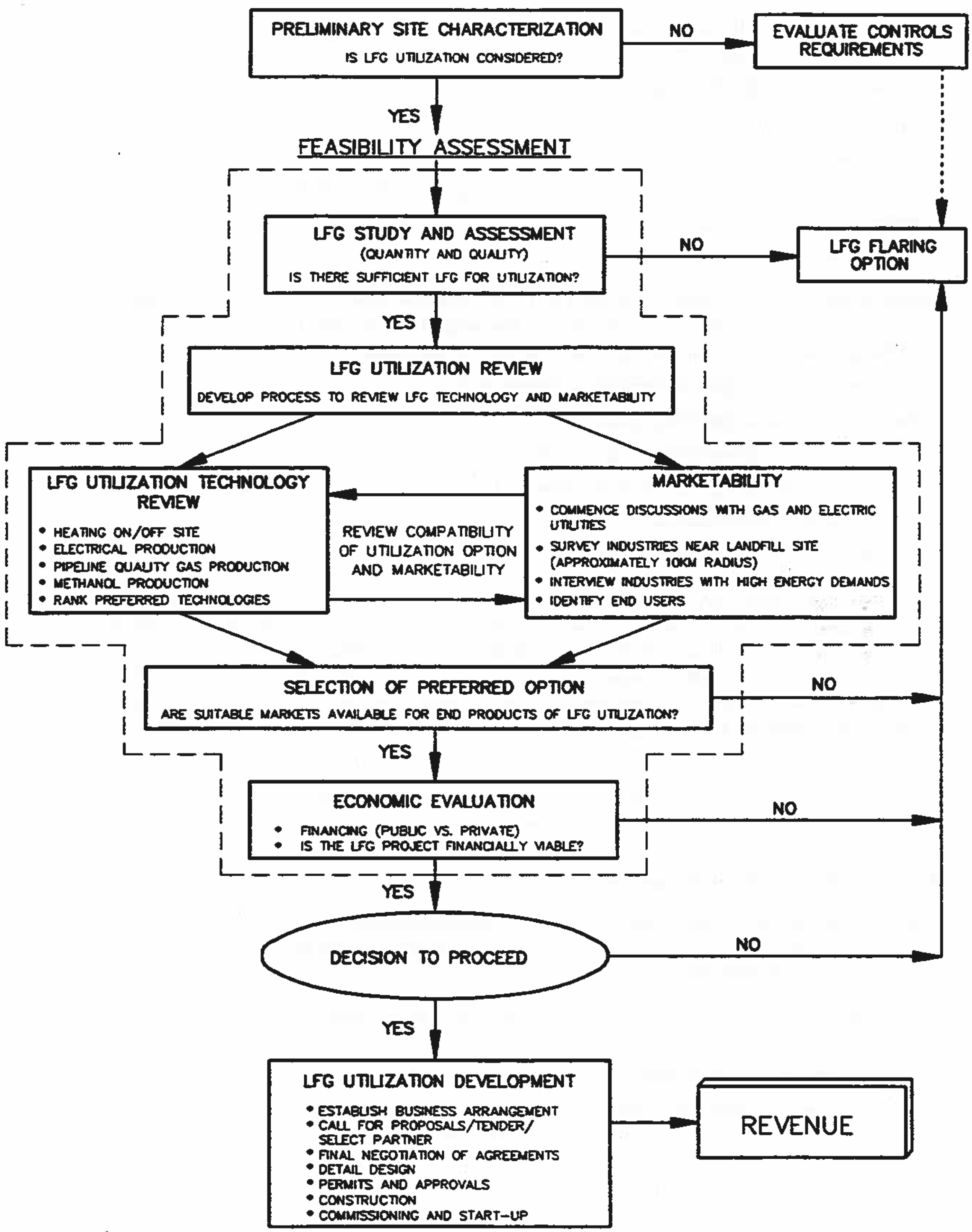


figure 7.10

LFG UTILIZATION DEVELOPMENT PROCESS

7.5.2 Review of LFG Utilization Technologies and Markets

The site-specific applicability of the various LFG utilization technologies should be evaluated. Factors that should be considered include the following:

- proven track record/reliability
- energy conversion efficiency
- technical feasibility
- compatibility with gas production projections (magnitude and duration)
- provisions for future expansion needs
- environmental factors (noise, wastes, emissions, etc.)

Potential markets for the various products of LFG utilization should be defined. Requirements to gain access to those markets should be determined. The market value of the LFG utilization products should be defined. The marketability study should include the following:

- the closest possible electrical grid interconnect point;
- the closest possible gas utility interconnect point;
- criteria for utility-grade pipeline-quality gas;
- a survey of industrial and institutional heating fuel consumers within 10 kilometres;
- identification of local markets for methanol; and
- review of possibilities for energy wheeling.

In Canada, the electrical power utilities have a monopolistic authority over the purchase and sale of electrical power. Currently, the only market for sale of electrical power is the local or provincial power utility. In some jurisdictions, power may be contributed by one organization into the electrical grid at one location to off-set consumption of power by that same organization at another location. This is commonly referred to as "wheeling power through the grid". Because of the electrical utility arrangements in Canada, the market for electrical power is largely dependent on the policies of the provincial or local utility.

If industrial fuel consumers are identified as potential end-users, additional information concerning fuel demand and quality criteria should be obtained.

7.5.3 Selection of Preferred Option

Once completed, the marketability study results should be compared with those from the review of LFG utilization technologies. It must be confirmed that accessible markets exist for products from the preferred technical utilization options.

From this review, two or possibly three preferred technologies should be identified.

7.5.4 Economic Evaluation

Cost and revenue projections should be prepared for the two or three preferred approaches. This will provide an indication of the magnitude of the potential revenue and allow for an equitable basis for comparison of the options. Yardsticks for costing LFG utilization systems are presented in Section 7.6. Revenue potential must be defined based on the markets that are available and current pricing for products.

As a basis for comparison, the internal rate of return (IRR) and the net present value (NPV) of each option should be calculated. The IRR is defined as the interest rate on an investment at which the net present value of an investment is equal to zero. The IRR is compared to the minimum attractive rate of return (i.e. available financing rate) to determine if the project is feasible. In calculating the IRR, the estimated capital financing costs are brought back to time zero (present worth) at the rate of inflation. If the NPV of the project is positive the LFG utilization project will earn more than the interest rate used in the financial calculation over the evaluation period.

An example of the criteria and assumptions typically adopted in conducting a preliminary financial review would include the following:

- The projects are evaluated over 20 years. The LFG production lifespan may be longer than 20 years but the life expectancy of many of the equipment components is on the order of 20 to 30 years. In addition, it is difficult to predict economic conditions beyond 20 years.
- Changes in operating and maintenance costs and the LFG selling price are calculated at appropriate annual rates.
- LFG collection efficiency should be estimated at no greater than 75 percent of the production volume. This efficiency of recovery is critical to the economic viability of the project. The design of the collection system is an important factor in assessing this. A sensitivity analysis at reduced LFG collection rates should be performed to assess the impact that this factor may have on the project economics.
- Raw LFG is assumed to be 50 percent methane by volume, and to have a heating value of 16.8 MJ/m^3 (450 BTU/scf).

Every effort should be made to use figures and estimates that are complete and representative during the initial economic assessment. A more detailed financial evaluation should be prepared once an approach is selected and a conceptual design is undertaken.

7.6 LFG Utilization System Costs

Ranges of costs for conducting extraction testing are presented in Table 6.6. The scope of extraction testing for utilization is similar to the LFG production assessment described in Section 5.4.

Table 7.2 presents approximate cost ranges for the various types of LFG utilization projects that may be undertaken. It should be noted that the ranges presented do not include costs for the LFG collection and flaring system. At sites where LFG control is mandated by regulations, the costs of the collection and flaring system should not be considered as costs associated with utilization. At sites where utilization is undertaken solely to generate revenues, the costs of the collection system should be included in the analyses. Refer to Table 6.6 for costs of LFG collection systems.

The capital costs shown in Table 7.2 are expressed in ranges of dollars per tonne of landfilled waste and dollars per kW generated. As a result, there is a broad range of variability due to variations in landfill densities, gas production rates, plant sizing limitations and economies of scale. Operation and maintenance costs are expressed in ranges of dollars per kW generated per year.

Note that the ranges of costs shown correspond to ranges of site sizes. The lower unit capital costs and the high annual operation and maintenance costs should be applied only to tonnages at the high end of the range of applicable site sizes. Conversely, smaller projects have higher capital unit costs and lower annual operation and maintenance costs associated with them.

Due to the possible variations in factors that may affect these costs, the figures shown in Table 7.2 are intended to be used only as guidelines.

Table 7.2 Budget Yardsticks for LFG Utilization Systems (1)

Utilization Technology	Typical Site Sizes (million tonnes)	Capital Costs ($/tonne) (2)	Capital Costs ($/kW generated) (3)	Annual Operations and Maintenance Costs ($/kW generated/yr) (3)
Boilers/steam turbine	> 6	$1.00 – $1.50	$830 – $1200	$45 – $70 /yr
Combined cycle	> 10	$1.10 – $1.60	$900 – $1300	$50 – $85/yr
Reciprocating engines	1 – 8	$1.10 – $1.60	$1200 – $1700	$150 – $180/yr
Gas turbine	3 – 12	$1.30 – $1.55	$1400 – $2000	$90 – $120/yr

Notes:
1. All costs are in 1995 dollars and exclude taxes.
2. Based on appropriate plant size for site tonnage.
3. Based on appropriate plant size for assumed site capacity and relative plant efficiency as shown in Table 7.1. (Assume 800 to 1200 kW/million tonnes of MSW)

7.7 Impediments to Utilization Projects

Impediments to LFG utilization projects are primarily related to the perceived risk associated with these projects and limitations on access to markets.

Financing for LFG utilization projects can be difficult to obtain if the perceived risks are not adequately addressed. The LFG development plan discussed in the preceding section, including a detailed feasibility assessment, is intended to address some of these concerns and to confirm or refute the economic viability of a particular project. As discussed previously, LFG utilization projects must be economically feasible to proceed. Risks in undertaking a LFG utilization project are related to the uncertainty of the following:

- quantity and quality of LFG resource
- stability of end-user
- approvals and permits
- access to markets

Quantity and Quality of LFG

Forecasting the quantity and quality of LFG available for energy production over the life of the utilization project is an uncertainty and therefore contributes to the financial risk. This risk can be reduced by modelling the gas yield based on site-specific knowledge. Field based gas production data may be estimated by conducting extraction tests as discussed in section 5.4.

Ideally, field data will be generated as a result of the operation of a LFG collection system. This requires that the collection system be designed and installed prior to finalizing plans for utilization. At many sites, this is the logical order of events due to the priority that environmental controls are given. At sites where LFG collection is carried out not as a control function but solely to generate revenue, reliance on extraction tests and modelling may be the only practical option. It should be noted that gas system operation and extraction tests provide data over a short period. Knowledge of long-term production trends and application of sound modelling techniques are the most reliable methods of predicting gas production into the future.

Plant capacity is based on the estimated gas production, which affects the capital cost of the project and the efficiency of the utilization operation. Flexible design of the collection and utilization systems to accommodate a range of anticipated gas quantities will aid in addressing some uncertainties.

Stability of End-user

A risk associated with providing LFG to a private end-user is related to the possibility that sometime over the utilization project, the end-user's demand for the product may change. This may be addressed by establishing multiple users, verifying the long-term nature of the demand, and establishing agreements or security related to the continued use of the gas.

Approvals and Permits

The time required to obtain the necessary approvals and permits can affect the scheduling of the LFG utilization project and may result in increased project costs and declining gas production. These approvals and permits represent an area of risk that is generally assumed by the developer. Typically a developer would ensure that all approvals and permits are in place prior to committing the capital funds to the project. These may include:

- provincial environment ministry — air and noise emissions;
- municipal approvals for zoning;
- building permit;
- approval from the provincial labour ministry;
- approval for local electrical utility interconnection into hydro grid (only for electrical generation option);
- approval for local gas utility interconnection into gas pipeline system (only for pipeline-quality gas option);
- approval from local electrical utility to transport power through a portion of the hydro grid to a remote end-user;
- approval to utilize an existing utility corridor or municipal right of way to transport steam or gas; and
- approval for disposal of effluent (i.e. condensate).

Access to Markets

Limited access to markets for sale of LFG products is a significant impediment to LFG utilization. For the on-site and off-site use of low- and medium-grade LFG fuel for processing and/or space heating, access to markets is defined by distance to fuel users. This is entirely a function of the site location. Markets for sale of by-products of LFG (CO_2, and methanol) are not yet well-defined.

The market for sale of electrical power consists of the local or provincial electrical utility. The sale of electrical power is subject to the policies of the utility. Many of the power sale agreements are negotiated on a case by case basis. In some regions, purchase of power from non-utility generators has been frozen or cut back due to a surplus of electrical power. In areas where the environmental benefits of electrical generation from LFG utilization are not specifically identified, access to the market for sale of power may be limited.

8.0 Canadian Case Studies

Case studies of the experiences of Canadian landfill site owners and/or operators and landfill gas (LFG) utilization developers are contained in Appendix A. Participants were invited to provide information concerning their site or project. General site data was requested, along with information regarding innovative practices or designs that have been developed, as well as difficulties that have been encountered and methods of overcoming them.

The sites and projects that were selected as case studies were chosen to reflect a national cross-section including various geographical and jurisdictional regions as well as differ status of LFG projects. Some of the site owners/operators who were contacted declined to participate in the program due to concerns about the sensitivity of the information to be discussed. Some Canadian LFG utilization developers declined to participate due to the potentially proprietary nature of the information requested.

The information in Appendix A is a compilation of the data provided by the participants. In each case, the name and telephone number of the primary source of the information has been given to allow interested parties to make inquiries should additional information be sought. Appendix A contains information provided by the site owners/operators, to illustrate their experience in LFG management. The following discusses a few of these landfill case studies.

The Keele Valley Landfill Site north of Toronto, Ontario, is owned and operated by the Municipality of Metropolitan Toronto and is one of Canada's largest sites. The LFG management system was installed progressively using horizontal collection trenches to allow LFG collection to be carried out while site filling is going on. Proposals for LFG utilization were solicited in 1989. Eastern Power Developers (EPD) was selected by the Municipality of Metropolitan Toronto to carry out the development of a large-scale combined-cycle plant to produce electricity for sale to Ontario Hydro. One of the challenges that had to be overcome was to coordinate and obtain all the necessary agreements and approvals from the various parties involved. Although this affected the project schedule, production of electrical power started in the spring of 1995.

The Brock West Landfill site in Pickering, Ontario is owned and operated by the Municipality of Metropolitan Toronto and contains approximately 17 million tonnes of refuse. The site is expected to close in 1996 and has a LFG collection system equipped with vertical extraction wells. Eastern Power Developers (EPD) developed and operate a combined-cycle plant to produce electricity (~25MW). This plant was one of the first large-scale LFG-powered electricity generation plants in Canada having first produced electricity in 1991.

Enercogen Limited was selected by the Municipality of Metropolitan Toronto to develop a 5MW electrical power generation plant at the Beare Road Landfill in Scarborough, Ontario. The site is a large landfill (~10 million tonnes) which was closed in 1983. The Enercogen development includes the installation of a LFG collection field (i.e. wells and piping), along with construction and operation of a power plant with seven reciprocating engine-generator sets and LFG treatment facilities. Some delays to project initiation were experienced due to obtaining the necessary local approvals. The project is currently under construction and is expected to be in service by early 1996. Enercogen's Beare Road project illustrates the need to give consideration to projects which may not fit the ideal profile. The age of the Beare Road site contributed to some uncertainty with respect to estimating the LFG supply. Enercogen overcame this primarily by collecting actual field data and by incorporating flexibility into the design of the system to allow for fuel augmentation with natural gas if necessary.

The Meloche landfill is a medium-sized, privately-owned site which is located in a quarry in the City of Kirkland, Quebec. The site was closed in 1990 and has a LFG collection system equipped with vertical extraction wells. A LFG utilization development has been proposed which makes use of gas turbines to produce electricity for sale to Hydro Quebec. Delays in starting the project are apparently due to difficulties in obtaining the necessary approvals. These delays have affected the planned lifespan of the utilization project.

The Miron landfill located in Montreal, Quebec, is currently Canada's largest landfill. The site makes use of vertical wells for LFG collection. Some difficulties related to build-up of liquid in the LFG piping were encountered and overcome with a system design change. Collected LFG is currently being flared, however an agreement has been reached to utilize the LFG in a 25MW steam turbine plant to produce electricity. It is expected that sale of electricity to Hydro Quebec will begin in the spring of 1996.

There are a number of LFG utilization projects that have been undertaken in British Columbia by E.H. Hanson Engineering Group Ltd. These tend to be small-scale projects where innovative approaches are required. Most of the projects identified involve use of the LFG as a heating fuel for space or process applications located within 10 km of the site. This experience illustrates the feasibility of small-scale utilization projects where the opportunity for direct use of LFG as a heating fuel exists.

Discussions with the participants and review of the case studies reveal the following common themes:

- technical difficulties associated with LFG collection, when encountered, can generally be overcome;
- impediments to LFG utilization that have been encountered are largely bureaucratic;
- access to markets for end-products of LFG utilization is limited; and
- long delays in the initiation of LFG projects can increase risk and erode the viability of the project.

Many Canadian landfill sites are currently being considered as candidates for LFG utilization. It is apparent that a large number of additional sites have some potential for viable LFG utilization.

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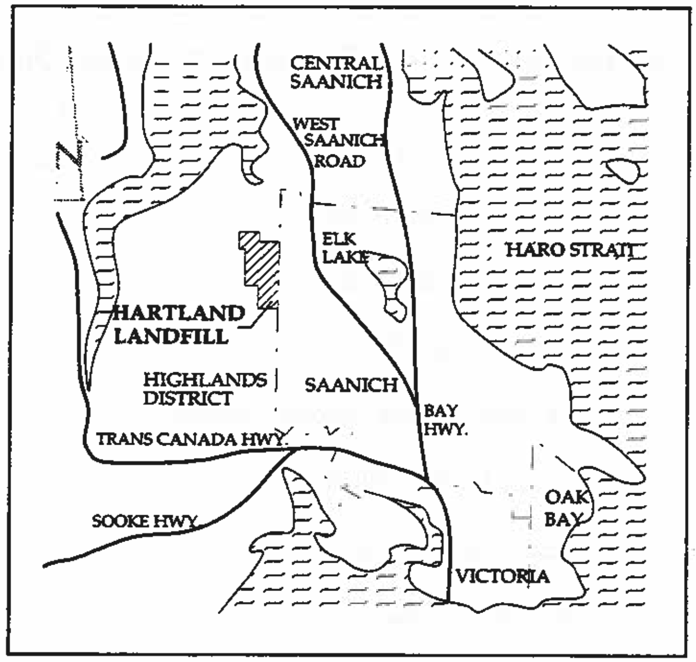
Appendix A — Canadian Case Studies

1. Hartland Landfill, British Columbia
2. Keele Valley Landfill, Ontario
3. Beare Road Landfill, Ontario
4. Brock West Landfill, Ontario
5. Upper Ottawa Street Landfill, Ontario
6. Lachenaie Landfill, Quebec
7. Meloche Landfill, Quebec
8. Miron Landfill, Quebec
9. Highway 101 Landfill, Nova Scotia

1. Hartland Landfill Site

Owner/operator:	Capital Regional District
Location:	Victoria, B.C.
Filling period:	1954/1996
Status:	Active
Capacity:	7.0 million tonnes
Stratigraphy:	Bedrock
Waste composition (%):	
- domestic	50
- industrial	40
- construction	10
Tonnage in place:	4.0 million tonnes
Approved landfill area:	50 ha
Area currently filled:	20 ha
Maximum depth of waste:	40 m
Daily cover type:	Synthetic material
Final cover type:	Clayey soil
% final cover in place:	0
Proposed end use of site:	Open space
Contact name:	Chris Riddell
Telephone number:	604-727-3331



Site Location (N.T.S.)

General Information:

The landfill is located in a rural area and consists of two phases. Phase I is the current landfill, which has a landfill gas (LFG) collection system in place. Phase II will start accepting refuse in 1996. A British Columbia Hydro easement crosses the north and east boundaries of the landfill. A natural gas line is approximately 8.0 km from the site.

The water table is located approximately 1 metre below the original ground surface. Phase I of the landfill does not have an engineered liner system. The leachate has a natural discharge into a pond, then it is pumped into a lagoon and discharged into the municipal sewer. The final grading of the site will have 3.5:1 (H:V) side slopes and 6 percent top slope for Phase I.

LFG Management:

The initial purpose of installing the LFG collection system in 1991 was to control odours. The capital cost of the system was $350,000. The annual operation and maintenance costs were estimated at $20,000. Following site closure, a new LFG collection system will be installed.

The existing LFG collection system consists of 33 collection wells, high-density polyethylene (HDPE) piping 200 mm diameter, one LFG blower, an open-sided LFG blower building and an open candle-type flare. The gas is drawn from the landfill using a Spencer Turbo-Blower with a capacity of 1,880 m^3/hr (1,102 cfm). Prior to flaring the gas, the moisture is collected by a condensate trap. Approximately 7,700 litres (1,700 gallons) of liquid is collected per day from the LFG system. The condensate is pumped into the leachate collection system. The LFG is flared at a temperature of approximately 1000 to 1200°F. The system is currently operating at 37 percent of its maximum capacity, drawing 700 m^3/hr (415 cfm) of LFG.

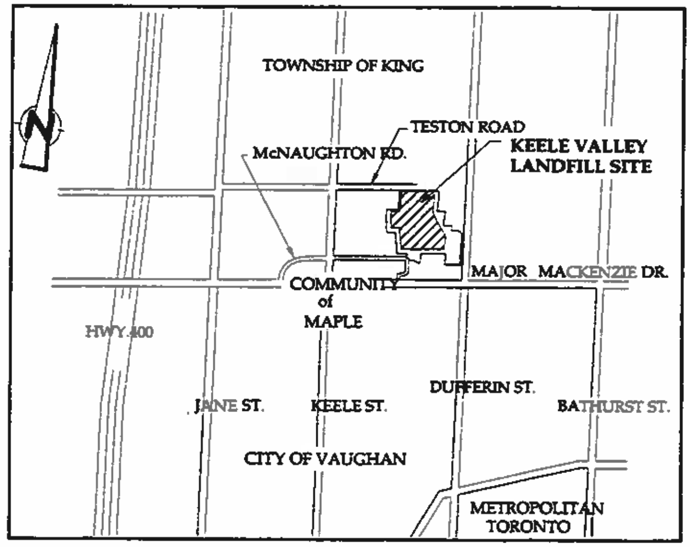
Migration monitoring probes are to be installed in the near future.

LFG Utilization:

Economic feasibility studies have been carried out in the past to evaluate the possibility of LFG utilization. Electrical power generation is the most likely option, although B.C Hydro declined to purchase the electricity generated since the anticipated production rate was very low.

2. Keele Valley Landfill Site

Owner/operator:	Municipality of Metro Toronto
Location:	Vaughan, Ont.
Filling period:	1983/1998
Status:	Active
Capacity:	20-25 million tonnes
Stratigraphy:	Silty sand
Waste composition (%):	
- domestic	45
- industrial	45
- construction	10
Tonnage in place:	16.5 million tonnes
Approved landfill area:	99.2 ha
Area currently filled:	99.2 ha
Depth of waste:	60 m
Daily cover type:	Clean soil
Final cover type:	Clean soil
% final cover in place:	0
Proposed end use of site:	Passive recreation
Contact name:	Martin Edelenbos
Telephone number:	905-832-0682



Site Location (N.T.S.)

General Information:

The landfill is located in the former Maple Pit site, where the extraction of granular material took place prior to landfilling operations. The area surrounding the site includes the City of Vaughan and the disposal services landfills to the north; industrial and aggregate extraction to the west, and a woodlot and a former ski area on the east. Residences are located approximately one kilometre from the site.

The water table varies in depth from 10 to 20 m below grade in the vicinity of the landfill. The nearest surface watercourse is located approximately 300 m northeast of the site. Dewatering a portion of the site was required to allow for the installation of the liner and leachate collection systems. The liner consists of a 1.2m thick layer of clayey till on the base and a 2.0m thick layer of clayey till on the side slopes. An extensive liner-performance monitoring network consisting of lysimeters, piezometers, conductivity sensors and sub-liner groundwater samples has been installed at the site.

The leachate collection system consists of a granular drainage blanket, five high-density polyethylene (HDPE) collection tiles ranging in size from 150 to 200 mm in diameter and in length from 285 to 1325 m, and a HDPE header pipe 300 mm in diameter. The leachate drains by gravity through the collection pipes to the leachate pumping station. The leachate is then discharged via the sanitary sewer to the Duffin's Creek Water Pollution Control Plant.

The final grade of the landfill has been designed to have 4:1 (H:V) side slopes and a 5 percent top slope.

LFG Management:

The LFG collection system at the site is installed and upgraded on a continuing basis. The LFG collection system includes:

- a network of horizontal collection trenches within the solid waste mass
- dual LFG headers
- a central LFG flare and blower station, consisting of blowers and three flares
- a network of migration monitoring probes located around the site's perimeter

To date, approximately 85 percent of the collection system has been installed, incorporating 150 to 600 mm HPDE piping. The system will be expanded in the future to suit the gas production rate. The operations compound includes the flare and a block building which houses the blowers. The compound is fenced and paved.

Condensate is collected from the LFG and drains to the leachate collection system for disposal. Currently the system is operating at 66 percent of its extraction capacity, collecting 13,600 m^3/hr (8,000 cfm). The extraction system is currently designed for a maximum capacity of 20,400 m^3/hr (12,000 cfm). Currently the system operates with two blowers and two flares. The flare emissions were tested and found to be in compliance with Ontario regulations.

Monitoring the LFG collection system includes daily plant monitoring, weekly landfill monitoring, and gas quality and quantity monitoring. An annual operations summary report is submitted to the Ontario Ministry of the Environment and Energy. Monthly pressure and gas readings are taken at all levels of the perimeter migration monitoring probes. Weekly monitoring is conducted by site personnel to detect the presence of volatile organic compounds in the air.

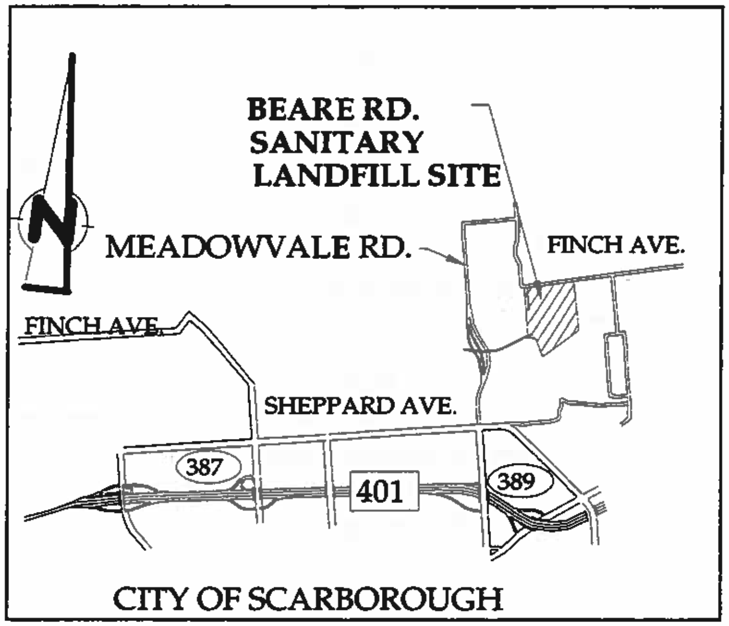
LFG Utilization:

In 1989, proposals for LFG utilization were solicited. The criteria for evaluating the utilization proposals included technical feasibility, environmental impact and economic viability. In 1994, an agreement was reached between Eastern Power Developers (EPD) and Metro Toronto for electricity production. EPD offers a "combined-cycle" power plant including two gas-turbine generator sets, an exhaust gas-boiler with supplemental firing, and a large steam-turbine generator set. The capital costs for the power generation plant are expected to be approximately $17 million. The power plant is being constructed with a 30 MW generating capacity. If necessary, the LFG fuel supply may be augmented with natural gas to maximize power generation. Ontario Hydro has agreed to purchase the electricity generated. LFG collection will be the site owner's responsibility, and in exchange the developer will pay royalties.

Electrical generation began in 1995. Power generation is expected to be viable for 20 to 40 years. Prior to project start-up, the developer had to obtain approvals for air quality, zoning and easement.

3. Beare Road Landfill Site

Owner/operator:	Municipality of Metropolitan Toronto
Location:	Scarborough, Ont.
Filling period:	1967/1983
Status:	Closed
Capacity:	9.6 million tonnes
Stratigraphy:	Silty sand/clay
Waste composition (%):	
- domestic	71
- liquid industrial	18
- sewage sludge	11
Tonnage in place:	9.6 million tonnes
Approved landfill area:	65 ha
Area currently filled:	65 ha
Depth of waste:	25–65 m
Daily cover type:	Clean Soil
Final cover type:	Clean Soil
% final cover in place:	100
Proposed end use of site:	Green Space
Contact name:	Lou Ciardullo
Telephone number:	905-832-0682



Site Location (N.T.S.)

General Information:

The site is separated from the surrounding predominantly residential areas by designated green spaces and a hydro corridor, except to the north where it fronts on Finch Avenue on which there are scattered rural residential units. The federally-funded Rouge Valley Park is planned for lands to the west of the landfill. The south half of the landfill is located in the former Reagan Sand and Gravel Pits.

A leachate collection system was installed at the south end of the landfill. The leachate drains by gravity through a lagoon system spread out on the side of the landfill at different elevations. A leachate lagoon halfway up the slope collects overflow leachate from the lagoons above it and discharges the leachate via three dispersion pipes 200 mm in diameter to the centre of the lagoon at the foot of the landfill.

LFG Management:

In the past, the LFG generated at the site was flared through passive steel vents. The vents are constructed of 75 to 300 mm steel pipes.

A LFG collection system is currently being installed at the site that includes:

- 52 wells within the solid waste mass connected to 150 mm high density polyethylene (HDPE) lateral feeders via floating well head assemblies
- LFG headers, constructed of 300 mm HDPE pipes, running in a loop around the landfill
- power plant housing two blowers

The well layout allows for additional LFG collection wells to be installed at a later date as required. The operations compound houses the power plant building. The power plant building is a masonry construction consisting of three rooms, separated for explosion safety purposes. The first section of the building houses a knockout pot and water scrubber, which the LFG passes through prior to entering the two centrifugal blowers (2400 scfm/150 kW). The blowers have an inlet vacuum of 20-inch water column at the furthest point in the landfill and an 8-inch water column of outlet pressures.

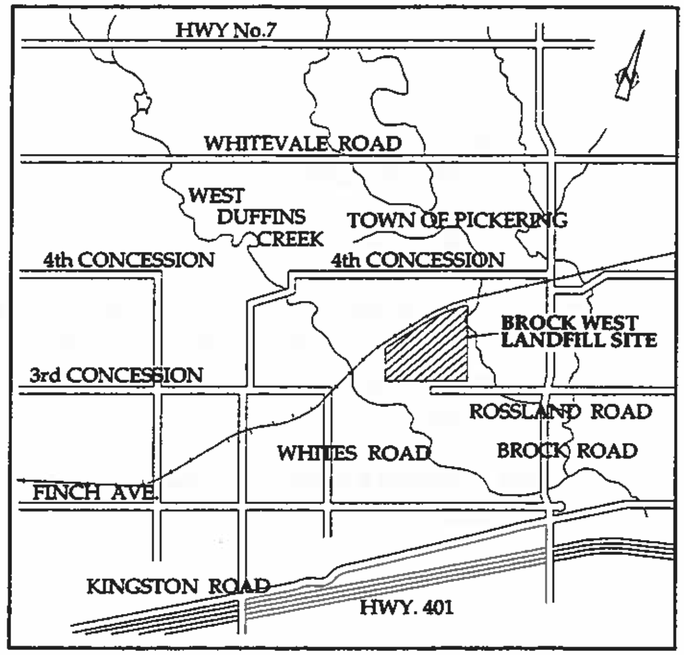
LFG Utilization:

The LFG was causing considerable odour problems for the residents in the vicinity of the site. Metro Toronto has signed an agreement with Enercogen (Beare Road) Limited (Aldworth Engineering, E.S. Fox Ltd.) to collect the LFG and generate electricity. Enercogen is installing the LFG collection system and donating it to Metro at the outset of the project. The power plant building houses seven Caterpillar 3516 engine generator sets. The power plant is rated to produce 5,684 kW of power. The overall up-time for the facility is estimated at 95 to 98 percent. The capital cost of the project, including the collection field, is estimated at $8.7 million. Ontario Hydro will purchase 5,000 kW at 6.12¢ during the first 10 years of the utilization plant operation. Royalty payments to Metro Toronto were agreed at a nominal rate of 2.5 percent of revenues.

The system is expected to be in operation by early 1996. Power generation is expected to be viable for the next 20 years.

4. Brock West Landfill Site

Owner/operator:	Municipality of Metro Toronto
Location:	Pickering, Ontario
Year opened/closed:	1975
Status:	Active
Capacity:	18 million tonnes
Stratigraphy:	Sand/gravel
Waste composition (%):	
- Domestic	80.3
- Industrial	18.2
- Construction	1.5
Tonnage in place:	17.7 million tonnes
Approved landfill area:	64 ha
Area currently filled:	62 ha
Depth of waste:	30 m
Final cover type:	Clean fill
% of cover in place:	75
Proposed end use of site:	Recreation
Contact name:	Lou Ciardullo
Telephone number.:	905-832-0682



Site Location (N.T.S.)

General Information

The landfill is located on a 123 ha parcel of land, situated in the Town of Pickering, west of Brock road, north of Concession 3. Prior to landfilling, extraction of granular materials took place at the site.

The watertable varies in depth from 15 to 20 m below grade in the vicinity of the landfill. Prior to landfilling operations, a portion of the site was dewatered to allow for the installation of the liner and leachate collection systems. The liner consists of a 0.1 m thick layer of bentonite with a sand blanket grade passing 75 percent on a 70 mesh sieve and a permeability of 10^{-3} m/sec.

The leachate system at the site consists of a perforated tile drain 0.2 m in diameter installed at each of the eight cells which drain the leachate to an on-site pumping station where it is directed to a local sanitary sewer for treatment.

The final grade of the landfill has been designed to have 4:1 (H:V) side slopes.

LFG Management

The LFG collection system at the site includes:

- a system of 21 horizontal collection trenches and 90 vertical wells within the solid waste mass
- 68 gas interceptor wells located outside the landfill perimeter
- HDPE header
- a central LFG flare and blower station, consisting of blowers and four flares

Construction of the LFG collection system is complete and incorporates lateral high density polyethylene (HDPE) piping 150 mm in diameter connected to a 500 mm HDPE header. Currently, the system operates on four landfill gas blowers drawing 12,750 m^3/hr (7,500 cfm) approximately at 41 percent methane (CH_4) content.

Monitoring of the LFG collection system takes place four to six times per year.

LFG Utilization:

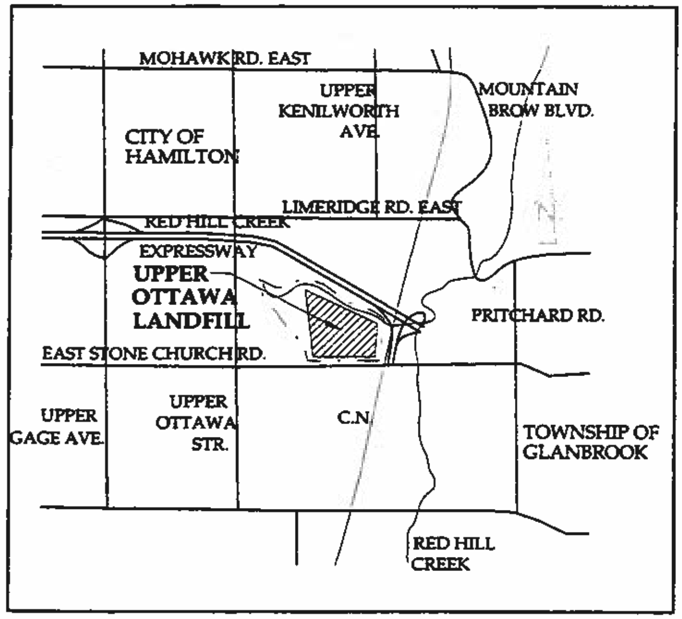
As of 1991 the LFG has been utilized as a energy source in a boiler and steam turbine-driven electrical generating plant, which is capable of producing up to 25 megawatts of electricity. If necessary, the LFG fuel supply may be augmented with natural gas to maximize power generation. The plant was constructed between 1989 and 1990 at a capital cost of $26 million dollars. The plant is owned and operated by Eastern Power Developers (EPD), which sells the electrical energy produced to Ontario Hydro. Metro receives royalty payments from the sale of the electricity.

Power generation is expected to be viable for 20 to 40 years.

5. Upper Ottawa Street Landfill Site

Regional Municipality of Hamilton-Wentworth

Location:	Hamilton, Ont.
Filling period:	1952/1980
Status:	Closed
Capacity:	1.35 million tonnes
Stratigraphy:	Fractured bedrock
Waste composition (%):	Various domestic and industrial, commercial, institutional (ICI)
Tonnage in place:	1.35 million
Approved landfill area:	16 ha
Area currently filled:	16 ha
Maximum depth of waste:	30 m (approx.)
Final cover type:	Clay
% final cover in place:	100
Contact name:	Val Terluk
Telephone number:	905-546-2158



Site Location (N.T.S.)

General Information:

The landfill sits on fractured bedrock in contact with groundwater. Initially, the landfill was a rural quarry dumpsite. The landfill received domestic and commercial waste, as well as solid and liquid industrial wastes.

A leachate collection system was installed around the west, south and east sides of the landfill to collect leachate. On the south slope of the landfill there is a French drain beneath the cover. The leachate then flows by gravity or it is pumped into a leachate collection manhole, which also collects surface runoff. The manhole empties into a sanitary sewer, which leads to Hamilton's sewage treatment plant.

Extensive residential development around the landfill began in the mid-1970s. There are over 1,500 households located within 750 metres of the landfill.

LFG Management:

In 1981, the Regional Municipality of Hamilton-Wentworth requested that the Ontario Ministry of Health establish a committee to carry out a study to determine possible hazards to human health due to the landfill. The study included analyses of leachate, surface waters, sediments, groundwater and landfill gas.

The studies did not conclusively identify that a gas control system was required from a health point of view. However, the committee concluded that the need to eliminate the odour problem alone provided sufficient reason for installing a landfill gas control system. An active landfill gas collection and flaring system was recommended.

A study of the feasibility of collecting and flaring the landfill gas was carried out between 1982 and 1983. The study involved an estimate of the LFG production rate and its composition. Flaring of the gas was evaluated as an option for destroying the trace contaminants.

In 1989 and 1990, a landfill gas control system was installed. The system consists of 27 vertical wells, subheaders, header, blower building, control building and an enclosed drum flare.

The vertical wells were installed within the limits of refuse to an average depth of 11 m. Each well was constructed using perforated and solid schedule 80 polyvinyl chloride (PVC) piping 100 mm in diameter. A sampling port and butterfly valve were installed at each well. The header and subheaders vary from 315 mm in diameter to 100 mm in diameter and are constructed of HDPE. All piping was installed to promote positive drainage of condensate.

A condensate trap chamber is located immediately outside the blower building to collect any condensate that forms in the main header. A centrifugal condensate separator located outside the blower building is used to remove large droplets of moisture from the gas.

The blower building houses two 650 cfm centrifugal blowers. The blowers are rated at 10 HP each and the gas is flared in a single 1200 cfm enclosed drum flare. A drain is installed in the discharge header at the flare. This drain discharges to a condensate trap chamber located at the flare, which in turn discharges to the main condensate trap chamber. Collected condensate is discharged to the leachate collection system. The flare is 8.84 m tall and 2.44 m in diameter.

The electrical control room is a separate building adjacent to the blower room and contains an electrical distribution panel, motor controls, and a programmable logic controller with automatic flare damper and temperature controls. The electrical equipment room also contains equipment to provide continuous monitoring of LFG methane and oxygen content. Additional monitoring equipment located in the electrical room monitors the concentration of potentially explosive methane gas in the plant ambient air.

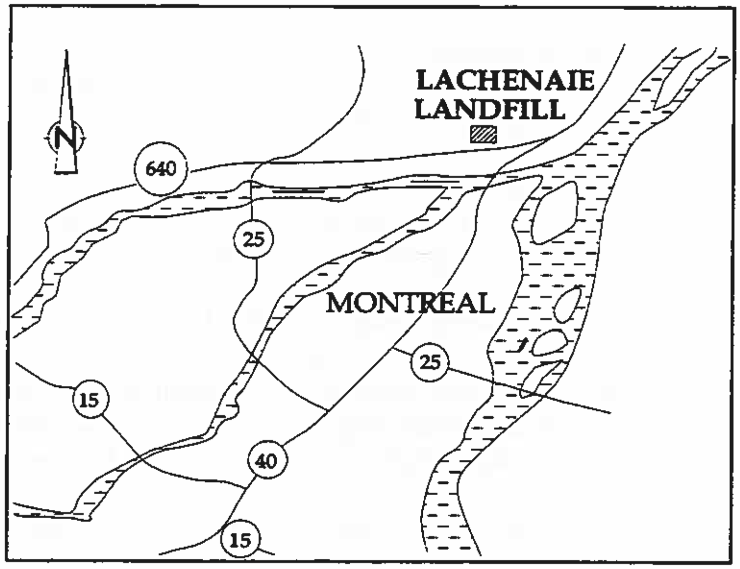
When the system was initially commissioned in 1989 it was operating on a continuous basis. As LFG quality and quantity diminished, system operation has been reduced to an intermittent basis, approximately every two days.

LFG Utilization:

The LFG produced is not utilized.

6. Lachenaie Landfill

Owner/operator:	Browning-Ferris Industries (BFI)
Location:	Lachenaie, P.Q.
Filling period:	1968/present
Status:	Active
Capacity:	6.5 million tonnes
Stratigraphy:	Native clay
Waste Composition (%):	
- Domestic	50
- Industrial, commercial, institutional (ICI)	50
Tonnage in place:	>2 million tonnes
Approved landfill area:	62 ha
Area currently filled:	61 ha
Average depth of waste:	17 m
Daily cover type:	Sand
Final cover type:	Clay
% final cover in place:	70
Proposed end use of site:	Park
Contact name:	Jean-Luc Viau
Telephone number:	514-474-2423



Site Location (N.T.S.)

General Information:

The landfill is located in a rural setting and the nearest residence is more than 1 km from the site.

The landfill is situated in a natural clay deposit. Prior to landfilling operations, each cell in the landfill was constructed by excavating about ten metres into the clay. The natural clay deposit forms the liner for the site. The landfill is capped with a 4 m thick layer of native clay.

The leachate collection system at the site consists of a granular drainage blanket, and high-density polyethylene (HDPE) pipes 200 mm in diameter. The condensate collected in the landfill gas system will be discharged to the leachate collection system. The leachate is treated at an on-site treatment plant and discharged to the Mille-Îles River south of the landfill. The final grade of the landfill has been designed to have 3:1 (H:V) side slopes and a 5 percent top slope.

LFG Management

The LFG collection system is currently under construction at the site. The primary reason for installing the system is for utilization, however, a few odour complaints have been received at the site.

Prior to designing the system, several gas probes were installed in the landfill. Gas samples were taken from these probes and analyzed to determine the quality of the gas. Gas extraction tests were not conducted, as the final cover was not in place. Browning-Ferris Industries (BFI) has developed its own gas generation model based on its experience in the United States. This model was applied to the landfill to size the collection system and determine the feasibility of utilization.

The LFG collection system will include over 80 vertical collection wells. The risers will be constructed of HDPE and contain a valve and pitot tube for flow measurement at the well head. The collection header will be constructed of polyvinyl chloride (PVC) piping 250 mm in diameter and buried below grade. The collection system will also include two 8,500 m^3/hr centrifugal blowers and a flare.

The leachate pumping station and the leachate cleanouts will be sealed to prevent the introduction of air into the landfill and gas collection system.

Monthly migration monitoring is conducted by BFI. Currently 13 migration monitoring probes are in place, 300 m apart.

LFG Utilization

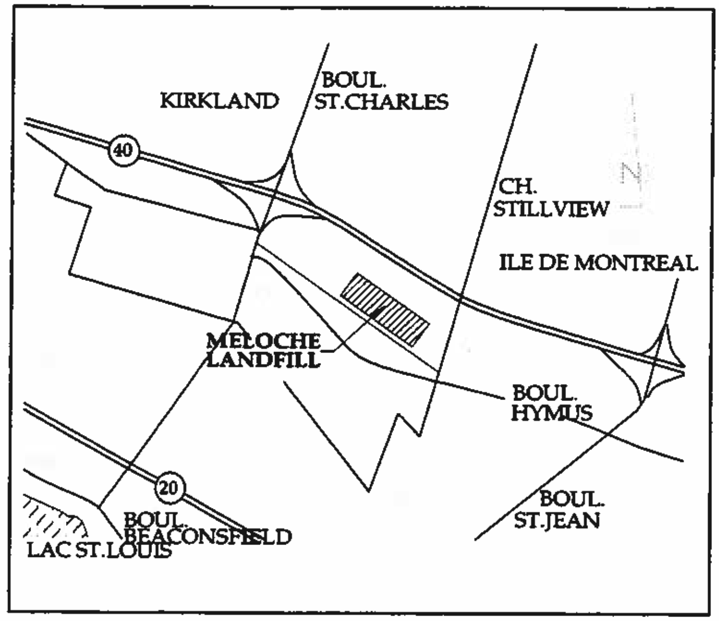
BFI began utilizing the LFG to produce electricity in January 1996. The gas is treated and then used as fuel for four reciprocating engines. Each engine drives a 1 MW generator to produce electricity. A 25-year agreement has been reached to sell the power generated to Hydro-Québec.

Treatment includes cycles of compression, chilling, filtering and reheating of the gas. Moisture and particulates are removed. An enclosed drum flare serves as back-up. The flare will be operated during regular maintenance and breakdowns. The flare has been designed to meet the stringent California air codes.

The total capital cost of the project is $7.5 million, and it includes the construction of the LFG collection system and the LFG utilization system.

7. Meloche Landfill Site

Owner/operator:	La Compagnie Meloche
Location:	Kirkland, PQ.
Filling period:	1980/1990
Status:	Closed
Capacity:	3.5 million tonnes
Stratigraphy:	Bedrock
Waste composition (%):	
- domestic	50
- industrial	30
- construction	20
Tonnage in place:	3.5 million tonnes
Approved landfill area:	9 ha
Area currently filled:	9 ha
Average depth of waste:	61 m
Maximum depth of waste:	67 m
Daily cover type:	Sand
Final cover type:	Native soil
% final cover in place:	100
Proposed end use of site:	Golf course
Contact name:	Michel Meloche
Telephone number:	514-695-3395



Site Location (N.T.S.)

General Information:

The landfill is located in the eastern half of a former quarry. The western half of the quarry is occupied by an asphalt plant. Residential subdivisions and an industrial warehouse are located within a 200 m radius of the site. An overhead power line borders the landfill on the south. A natural gas line is located adjacent to the site and provides fuel to the asphalt production operations.

The watertable is located approximately 18.3 m below ground level with respect to the surrounding ground. Dewatering of the former quarry pit was required prior to the installation of the leachate collection and liner system. The liner consists of a 75 mm thick asphalt layer which covers the bottom of the pit. The asphalt was coated with an asphalt sealant and topped with 300 mm of clay soil. A clay liner was constructed on the side slopes of the pit at a 1:1 (H:V) slope and a minimum thickness of 600 mm. French drains were installed at the base of the pit to collect leachate. The final grade of the top of the landfill has been constructed with 2 percent side slopes, and a relatively flat top. The surface runoff is collected and diverted to the leachate collection system. The collected water from the leachate and surface water collection systems is treated with chlorine and discharged to the municipal sewer.

LFG Management:

Several landfill gas collection systems were installed prior to 1990, but did not prove effective. The current landfill gas collection system was installed in 1990. This system was constructed on top of the final cover to provide easy access for maintenance and servicing. The landfill gas collection system consists of insulated polyethylene piping 200 to 250 mm in diameter, approximately 100 gas extraction wells, two blowers and two flares. The wells are arranged with spacings ranging between 30 m and 60 m. The wells were installed in 2.5 m vertical sections prior to refuse being placed. A 100 mm polyvinyl chloride (PVC) pipe was placed in the center of a steel casing, 750 mm in diameter, and the gap around the PVC pipe inside the steel casing was filled with crushed stone.

The gas collection system operates at 100% of its extraction capacity, drawing 7650 m^3/hr (4500 cfm) of landfill gas from the site. Condensate from the landfill gas is collected and pumped into the leachate collection system. Two 40 horsepower Chicago blowers have been installed, with one in operation and the other for backup. Two flares are in place. One is flaring 7650 m^3/hr (4500 cfm) gas at 50 million Btu and the other is for backup. The flare received approval by the Montreal Urban Community .

Capital cost of the construction of the landfill gas collection system was between $2.0 and $2.5 million.

Monitoring at the site includes gas analysis, daily gas migration monitoring and watertable monitoring. If gas migration is detected above a certain value, the City of Kirkland and Environment Quebec must be notified. Approximately 20 migration monitoring probe nests were installed at 30 m spacing along the site boundaries adjacent to the residential subdivisions. Annual air quality monitoring is conducted by the site owner and also by the Montreal Urban Community.

In 1994, gas migration was detected around the site. The cause of the migration was thought to be a result of capping the site. A perimeter trench was constructed to intercept migrating landfill gas. This solution proved to be effective.

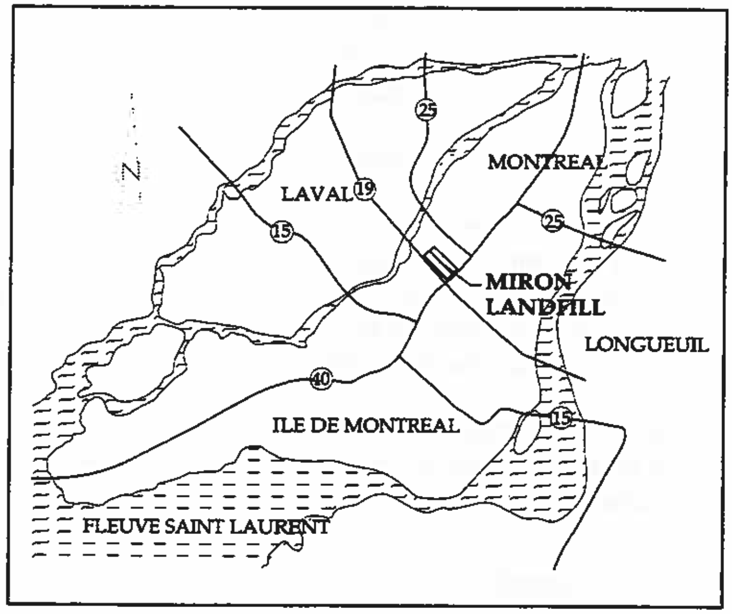
LFG Utilization:

In 1990 and 1991, Environmental Technology Incorporated (ETI) of Calgary conducted a study on landfill gas utilization at the site. The study suggested two options for utilization: converting the landfill gas into natural gas or generating electricity. Electricity generation was favored over natural gas production since the Montreal Metropolitan Gas Authority sets strict criteria on natural gas quality. The primary criterion for the selection was technical feasibility, although economic aspects were also taken into consideration. The commencement of this project was approved by the City of Kirkland in April 1995.

In April 1995, Highland Energy Incorporated took over from ETI to develop the project. The developer is responsible for the gas collection system and the power generation facilities. The power generation facilities consist of two Caterpillar gas-turbine generator sets. A large percentage of the landfill gas is expected to be consumed by power generation while the remainder will be flared. The LFG will be pretreated in order to reduce the condensate and the contaminants. The capital cost for the power generating plant is expected to be approximately $2.5 million. The developer predicts a minimum power generation rate of 2.4 MW. Hydro Quebec agreed to buy the electricity for $0.055 per kWhr, although if the electricity production rate drops below 2 MW a penalty will be applied. The developer has an agreement with Gas Metropolitan that if the power generation drops, natural gas will be supplied to compensate for the methane shortage.

8. Miron Landfill

Owner/operator:	City of Montreal
Location:	Montreal, P.Q.
Filling period:	1968/1998+
Status:	Active
Capacity:	33 million tonnes
Stratigraphy:	Limestone
Waste composition (%):	
- domestic	45
- industrial	1
- construction	45
- other	9
Tonnage in place:	31 million tonnes
Approved landfill area:	75 ha
Area currently filled:	75 ha
Average depth of waste:	70 m
Daily cover type:	Native material
Final cover type:	0.3 m native material
% final cover in place:	0
Contact name:	Sylvain Leroux
Telephone number:	514-872-7683



Site Location (N.T.S.)

General Information:

The Centre de tri et d'élimination des déchets (CTED) — Miron Landfill is located within the City of Montreal. The city has grown around the landfill, and presently residential and commercial developments surround the site. CTED was originally a quarry which began operations around 1950. Landfill operation began in 1960.

There is a leachate collection system at the site. The collected leachate is treated with hydrogen peroxide prior to discharge to the sanitary sewer.

LFG Management:

The initial phase of the LFG system was installed in 1980. The purpose of this system was to control odours, and also to control subsurface migration of LFG. The initial system had a capacity of 5,100 m^3/hr (3,000 scfm) and included 40 extraction wells. The system has been expanded and upgraded over the years, and the current total capacity is approximately 40,800 m^3/hr (24,000 scfm).

The current system includes the collection field with 280 extraction wells, four blowers, five compressors and eight flares. The collection piping within the landfill is constructed of high-density polyethylene (HDPE). The collection header is PVC and runs along the top of the old quarry on native ground. Each blower has a capacity of 3,400 m^3/hr (2,000 scfm) with an inlet vacuum of 35 in WC and an outlet pressure of 5 in WC. The compressors are rated at 5,450 m^3/hr (3,200 scfm) and have an inlet vacuum on 150 in WC and an outlet pressure of 5 in WC.

Where possible, the condensate that forms in the collection piping is returned to the landfill through the extraction wells. Condensate that is collected prior to flaring is pumped to the leachate collection system, where it is treated and discharged. In the past, some operation problems have been encountered due to the accumulation of condensate in the collection piping between wells, resulting from the settlement of the landfill. This problem was solved by increasing the slope on the collection piping to ensure drainage of condensate.

Currently, the system is operating at 30,600 m^3/hr (18,000 scfm) and the peak collection rate is estimated at 37,400 m^3/hr (22,000 scfm). Perimeter probe monitoring results, volume of gas flared, and quality of gas collected are reported monthly.

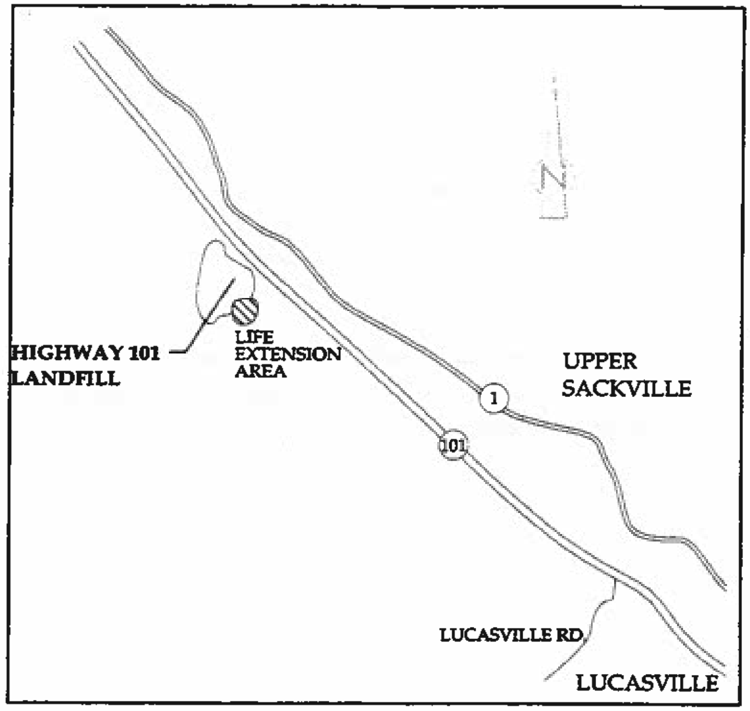
LFG Utilization:

An agreement between CTED and the developer, Gazmont, has been reached for the construction of LFG utilization facilities. Construction began in April 1995 and the facility is expected to be in operation by the spring of 1996. CTED will supply the LFG to the developer who will be responsible for producing the electricity.

The utilization facility will use steam turbines to produce an estimated 25 MW of electricity. The electricity will be sold to Hydro-Québec. The capital cost of the facility is $35 million, and the annual costs are estimated at $750,000.

9. Highway 101 Landfill Site

Owner/operator:	Province of Nova Scotia/Halifax Metropolitan Authority
Location:	Upper Sackville, N.S.
Filling period:	1977/1996
Status:	Active
Capacity:	4.0 million tonnes
Stratigraphy:	Shallow clay overburden underlain by rock
Waste composition (%):	
- domestic	48
- industrial	52
- construction	0
Tonnage in place:	3.7 million
Approved landfill area:	120 ha
Area currently filled:	32 ha
Average depth of waste:	12 m
Maximum depth of waste:	25 m
Daily cover type:	Clay soil
Final cover type:	Clay soil
% final cover in place:	85
Proposed end use of site:	Green space
Contact name:	Rene MacEachem
Telephone number:	902-421-7882



Site Location (N.T.S.)

General Information:

The landfill is located in a lightly populated rural area. Single family dwellings and a small quarry are located within 500 m of the site. The Sackville River is located approximately 100 m south of the site. An electrical power line crosses the landfill in a north-south direction.

Due to the surrounding site stratigraphy and the Sackville River, the watertable is located near ground surface over much of the site. As a result, the landfill was expanded and now includes the life extension area. The life extension area is the location of the current landfilling operations.

The landfill liner system consists of a layer of clay a minimum of 1.0—m thick on the base and side walls of the excavation. Prior to landfilling, a leachate collection system was installed above the liner, consisting of perforated polyvinyl chloride (PVC) pipe 200 mm in diameter bedded in a gravel trench and underlain by a geotextile liner. The collected leachate is processed by bio-treatment, activated sludge treatment and wetland treatment prior to discharge into the Sackville River. The cover's final grade is constructed with 2.5:1 (H:V) side slopes and a relatively flat top.

LFG Management:

Landfill gas management at the site has been divided into two phases. Phase I of the gas collection system was installed in 1994 at a total capital cost of $1.4 million. In the 1995 budget, $750,000 has been allocated for further expansion of the system.

The LFG collection system consists of 22 gas extraction wells; 2,150 meters of 200-mm, 150-mm and 100-mm gas collection headers; a blower building; blowers and a gas-burning flare. The wells are 15 to 20 metres deep, 750 mm in diameter, with a 100 mm perforated PVC pipe in the center, gravel packed with a 300-mm bentonite seal 2.0 metres from the surface. Moisture content of the collected gas is reduced by a condensate trap. Condensate is collected and pumped into the leachate collection system.

The landfill gas blower building is 7 m x 7 meters in size and is of concrete block construction. The landfill gas enters the building through two 200 mm diameter high-density polyethylene (HDPE) pipes. The gas is drawn from the landfill using two blowers each with a capacity of 680 m^3/hr (400 cfm). The gas flows through a flame trap assembly to an enclosed gas burning flare equipped with a propane fueled pilot ignition system. The flare received approval from the Canadian Gas Association. At present, the LFG collection system operates at 36 percent of its extraction capacity.

LFG monitoring at the site includes gas flow analysis and migration monitoring. Migration monitoring readings are submitted to the Nova Scotia Ministry of the Environment for review. A passive gas interceptor system has been installed along site boundaries adjacent to the residential areas. The interceptor system vents LFG to the atmosphere. Air quality monitoring of the vent emission is to be carried out by Nova Scotia Ministry of the Environment at a later date.

The LFG collection system will remain in operation as long as there is sufficient quantity of gas being generated to operate the flare. The operational life of the LFG collection system is estimated to be a minimum of 20 years.

LFG Utilization:

Landfill gas utilization at the site was considered in the past. The primary criteria for the selection was based on economics and none of the options considered were economically feasible. Therefore, the LFG collected is not utilized.

LFG Utilization Case Studies

E.H. Hanson Engineering Group Ltd., British Columbia

- Port Mann Landfill, B.C.
- Coquitlam Landfill, B.C.
- Jackman Landfill, B.C.
- Premier Street Landfill, B.C.
- Richmond Landfill, B.C.
- Tretheway Landfill, B.C.
- Valley Road Landfill, B.C.
- Heritage Subdivision, B.C.

Project Profile #1

Name:	PORT MANN LANDFILL
Location:	Surrey, B.C.
Collection system status:	Operational
Collection system start-up date:	February 1993
Utilization system status:	Operational
Start-up date:	February 1993
Landfill data	
Landfill owner:	City of Surrey
Landfill status:	Operational
Year landfill opened:	1968
Projected closure date:	1996
Total landfill acreage:	25 hectares
Area devoted to methane recovery:	5 hectares
Current mass of refuse on site:	3.0 million tonnes
Projected mass of refuse on site:	4.0 million tonnes
Average depth of fill:	35 m
Site setting:	Residential
Landfill gas collection system	
Volume of gas from system (scfd):	576,000
Projected gas volumes (scfd):	792,000 (1995) t,152,000 (1996) 1,728,000 (1997)
Collection system owner:	City of Surrey
Collection system designer:	E.H. Hanson Engineering Group Ltd.
Collection system operator:	E.H. Hanson Engineering Group Ltd. for Norseman Engineering Ltd.
Collection system cost:	$400,000
Reason for installation:	Control gas migration and emissions and sale of gas
Amount of gas flared:	0%
Amount of gas utilized:	100%
Number of wells:	80
Depth of wells:	15 m
Well pipe material:	polyvinyl chloride (PVC)
Lateral/header pipe material:	PVC
Type of blower/compressor:	Hybon sliding vane (two units in place)
Blower/compressor capacity:	230 scfm per unit @ 40 psig each
Number of flares:	0

Landfill gas utilization system

Energy value of gas:	580 BTU/scf
Gas treatment:	Dehydration using ethylene glycol
Type of use:	Direct firing of pure landfill gas and direct firing of landfill gas/natural gas mix. Some gas used in IC engine at compressor station to produce electricity to run compressors.
Distance from landfill to utilization location:	6 km
Transmission pipeline size:	150 mm
Transmission pipeline material:	High density polyethylene (HDPE)
Transmission pipeline operating pressure:	40 psig
Utilization system cost:	$500,000
Utilization system capacity (scfd):	576,000 (current) 797,000 (1996) 1,152,000 (1997) 1,728,000 (1998)
Type of blower/compressor:	Hybon sliding vane (two units in place)
Blower/compressor capacity:	230 scfm per unit @ 40 psig
Regulatory approvals:	Road R.O.W. for pipeline — City of Surrey Railway crossing — CN Highway crossing — Ministry of Highways Plant piping and control system — B.C. Gas Safety Branch
Revenue information:	Domtar pays Norseman Engineering Ltd. for gas, based on energy consumed.
Royalty information:	Surrey receives royalty of 8 percent of gross sales after five years.
Type of metering equipment:	Johnson Yokogawa Votex Shedding Meter
Utilization system developer:	Norseman Engineering Ltd.
Utilization system design:	E.N. Hanson Engineering Group Ltd.
Utilization system operator:	E.H. Hanson Engineering Group Ltd.
Gas customer:	Domtar Gypsum

Project Profile #2

Name:	COQUITLAM LANDFILL
Location:	Coquitlam, B.C.
Collection system status:	Operational
Collection system start-up date:	May 1994
Utilization system status:	Operational
Start-up date:	May 1994
Landfill data	
Landfill owner:	Greater Vancouver Regional District
Landfill status:	Closed
Year landfill opened:	N/A
Projected closure date:	1983
Total landfill acreage:	40 acres
Area devoted to methane recovery:	30 acres
Current mass of refuse on site:	2.5 million tonnes
Projected mass of refuse on site:	2.5 million tonnes
Average depth of fill:	12 m
Site setting:	Industrial location, but residential close enough to get odour.
Landfill gas collection system	
Volume of gas from system (scfd):	864,000
Projected gas volumes (scfd):	864,000 (1996) 750,000 (1997) 600,000 (1998)
Collection system owner:	Greater Vancouver Regional District
Collection system designer:	E.H. Hanson Engineering Group Ltd.
Collection system operator:	E.H. Hanson Engineering Group Ltd.
Collection system cost:	$400,000
Reason for installation:	Control gas emissions and sell gas.
Amount of gas flared:	0%
Amount of gas utilized:	100%
Number of wells:	125
Depth of wells:	35 feet
Well pipe material:	polyvinyl chloride (PVC)
Lateral/header pipe material:	PVC
Type of blower/compressor:	Gardner Denver Cyclo blower
Number of flares:	0

Landfill gas utilization system

Energy value of gas:	400 to 550 BTU/scf
Gas treatment:	None
Type of use:	Direct firing in boilers at Newstech Recycling Ltd.
Distance from landfill to utilization location:	600 m
Transmission pipeline size:	150 mm
Transmission pipeline material:	High Density Polyethylene (HDPE)
Transmission pipeline operating pressure:	10 psig
Utilization system cost:	$300,000
Utilization system capacity (scfd):	864,000
Type of blower/compressor:	Gardner Denver Cyclo blower
Regulatory approvals:	Revision to Newstech's Air Emissions Permit — GVRD Road R.O.W. allowance — City of Coquitlam
Revenue information:	Newstech pays Coquitlam Landfill Gas Company Ltd. for gas based on energy consumed.
Royalty information:	GVRD receives royalty of 8 percent of gross sales after four years of operation.
Type of metering equipment:	Johnson Yokogawa Vortex Shedding Meters
Utilization system developer:	Coquitlam Landfill Gas Co. Ltd.
Utilization system design:	E.H. Hanson Engineering Group Ltd.
Utilization system operator:	E.H. Hanson Engineering Group Ltd.
Gas customer:	Newstech Recycling (newsprint recycling)

Project Profile #3

Name:	JACKMAN LANDFILL
Location:	Langley, B.C.
Collection system status:	Operational
Collection system start-up date:	April 1993
Utilization system status:	Operational
Start-up date:	January 1995
Landfill data	
Landfill owner:	Township of Langley
Landfill status:	Closed
Year landfill opened:	N/A
Projected closure date:	1989
Total landfill acreage:	14 hectares
Area devoted to methane recovery:	14 hectares
Current mass of refuse on site:	500,000 tonnes
Projected mass of refuse on site:	N/A
Average depth of fill:	12 m
Site setting:	Semi-rural setting
Landfill gas collection system	
Volume of gas from system (scfd):	360,000
Projected gas volumes (scfd):	360,000 (1996)
Collection system owner:	Township of Langley
Collection system designer:	E.H. Hanson Engineering Group Ltd.
Collection system operator:	E.H. Hanson Engineering Group Ltd.
Collection system cost:	$300,000
Reason for installation:	Control gas emissions and migration
Amount of gas flared:	0%
Amount of gas utilized:	100%
Number of wells:	48
Depth of wells:	35 feet
Well pipe material:	polyvinyl chloride (PVC)
Lateral/header pipe material:	PVC
Type of blower/compressor:	Rotron Regenerative Blowers
Number of flares:	1
Landfill gas utilization system	
Energy value of gas:	580 BTU/scf
Gas treatment:	None
Type of use:	Direct firing in boiler. Currently utilizing combustion gases for CO_2 supplement for plant growth.
Distance from landfill to utilization location:	1450 m
Transmission pipeline size:	6
Transmission pipeline material:	High Density Polyethylene (HDPE)

Transmission pipeline operating pressure:	10 psig
Utilization system cost:	$200,000
Utilization system capacity (scfd):	360,000
Type of blower/compressor:	Lamson Turbotron
Regulatory approvals:	R.O.W. approval — Township of Langley Plant Piping — B.C. Gas Safety Branch
Revenue information:	Topgro Greenhouses pay Norseman Engineering Ltd. for gas based on energy consumed.
Royalty information:	Township of Langley receives 8 percent royalty on gross sales after four years of operation.
Type of metering equipment:	Johnson Yokogawa Vortex Shedding Meter
Utilization system developer:	Norseman Engineering Ltd.
Utilization system design:	E.H. Hanson Engineering Group Ltd.
Utilization system operator:	E.H. Hanson Engineering Group Ltd.
Gas customer:	Topgro Greenhouses Ltd.
Gas migration control facility	
Type of system:	Air Injection
System configuration:	Ten wells, 35 feet deep. Air supplied with a Gast Regenerative blower. Approximately 120 scfm. Runs 10 hours per day.
Degree of success:	Methane reading in monitoring wells dropped from 30% to 30-40% to below detectable limits.
Type of soil:	Loose, sandy gravel

Project Profile #4

Name:	PREMIER STREET LANDFILL
Location:	North Vancouver, B.C.
Collection system status:	Operational
Collection system start-up date:	1983
Utilization system status:	In planning
Start-up date:	November 1995
Landfill data	
Landfill owner:	District of North Vancouver
Landfill status:	Closed
Year landfill opened:	N/A
Projected closure date:	1989
Total landfill acreage:	N/A
Area devoted to methane recovery:	N/A
Current mass of refuse on site:	N/A
Projected mass of refuse on site:	N/A
Average depth of fill:	30 m
Site setting:	Residential
Landfill gas collection system	
Volume of gas from system (scfd):	720,000
Projected gas volumes (scfd):	N/A
Collection system owner:	District of North Vancouver
Collection system designer:	E.H. Hanson Engineering Group Ltd.
Collection system operator:	E.H. Hanson Engineering Group Ltd.
Collection system cost:	$500,000
Reason for installation:	Control odourous gas emissions
Amount of gas flared:	98%
Amount of gas utilized:	2%
Number of wells:	80
Depth of wells:	75 feet
Well pipe material:	polyvinyl chloride (PVC)
Lateral/header pipe material:	PVC
Type of blower/compressor:	Rotron Regenerative Blower
Number of flares:	One
Landfill gas utilization system	
Energy value of gas:	350 to 555 BTU/scf
Gas treatment:	Proposed Glycol Dehydration System
Type of use:	Proposed direct firing in boilers
Distance from landfill to utilization location:	5 km
Transmission pipeline size:	8
Transmission pipeline material:	High Density Polyethylene (HDPE)

Transmission pipeline operating pressure:	40 psig
Utilization system cost:	$800,000
Utilization system capacity (scfd):	1,152,000
Type of blower/compressor:	N/A
Regulatory approvals:	Highway R.O.W. — Department of Highways
Revenue information:	N/A
Royalty information:	N/A
Type of metering equipment:	N/A
Utilization system developer:	E.H. Hanson Engineering Group Ltd.
Utilization system design:	E.H. Hanson Engineering Group Ltd.
Utilization system operator:	N/A
Gas customer:	CanadianOxy Chemicals Ltd.
Other comments:	A small field house with showers and change rooms is currently being heated and supplied with hot water using landfill gas as the fuel. This system, which has been running since 1983, was rebuilt in 1990 and continues to run.

Project Profile #5

Name:	RICHMOND LANDFILL
Location:	Richmond, B.C.
Collection system status:	Operational
Collection system start-up date:	1986
Utilization system status:	Operational
Start-up date:	1986 (rebuilt 1994/95)
Landfill data	
Landfill owner:	Fraser River Harbour Commission
Landfill status:	Closed
Year landfill opened:	N/A
Projected closure date:	1986
Total landfill acreage:	20 hectares
Area devoted to methane recovery:	20 hectares
Current mass of refuse on site:	1.1 million tonnes
Projected mass of refuse on site:	N/A
Average depth of fill:	8 m
Site setting:	Rural, Industrial
Landfill gas collection system	
Volume of gas from system (scfd):	437,000
Projected gas volumes (scfd):	432,000(1996) 360,000 (1997) 288,000 (1998)
Collection system owner:	Fraser River Harbour Commission
Collection system designer:	E.H. Hanson Engineering Group Ltd.
Collection system operator:	E.H. Hanson Engineering Group Ltd.
Collection system cost:	$250,000
Reason for installation:	Control of gas emissions and sale of the gas.
Amount of gas flared:	0%
Amount of gas utilized:	t00%
Number of wells:	70
Depth of wells:	30 feet
Well pipe material:	polyvinyl chloride (PVC)
Lateral/header pipe material:	PVC
Type of blower/compressor:	Originally Gardner Denver Cyclo blower. Now Lamson Centrifugal blower
Number of flares:	None
Landfill gas utilization system	
Energy value of gas:	450 to 500 BTU/scf
Gas treatment:	None
Type of use:	Direct firing in cement kiln
Distance from landfill to utilization location:	1.6 km
Transmission pipeline size:	6

Transmission pipeline material:	High Density Polyethylene (HDPE)
Transmission pipeline operating pressure:	5 psig
Utilization system cost:	$150,000
Utilization system capacity (scfd):	432,000
Type of blower/compressor:	see above
Regulatory approvals:	R.O.W Dyke Road — Provincial Dyke Commission Plant Piping — B.C. Gas Safety Branch
Revenue information:	N/A
Royalty information:	N/A
Type of flow meter:	Originally Dietrich Standard Annubar — Updated to Johnson Vortex Shedding Meter
Utilization system developer:	E.H. Hanson Engineering Group Ltd.
Utilization system design:	E.H. Hanson Engineering Group Ltd.
Utilization system operator:	E.H. Hanson Engineering Group Ltd.
Gas customer:	Lafarge Canada Ltd.

Project Profile #6

Name:	TRETHEWAY LANDFILL
Location:	Matsqui, B.C.
Collection system status:	Operational
Collection system start-up date:	1983
Utilization system status:	Operational
Start-up date:	1993
Landfill data	
Landfill owner:	District of Matsqui
Landfill status:	Closed
Year landfill opened:	N/A
Projected closure date:	N/A
Total landfill acreage:	N/A
Area devoted to methane recovery:	N/A
Current mass of refuse on site:	500,000 tonnes
Projected mass of refuse on site:	N/A
Average depth of fill:	N/A
Site setting:	Residential
Landfill gas collection system	
Volume of gas from system (scfd):	N/A
Projected gas volumes (scfd):	N/A
Collection system owner:	District of Matsqui
Collection system designer:	E.H. Hanson Engineering Group Ltd.
Collection system operator:	District of Matsqui
Collection system cost:	N/A
Reason for installation:	N/A
Amount of gas flared:	N/A
Amount of gas utilized:	N/A
Number of wells:	N/A
Depth of wells:	N/A
Well pipe material:	polyvinyl chloride (PVC)
Lateral/header pipe material:	PVC
Type of blower/compressor:	Paxton
Number of flares:	One
Landfill gas utilization system	
Energy value of gas:	N/A
Gas treatment:	None
Type of use:	Direct firing in multiple furnaces
Distance from landfill to utilization location:	0 km
Transmission pipeline size:	150 mm
Transmission pipeline material:	PVC

Transmission pipeline operating pressure:	80 WC
Utilization system cost:	N/A
Utilization system capacity (scfd):	N/A
Type of blower/compressor:	Rotron Regenerative Blower
Regulatory approvals:	None
Revenue information:	None
Royalty information:	None
Type of flow metering equipment:	None
Utilization system developer:	District of Matsqui
Utilization system design:	E.H. Hanson Engineering Group Ltd.
Utilization system operator:	District of Matsqui
Gas customer:	District of Matsqui

Project Profile #7

Name:	VALLEY ROAD LANDFILL
Location:	Matsqui, B.C.
Collection system status:	Operational
Collection system start-up date:	1983
Utilization system status:	Operational
Start-up date:	1993
Landfill data	
Landfill owner:	District of Matsqui
Landfill status:	Closed
Year landfill opened:	1984
Projected closure date:	1990
Total landfill acreage:	16 acres
Area devoted to methane recovery:	10 acres
Current mass of refuse on site:	500,000 tonnes
Projected mass of refuse on site:	N/A
Average depth of fill:	1 0 m
Site setting:	Residential
Landfill gas collection system	
Volume of gas from system (scfd):	302,400
Projected gas volumes (scfd):	N/A
Collection system owner:	District of Matsqui
Collection system designer:	E.H. Hanson Engineering Group Ltd.
Collection system operator:	District of Matsqui
Collection system cost:	$180,000
Reason for installation:	Emission control
Amount of gas flared:	50%
Amount of gas utilized:	50%
Number of wells:	30
Depth of wells:	25 feet
Well pipe material:	polyvinyl chloride (PVC)
Lateral/header pipe material:	PVC
Type of blower/compressor:	Rotron Regenerative Blower
Number of flares:	One
Landfill gas utilization system	
Energy value of gas:	N/A
Gas treatment:	None
Type of use:	Direct firing in radiant heaters for heating of recycling building
Distance from landfill to utilization location:	500 m
Transmission pipeline size:	100 mm
Transmission pipeline material:	PVC

Transmission pipeline operating pressure:	30 WC
Utilization system cost:	$35,000
Utilization system capacity (scfd):	N/A
Type of blower/compressor:	Rotron Regenerative Blower
Regulatory approvals:	Interior
Revenue information:	None
Royalty information:	None
Type of flow metering equipment:	None
Utilization system developer:	District of Matsqui
Utilization system design:	E.H. Hanson Engineering Group Ltd.
Utilization system operator:	District of Matsqui
Gas customer:	District of Matsqui

Project Profile #8

Name:	HERITAGE SUBDIVISION
Location:	Prince George, B.C.
Collection system status:	None
Collection system start-up date:	N/A
Utilization system status:	None
Migration start-up date:	1992
Landfill data	
Landfill owner:	City of Prince George
Landfill status:	Closed
Year landfill opened:	N/A
Projected closure date:	1989
Total landfill acreage:	15 acres
Area devoted to methane recovery:	None
Current mass of refuse on site:	500,000 tonnes
Projected mass of refuse on site:	N/A
Average depth of fill:	20 m
Site setting:	Residential

Landfill gas collection system

No gas collection system installed.

Landfill gas utilization system

No gas utilization system installed.

Gas migration control facility

Type of system:	Air Injection
System configuration:	Thirty-five wells, 70 feet deep. Air supplied with a centrifugal blower. Approximately 250 scfm at 10 WC.
System designer:	E. H. Hanson Engineering Group Limited
Degree of success:	Methane reading in monitoring wells dropped from 30-40% to below detectable limits.
Type of soil:	Loose, sandy gravel
Comments:	A passive barrier system consisting of a rock-filled trench with a perforated pipe and vents had been installed previously. This system was ineffective in curtailing landfill gas migration. A number of fires occurred in some homes next to the landfill. Once the air barrier system was installed, the problem was solved.

Appendix B — Regulatory Agencies and Contacts

Province	Agency	Department	Contact and telephone
Alberta	Department of Environmental Protection	Action on Waste Division	Mr. Laury North Branch Head 403-427-5824
British Columbia	Department of Environment	Lands and Parks	Mr. Rob Dalrymple Waste Residuals Manager 604-387-1161
Manitoba	Department of Environment	Winnipeg Region	Mr. Cliff Lee Supervisor of Environment Act 204-945-0788
New Brunswick	Department of Environment	Solid Waste and Recycling Section	Mr. Barry Haines Manager 506-457-4848
Newfoundland	Department of Environment and Lands	Environmental Investigations Division	Mr. Carl Strong Director 709-729-2556
Northwest Territories	Environmental Protection Division	Renewable Resources	Mr. Neil Thompson Assistant Director 403-873-7752
Nova Scotia	Department of Environment	Municipal Waste Resource and Recovery	Mr. Dan Hiltz Acting Manager 902-424-2385
Ontario	Ministry of Environment and Energy	Environmental Engineering Services	Mr. Eric Loi Senior Engineer 416-323-5146
Prince Edward Island	Department of Environmental Resources		Mr. Kevin Curley Environmental Officer 902-368-5000
Québec	Ministère de l'environnement et de la faune	Direction des politiques du secteur municipal	Mr. René Binette 418-644-2832
Saskatchewan	Saskatchewan Environment and Resource Management	Standards and Approvals Unit	Mr. Darcy Paul 306-787-0469
Yukon	Community and Transportation Services	Engineering and Development Branch	Mr. Bob Gates Manager of Community Operations 403-667-3598

Appendix C — Conversions and Miscellaneous Data

Unit	Conversion
1m^3	35.31 ft^3
1m^3	1.308 yd^3
1m^3/hr	0.59 cubic feet per minute (cfm)
1 psi	27.73 inches water column (in W. C.)
1 psi	6.9 kilopascal
1 kilojoule	0.9478 Btu (British thermal unit)
1 kilowatt	0.9478 Btu/s (British thermal unit per second)
1 kilowatt	1.341 horsepower
1 Btu	1.056 kilojoules
Methane 100% (LHV)	33.8MJ/m^3 (909 BTU/ft^3)
Landfill Gas (50% CH_4 v/v) (LHV)	16.8 MJ/m^3 (450 BTU/ft^3)
1 hectare	10,000 m^2
1 acre	0.4047 hectare
1 m^2	1.196 yd^2
1 m^2	10.764 ft^2
1 m	3.281 ft
1 m	1.094 yard
1 km	0.6214 mile
1 L	0.2642 US gal
1 L	0.2200 I gal
1 kg	2.205 lb.
1 tonne	1,000 kg
1 ton (long, 2240 lb.)	1016.047 kg
1 ton (short, 2000 lb.)	907.185 kg
1 ton CH_4	1,475.8 m^3 CH_4
1 atmosphere	760 mm Hg
1 atmosphere	29.921 inches Hg
1 atmosphere	407.189 inches H_2O
1 atmosphere	14.696 psi
1 atmosphere	101.3 kilopascal

Appendix D — List of Abbreviations

Abbreviation	Reference
BTEX	Benzene, Toluene, Ethylbenzene, Xylenes
BTU	British Thermal Unit
C & D	Construction and Demolition
C of A	Certificate of Approval (Air)
FDM	Fugitive Dust Model
HDPE	High Density Polyethylene
HHV	High heating value
ICI	Industrial, Commercial and Institutional
ID	Internal Diameter
Igpm	Imperial Gallons Per Minute
in W.C.	Inches of water column
k	methane generation rate (1/year)
K	Hydraulic conductivity
kPa	Kilo Pascals
Lo	methane generation potential (m^3 of CH_4/tonne of refuse)
LEL	Lower explosive limit
LFG	Landfill Gas
LHV	Lower heating value
m	metre
mg/m^3	milligrams per cubic metre
MJ	mega joule
MSW	Municipal solid waste
MW	megawatt
NTS	Not to Scale
OD	Outside Diameter (for pipes and tubing)
PE	Polyethylene
POI	Point of Impingement
psi	Pounds per square inch
PVC	Polyvinyl chloride
QA/QC	Quality Assurance/Quality Control
SCBA	Self contained breathing apparatus
SDR	Standard Dimension Ratio (for pipes and tubing)
STEL	Short-term exposure limit
TLV	Threshold limit value
TWA	Time weighted average
UEL	Upper explosive limit
USEPA	United States Environmental Protection Agency
VC	Vinyl Chloride
VOC	Volatile Organic Compound
$\mu g/m^3$	micrograms per cubic metre

Glossary of Terms

The following is a glossary of terms that are used throughout the document. This glossary has been developed specifically for this project and as such, may not be consistent with other uses of this terminology on other projects or situations.

Absorption — the ability to selectively transfer one or more components of a gas mixture into a solvent liquid.

Adsorption — the process whereby molecular attraction holds solutes to the surface of solids such as rock or soil particles.

Advection — a physical process whereby LFG migrates through soil as a result of pressure gradients.

Air emissions — for stationary sources, the release or discharge of a pollutant from a facility or operation into the ambient air either by means of a stack or as a fugitive dust, mist or vapour.

Ambient air — that portion of the atmosphere external to buildings to which the general public has access.

Anaerobic — the biological state of living and growing in the absence of oxygen; absence of free oxygen.

Anthropogenic — man-made origin.

Avoided cost — when a electrical utility purchases power from a non-utility generator, it avoids the cost of providing and operating the facilities to generate this power itself. This avoided cost can be calculated and applied to purchase rates for non-utility generators.

Background level — amounts of pollutants present in the environment prior to establishment, start-up and operation of a facility or activity.

Barhole probe — a steel rod that is hammered into the soil to an approximate depth of one metre to allow sampling or measurement of soil vapours in the resulting void.

British thermal unit (Btu) — the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit. (1 Btu = 1.056 kilojoules.)

Calorie — The energy required to heat one gram of water at standard atmospheric pressure through one degree celsius.

Calorific value — the amount of heat obtained by the complete combustion of a unit mass of fuel. Usually expressed in calories or British thermal units (Btu).

Capital costs — expenditures incurred for the purchase or construction of materials and facilities that will have a useful life.

Capture zone — volume of refuse where effective collection of LFG occurs.

Carbon dioxide — one of the principle gases which comprises LFG. A greenhouse gas.

Carcinogenic — capable of causing the cells of an organism to react in such a way as to produce cancer.

Cell — with respect to a landfill site, means a deposit of waste that has been sealed by cover material so that no waste deposited in the cell is exposed to the atmosphere.

Clay — soil size particles smaller than 0.005 mm.

Co-generation — the production of both useful heat (usually steam) and electricity from a single fuel.

Combustible — able to undergo a chemical reaction resulting in release of both heat and light. Typically in combination with oxygen.

Commercial waste — non-hazardous solid waste that is generated from commercial establishments.

Concentration — the relative fraction of one substance in another, normally expressed in mass percent, mass/volume, volume percent (%v/v) or as a percentage of the lower explosive limit (%LEL).

Construction and demolition waste (C&D) — waste resulting from construction, remodeling, repair and demolition of structures, road buildings and land clearing. Such wastes include bricks, concrete and other masonry materials, soil, rock, lumber, road spills, paving material, tree and brush stumps.

Contaminant — means any solid, liquid, gas, odour, heat, sound, vibration, radiation or combination thereof, resulting directly or indirectly from human activities and that may cause an adverse effect.

Damper — a manually or automatically controlled device to regulate draft or the rate of flow of air or other gases.

Dew point — the temperature at which a gas is saturated with water vapour at a given pressure.

Diffusion — migration of molecules or ions in air or water as a result of their own random movements from a region of higher concentration to a region of lower concentration. Diffusion can occur in the absence of any bulk air or water movement.

Dilution — increasing the proportion of solvent to solute in solution, and thereby decreasing the concentration of solute per unit volume.

Dispersion modelling — the calculation of ambient air concentrations of a subject pollutant by means of computer algorithms.

Domestic waste — non-hazardous solid waste generated from households. Also referred to as residential waste or municipal solid waste (MSW). It does not include liquid waste or hazardous waste.

Emission rate — the amount of pollutant emitted per unit of time.

Emissions — pollutants in the form of gases or fine particles released into the atmosphere, usually from a stack.

Evapotranspiration — the combined loss of water from soil and plant surfaces by direct evaporation and by transpiration.

Explosion — extremely rapid combustion of a compound resulting in an increase in volume and creation of pressures when enclosed.

Explosive limit — The range of concentrations in air within which a compound is combustible. Methane is combustible when mixed with air in the range of 5 to 15 percent by volume. Five percent by volume is referred to as the lower explosive limit (LEL) of methane in air. Fifteen percent by volume is referred to as the upper explosive limit (UEL) of methane in air.

Field capacity — quantity of water held by soil or compacted solid waste where application of additional water will cause it to drain to underlying material.

Fissure — a narrow opening, cleft, crevice or furrow.

Flammable — able to ignite. (See *Combustible.*)

Footprint — the area of the site within the limit of solid waste.

Frictional losses — energy losses in the piping and equipment due to resistance to the gas flow.

Fugitive emissions — emissions other than those from stacks or vents, which are not planned.

Gaussian dispersion — a framework of empirical equations which forms a basis for estimating concentrations from point sources.

Gradient — slope along a specific route, as of a road surface, channel, pipe or water tables. Expressed as a change in elevation corresponding to a horizontal distance (e.g. metres/metre).

Grading — manipulation of the elevations or contours of the ground.

Greenhouse gases — infrared absorbing gases which allow incoming solar radiant energy to penetrate to the earth's surface while re-absorbing infrared radiation emanating from the earth's surface. These gases then re-emit this thermal energy to the earth.

Halogenated — refers to compounds containing fluorine, chlorine, bromine, iodine or astatine.

Heating value — the heat released by combustion of a unit quantity of waste or fuel, measured in British Thermal Units (Btu) or kilojoules (1Btu = 1.056 kilojoules).

Hectare — a unit of area in the metric system equal to 10,000 square metres and equal to approximately 2.47 acres.

High heating value (gross heating value) — the total heat obtained from combustion of a fuel.

Hydraulic conductivity — the ability of soil or rock to transmit liquid. The higher the hydraulic conductivity, the greater the ability to transmit fluid.

Industrial waste — waste from an enterprise or activity involving warehousing; storage; industrial, manufacturing or commercial processes or operations; research; medical diagnosis or treatment; schools; laboratories; or hospitals.

Institutional waste — non-hazardous solid waste generated by schools, hospitals, nursing homes, etc.

Landfill — a land-based disposal site employing an engineered method of disposing of wastes on land in a manner that minimizes environmental hazards by spreading wastes in thin layers, compacting the wastes to the smallest practical volume, and applying cover materials at the end of each operating day.

Landfill gas (LFG) — the mixture of gases generated by the decomposition of putrescible organic wastes.

Landfilling — disposal of waste by deposit, under controlled conditions on land. Includes compaction of the waste into a cell and covering the waste with cover materials at regular intervals.

LFG collection rate — the quantity of LFG that is extracted from a site in a given period.

LFG control — collection and disposal (i.e. flaring) of LFG for the purpose of controlling potential environmental impacts.

LFG emission — the portion of LFG production that is released to the atmosphere (i.e. does not include LFG that is collected or migrates into the surrounding soil).

LFG generation rate — the quantity of LFG that results from decomposition of a unit of refuse in a given period (i.e. m^3/kg/yr, cubic feet per pound per year).

LFG management — LFG control with LFG utilization as an alternative to flaring.

LFG production rate — the total quantity of LFG generated by the total amount of refuse in a site at a given time (i.e. cubic metres in a given year). This may also be expressed as an average rate when divided by the duration of the given time period (i.e. cubic metres per hour during a given time).

LFG recovery rate — similar to LFG collection, however generally applied only in the context of LFG utilization (i.e. the quantity of LFG that is extracted from a site for the purpose of utilization).

LFG utilization — use of collected LFG as a fuel (for heating, production of electricity, etc.) or for use as an input in a production process (i.e. methanol).

LFG yield — the total quantity of LFG that is given off by a unit mass of refuse (i.e. cubic feet per pound). This quantity is highly dependent upon the character of the waste. The theoretical LFG yield may be as much as ten times greater than actual.

Limit of landfill/solid waste — a line delineating the limit within which municipal solid waste is contained (footprint).

Liner — a relatively thin structure of compacted natural clayey soil or manufactured material (i.e. plastic) which serves as a barrier to control the amount of leachate that reaches or mixes with groundwater.

Lower heating value (net heating value) — the gross heating value minus the latent heat of vaporization of the water vapor formed by the combustion of fuel.

Lysimeter — a sampling instrument used to monitor and measure the quantity or rate of water movement through soil or natural or artificial lines, or to collect percolated water for analyses.

Mercaptan — see *Thiol.*

Methane — an odourless, colourless, non-poisonous and explosive gas when mixed with air or oxygen in certain proportions. It is one of the two principal gases which comprise landfill gas.

Migration — LFG movement from one place to another, moving under natural forces.

Molecular diffusion — see *Diffusion.*

Municipal solid waste (MSW) — consists of domestic or residential waste and industrial, commercial and institutional (ICI) wastes of similar composition in any combination or proportion, but does not include liquid waste or hazardous waste.

Municipal waste landfill — a waste disposal site operating under a permit to accept MSW and/or C&D non-hazardous wastes.

Non-utility generators — electrical producers connected to the local utility electrical system. The non-utility generator is then able to both sell surplus electricity and buy electricity when the generating equipment is not operating. Non-utility generators are also referred to as parallel generators, independent generators or private power producers.

Peak emissions — the maximum emissions that may occur.

Permeability — the capacity of a porous medium to transmit a liquid. (See *Hydraulic Conductivity.*)

Permeable — permitting the flow of water or other liquids. The property of a solid material that allow fluids to flow through it. Usually described as a rate of penetration at a defined pressure.

Phenols — organic compounds that contain a hydroxyl group (OH) bound directly to a carbon atom in a benzene ring (e.g. phenol, cresol, and naphthol).

Point of emission — means the point at which a contaminant enters the natural environment.

Point of impingement — the point where the pollutant comes into contact with a receptor that could include humans, animals, vegetation or property.

Porosity — the ratio of the volume of pores in a material to the total volume of thermoteriol.

PPB/ppb — parts per billion (mass of substance (mg)/mass of solution (1,000kg)).

PPM/ppm — parts per million (mass of substance (mg)/mass of solution (kg)).

Pressure head — a measurement of pressure in a fluid system expressed as the height of an enclosed column of fluid which can be balanced by the pressure in the system.

Receptor — people (as defined by a residence) in the vicinity of an operation, or a landuse or an environmentally sensitive area who could potentially be adversely affected by the operation in some way.

Refuse — see *Solid Waste*

Renewable resource — a source of supply that is replaceable naturally or by human activity.

Solid waste — all non-hazardous solid materials that are discarded (also referred to as refuse).

Stability class — atmospheric stability is expressed through six stability categories (classes). A (unstable) through F (very stable).

Thiol (mercaptan) — group of organic compounds having the oxygen of the hydroxyl group (OH) replaced by sulfur. Many thiols are characterized by strong and repulsive odours.

Total pressure or total head — measure of the energy (potential and kinetic) available expressed in units of pressure (inches of water column, or pascal).