

---

**4**

WORKING  
PAPER  
SERIES

# **Guidance Note on Recuperation of Landfill Gas from Municipal Solid Waste Landfills**

Lars Mikkel Johannessen



Urban Development Division  
Urban Waste Management Thematic Group

---

---

Copyright ©1999  
The International Bank for Reconstruction  
and Development/THE WORLD BANK  
1818 H Street, N.W.  
Washington, D.C. 20433, U.S.A.

All rights reserved  
Manufactured in the United States of America  
First printing August 1999

Urban and Local Government Working Papers are published to communicate the results of the Bank's work to the development community with the least possible delay. The typescript of this paper therefore has not been prepared in accordance with the procedures appropriate to formal printed texts, and the World Bank accepts no responsibility for errors. Some sources cited in this paper may be informal documents that are not readily available.

The findings, interpretations, and conclusions expressed in this paper are entirely those of the author(s) and should not be attributed in any manner to the World Bank, to its affiliated organizations, or to members of its Board of Executive Directors or the countries they represent. The World Bank does not guarantee the accuracy of the data included in this publication and accepts no responsibility for any consequence of their use. The boundaries, colors, denominations, and other information shown on any map in this volume do not imply on the part of the World Bank Group any judgment on the legal status of any territory or the endorsement or acceptance of such boundaries.

The material in this publication is copyrighted. Request for permission to reproduce portions of it should be sent to the Urban Development Division at the address in the copyright notice above. The World Bank encourages dissemination of its work and will normally give permission promptly and, when reproduction is for noncommercial purposes, without asking a fee.

---

**TABLE OF CONTENTS**

**1. INTRODUCTION ..... 1**

    1.1 Background ..... 1

    1.2 Objective ..... 1

    1.3 Target groups ..... 1

    1.4 Information not covered ..... 2

    1.5 Cross reference ..... 2

**2. DEFINITIONS ..... 2**

**3. THE LANDFILL AS A BIOREACTOR ..... 3**

    3.1 Mechanisms for biodegradation of organic matter in a landfill ..... 3

        3.1.1 Landfill gas generation ..... 4

        3.1.2 LFG emissions control ..... 6

    3.2 Leachate ..... 7

        3.2.1 Leachate composition ..... 7

        3.2.2 Recirculation of leachate ..... 7

**4. REQUIREMENTS FOR PROJECT PREPARATION ..... 8**

    4.1 Baseline study ..... 8

    4.2 Regulatory requirements ..... 9

    4.3 Construction requirements ..... 10

    4.4 Operation requirements ..... 11

    4.5 Training needs ..... 12

**5. THE ENHANCED BIOREACTOR LANDFILL ..... 12**

    5.1 Advantages and disadvantages of an enhanced bioreactor landfill ..... 14

**6. COST AND BENEFITS ..... 15**

    6.1 Costs ..... 15

        6.1.1 Baseline study ..... 15

        6.1.2 Investment costs in LFG recovery system ..... 15

        6.1.3 Operation and maintenance costs ..... 17

    6.2 Benefits ..... 17

        6.2.1 Revenue from LFG recovery ..... 17

        6.2.2 Global environmental benefits ..... 17

    6.3 Compared economies for an enhanced bioreactor landfill—an example ..... 18

**ANNEXES**

**Annex A:** Fundamental Mechanisms for Biodegradation of Organic Waste in a Landfill ..... 21

**Annex B:** Monitoring Program for Enhanced Bioreactor Landfills ..... 22

**Annex C:** Landfill Mining ..... 23

**Annex D:** Examples of Costs and Benefits from LFG Recovery ..... 24

## **ACKNOWLEDGMENTS**

The World Bank gratefully acknowledges the Danish Ministry of Foreign Affairs, DANIDA, for providing the financial support to prepare this guidance note.

I sincerely acknowledge the input of Hans C. Willumsen from LFG Consult, Denmark, for his valuable contribution to the chapter on compared economies and comments on drafts of this guidance note.

I am grateful for the assistance of Carl Bartone and Gabriela Boyer of TWURD and Dan Hoornweg of EASUR at the World Bank, Tom Kerr of the U.S. Environmental Protection Agency, and Philip Rushbrook of WHO for their patience and valuable comments to draft versions of the note. I also extend my appreciation to N.C. Vasuky of the Delaware Solid Waste Authority and to Luiz Dias for their valuable comments.

In addition, I extend a personal thanks to Tania Hollestelle of TWURD for her help in preparing the manuscript of the guidance note.

## 1. INTRODUCTION

### 1.1 Background

Any place where municipal solid waste (MSW) is dumped or disposed of in large quantities is, in principle, a bioreactor generating leachate and gases. The bioreactions in the waste are dependent upon a series of conditions (e.g., moisture content of waste composition, availability of oxygen [redox potential], temperature, microflora, and compaction rate). Under strict anaerobic conditions, methane and carbon dioxide are often the primary gases generated. When generated in a landfill, this gas is often known as landfill gas (LFG). However, when the biodegradation happens under uncontrolled conditions, the process occurs randomly in the landfill waste. In this scenario, it is difficult or impossible to predict the level of biodegradation and the timeframe over which it occurs. Years of experience from research and practice have helped us gain a better understanding of MSW biodegradation in a landfill and how to predict the development and fate of leachate and LFG yields and composition.

LFG is a powerful greenhouse gas. When released in an unmanaged fashion, LFG may contribute anywhere from 2-4% of total global greenhouse gas emissions.<sup>1</sup> When LFG is combusted, its effect as a greenhouse gas is significantly reduced. If LFG is recovered, it provides a source of energy that can be utilized for several energy-producing purposes and thereby generate revenue for the landfill. Though only a few landfills in developing countries currently recover LFG for flaring or energy production, LFG recovery for energy production may have more widespread applications throughout the developing world. The promise of greenhouse gas mitigation combined with low-cost energy production could also mean wider opportunities for funding. Specifically, this combination of energy/environmental benefits is likely to fall within the scope of the Global Environment Facility (GEF).

By intentionally developing a *bioreactor* in a landfill, it is possible to enhance conditions for biodegradation of the organic components in the waste, and thereby increase both the time required for organic stabilization of the waste as well as the annual LFG yield. This knowledge can be applied to tailor both landfill operations and environmental protection measures.

### 1.2 Objective

The objective of this technical guidance note is to provide practical guidance in order to better prepare for projects that involve landfilling of municipal solid waste and, in particular, those projects that involve LFG recovery and developing an enhanced bioreactor landfill.

### 1.3 Target groups

This document is designed to reach task team leaders and team members who are working on urban, environmental, and solid waste projects. This guidance note will also provide essential information for solid waste and environment decision-makers and professionals involved in project preparation and implementation in client countries.

---

<sup>1</sup> According to the Intergovernmental Panel on Climate Change (IPCC). However, this estimate is based on very general assumptions.

#### 1.4 Information not covered

This note does not provide any technical advice on how to design or construct a sanitary landfill, nor does it contain detailed technical design measures for an enhanced bioreactor landfill.

#### 1.5 Cross references

More detailed technical guidelines for designing and constructing a landfill for solid waste are provided in the following publications:

- Rushbrook, P.E., Pugh, M.P., “Solid Waste Landfills in Middle- and Lower-Income Countries: A Technical Guide to Planning, Design, and Operation.” The World Bank, World Health Organization, the Swiss Agency for Development and Cooperation (SDC), and the Swiss Center for Development Cooperation in Technology and Management (SKAT), 1998.
- Johannessen, L.M., “Guidance Note on Leachate Management for Municipal Solid Waste Landfills.” The World Bank, Urban and Local Government Working Paper Series, 1999.

In addition, further details on landfill gas management and enhanced bioreactor landfills may be found in:

- Christensen, T.H., Cossu, R., Stegmann, R. (ed.), “Landfilling of Waste: Biogas.” Elsevier Applied Science, Elsevier Science Publisher, 1996.
- Department of Environment, 1991: “Waste Management Paper No. 27: Landfill Gas.”
- Solid Waste Association of North America (SWANA), 1998. *See current “Landfill Gas Readings,” at [www.swana.org](http://www.swana.org) for a list of selected background research papers on landfill gas.*

## 2. DEFINITIONS

*Enhanced bioreactor landfill:* A containment landfill designed to dispose of organic waste with the intention of optimizing biodegradation, reducing the organic load in leachate, and enhancing the generation of landfill gas to be recovered for energy production purposes.

*Leachate:* Polluted liquid produced as a result of rain or other water percolating through waste that is landfilled or dumped.

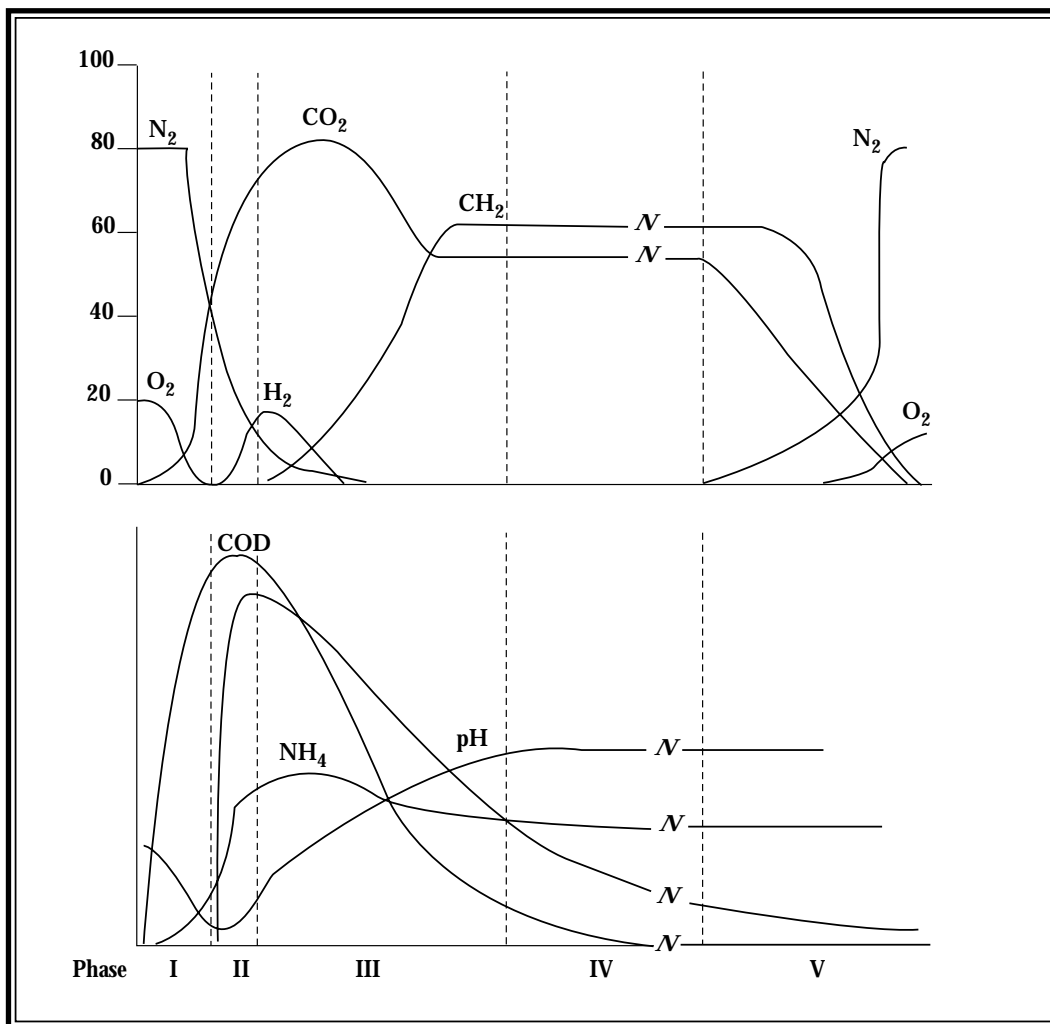
*Landfill gas (LFG):* A mixture of gases (predominantly methane and carbon dioxide) produced through microbial activity in anaerobic conditions during the degradation of waste that is landfilled or dumped.

*Municipal solid waste (MSW):* A heterogeneous mixture of materials that has no further use to consumers. It is usually discarded as refuse from households and residential areas; nonhazardous waste from industrial, commercial, and institutional establishments (including hospitals and clinics); market waste; yard waste; and street sweepings. Hazardous waste and special healthcare waste are by definition not MSW. Demolition and construction waste are also not considered MSW.

### 3. THE LANDFILL AS A BIOREACTOR

#### 3.1 Mechanisms for biodegradation of organic matter in a landfill

The biodegradation of organic waste follows a pattern of five phases. These five phases are fundamental, and they affect the LFG and the leachate composition. Through development of an enhanced bioreactor landfill, the time that elapses between these phases may be influenced (*see Chapter 5*). The five phases are illustrated in Figure 1 and described in more detail in Annex A.



**Figure 1:** Idealistic Development of LFG and Leachate within a Landfill Cell

Each layer of waste disposed of in a landfill undergoes the biodegradation phases illustrated in Figure 1. The main factors that influence the time that elapses for each phase are climactic conditions and operational factors.

**Phases I and II** may last from several weeks to two years (or longer). A higher ambient air temperature will enhance the biodegradation processes. High compaction rates and placing waste in thin layers will also enhance the biodegradation processes. Landfilling waste in small cells will also reduce the elapsed time for Phases I and II.

**Phases III and IV** may last for approximately five years at high peak and fade thereafter, depending on the landfill operation and, in particular, the moisture content of the waste. Because high moisture content will significantly increase bioreactions, precipitation will reduce the time elapsed in Phases III and IV and thus increase the quantity of LFG generated over time. Operational measures to enhance biodegradation include recirculation of leachate and extraction of generated LFG.

**Phase V** of the landfill lifecycle depends to a great extent upon the operational steps taken earlier in the landfill's life. However, it may take several decades or even centuries before the disposed of waste is finally stabilized. Ammonia is the limiting factor and will constitute potential pollution for an anticipated 100 years or more.

### ***3.1.1 Landfill gas generation***

The theoretical total quantity of LFG generated from 1 tonne of biodegradable carbon is 1868 Nm<sup>3</sup> (Normal Cubic Meter=Nm<sup>3</sup>). From industrialized countries, the theoretical total quantity of LFG potential to be generated is about 370 Nm<sup>3</sup> of MSW in place. The quantity of LFG generated is influenced by several factors, the data for which are not available from developing countries.

Because of uneven and incomplete biodegradation, it is generally accepted that a maximum volume of around 200 Nm<sup>3</sup> of LFG can be generated from 1 tonne of landfilled MSW.

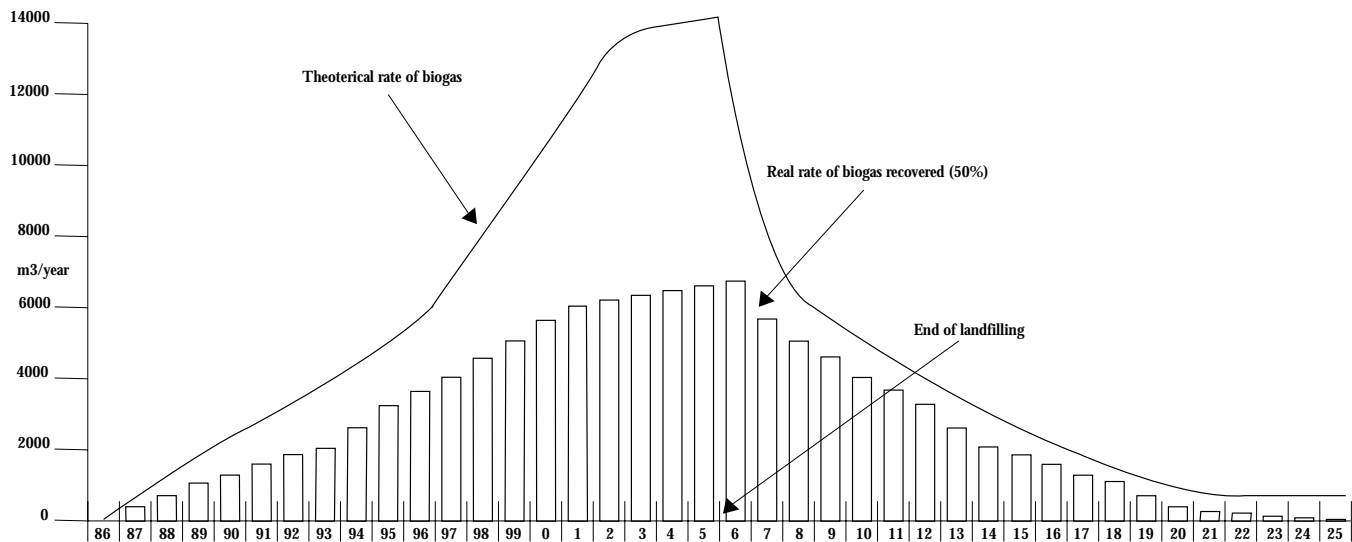
Several practical factors influence the possibility of capturing the total volume of LFG generated. The most important are:

- LFG losses to the atmosphere through the surface or through lateral gas migration;
- Pre-closure loss due to decomposition of organic material under aerobic conditions;
- Boundary effects causing incomplete anaerobic decomposition of the near-surface layer (e.g., air intrusion due to gas extraction);
- Other losses such as washout of organic carbon via leachate.

These losses are significant and real. Even with well-designed covers, few landfills are thought to recover more than 60% of available LFG. Normal recovery rates are considered to be in a range of



40 - 50% by volume (see Figure 2). Thus, it is prudent to assume this level for planning purposes. The upper yield of LFG generated for practical commercial recovery is about 100 Nm<sup>3</sup>/tonne of waste in place, generated over 15-20 years. By employing enhanced bioreactor landfill techniques, the total LFG yield per tonne of waste will be of the same magnitude as mentioned previously. However, gas generation will occur over a much faster time period (5-10 years), and the average annual flow of LFG will be up to four times higher during this time.



**Figure 2:** Fate of LFG Production over Time

**Source:** M.E. Fernandez et. al., "Production Potential of Biogas in Sanitary Landfills." Sardinia, Fifth International Landfill Symposium, 1995.

**LANDFILL GAS ALERT:** Spatial and temporal variability of biogas generation is a fundamental feature of a landfill cell. Failure to take this variability into account when calculating the total potential biogas reserve, biogas extraction potential from the landfill, and other characteristics, can lead to errors in design and in estimates of needed investments.

**Source:** Lifshits, A.B. and Minko, O.I., "Spatial Heterogeneity of Gas Generation in Landfill Sites." Sardinia, Fourth International Landfill Symposium, 1993, pp. 557-551.

LFG consists of a number of components, as illustrated in Table 1. The most important LFGs are methane and carbon dioxide. At its peak, the methane to carbon dioxide ratio is 1.2:1. For commercial calculation purposes, however, a ratio of 1:1 is normally assumed.

| Parameter          | Unit                | Range of Variation |
|--------------------|---------------------|--------------------|
| Methane            | CH <sub>4</sub> %   | 30-65              |
| Carbon dioxide     | CO <sub>2</sub> %   | 20-40              |
| Nitrogen           | N <sub>2</sub> %    | 5-40               |
| Hydrogen           | H <sub>2</sub> %    | 1-3                |
| Oxygen             | O <sub>2</sub> %    | 0-5                |
| Argon              | Ar%                 | 0-0.4              |
| Hydrogen sulfide   | H <sub>2</sub> S%   | 0-0.01             |
| Total sulfate      | S%                  | 0-0.01             |
| Total chloride     | Cl%                 | 0.005              |
| Temperature        | °C                  | 10-40              |
| Moisture content   | % relative humidity | 0-100              |
| Mass               | kg/m <sup>3</sup>   | 1,1-1,28           |
| Lower energy level | MJ/Nm <sup>3</sup>  | 10.8-23.3          |

**Table 1:** Range of LFG composition from MSW landfills<sup>2</sup>

**LANDFILL GAS ALERT:** If LFG is not properly managed at a landfill, the gas may migrate to neighboring areas. In a worst-case scenario, this situation can cause explosions.

### 3.1.2 LFG emissions control

The methane in LFG is a powerful greenhouse gas. According to the IPCC, 1 gram of methane has 21 times the impact of 1 gram of carbon dioxide, over a 100-year period. It therefore becomes important to reduce the level of methane in LFG before it is released into the atmosphere. Burning LFG reduces the methane content to carbon dioxide and water. This may be done through flaring or by utilizing the LFG in a gas engine or furnace to generate energy.

Also, LFG migrating through the top cover of a landfill, to a large extent, will convert methane into carbon dioxide and water through microbial oxidation in the upper part of a landfill top cover. The conversion capacity for a landfill top cover varies depending on soil texture, moisture content, and the amount of organic matter available in the soil. Some landfill top covers have shown complete oxidation of methane, especially if the soil is porous and organic material is available. Therefore, a landfill that has a porous top cover with a proportion of organic matter (e.g., compost) should be viewed as practicing “LFG management” rather than as operating with a passive LFG ventilation system.

<sup>2</sup> LFG may also contain several volatile organic compounds in small quantities. However, where hazardous waste has been disposed of, the level of volatile organic compounds may rise to a level that may cause concern. In concentrations of 5-12%, methane in atmospheric air is an explosive gas.

Flaring of LFG collected by gas wells is a simple solution to methane emissions reduction. Active flaring may be one option, for example, through the installation of solar panel-activated flares at the gas wells. LFG recovery, however, may be the most efficient way to reduce atmospheric emissions of methane from landfills.

## 3.2 Leachate

### 3.2.1 Leachate composition

Table 2 shows the typical composition of leachate from a MSW landfill. For simplicity's sake, the composition is displayed for the so-called acidic phase (Phases I and II of Annex A) and the methanogenic phase (Phases III and IV of Annex A). As for the LFG, there are wide variations influenced by climactic and operational factors, which are described for each phase in Annex A.

| Parameter               | Unit | Acidic Phase<br>(6 months to 2 years) | Methanogenic Phase<br>(2 to 100+ years) |
|-------------------------|------|---------------------------------------|---|
| pH                      |      | 5-6.5                                 | 7.5-9                                   |
| COD*                    |      | mg/l 20,000-30,000                    | 1,500-2,000                             |
| BOD <sub>5</sub> **     | mg/l | 10,000-25,000                         | 500-1,000                               |
| Iron                    | mg/l | 5-20                                  | < 5                                     |
| Zinc                    | mg/l | 1-5                                   | 0.03-1                                  |
| Cadmium                 | ug/l | < 30                                  | 6                                       |
| Ammonia                 | mg/l | 900-1,500                             | 900-1,500                               |
| Chloride                | mg/l | 1,200-3,000                           | 1,000-3,000                             |
| *Chemical Oxygen Demand |      | **Biological Oxygen Demand            |   |

**Table 2:** Typical Leachate Composition in a MSW Landfill<sup>3</sup>

#### LANDFILL GAS ALERT

The pollution potential in leachate from nutrients (especially ammonia) and salts is not necessarily reduced through bioreactions in a landfill, but requires further remediation.<sup>4</sup>

### 3.2.2 Recirculation of leachate

The recirculation of leachate serves three purposes: 1) to enhance the biodegradation of organic waste; 2) to reduce the organic load in the leachate; and, 3) thus generate large quantities of LFG.

<sup>3</sup> Note that leachate composition figures are based on data from wet climate conditions in the northern hemisphere. Adequate data are not available from developing countries.

<sup>4</sup> See also Johannessen, L.M., "Guidance Note on Leachate Management for Municipal Solid Waste Landfills," The World Bank, Urban and Local Government Working Paper Series, 1999.

Recirculating the leachate in a landfill adds to moisture to the disposed waste and thereby enhances the biodegradation process in the waste. When the lowest 1-2 meters of waste in the landfill becomes anaerobic and methanogenic conditions prevail (*see Section 3.1*), leachate recirculation will be optimal e.g., the organic load in leachate will be significantly reduced and LFG will be produced. This situation may occur between 6 months and 2 years after disposal has started.

The optimal recirculation of leachate requires that the landfill be divided into cells. Leachate from “young cells” (where the organic load in leachate is high) can be recirculated into “old” cells, where methanogenic conditions prevail. LFG extraction should then only be done from “old” cells because the LFG yield there will be optimal.

Recirculation of leachate can be accomplished in several ways, including: 1) sprinkling leachate onto the waste surface from a tank mounted to a truck/tractor; 2) placing an irrigation system in areas for recirculation of leachate; and, 3) placing vertical or horizontal drains in the waste matrix from which leachate is distributed in the waste matrix. Options 1) and 2) may provide some evaporation of leachate, however, while at the same time generating aerosols that may affect people working at the landfill. Option 3) provides efficient recirculation and good distribution of leachate, though there is a risk of pipes clogging (from carbonates and iron). Option 3) is also a more sophisticated and expensive solution.

#### **4. REQUIREMENTS FOR PROJECT PREPARATION**

Biodegradation of MSW disposed of in a landfill will eventually follow the patterns for the phases described in Chapter 3. Within a few months to two years, LFG will be generated in quantities that should be managed, either through flaring or through recovery and utilization. It is advisable to consider LFG recovery projects only where appropriate landfill management has been proven. Where a project includes LFG recovery, a number of requirements should be considered in addition to the requirements for landfill project preparation and implementation. These include a baseline study; careful attention to the local regulatory regime, landfill construction, and operations; and consideration of the training needs of local officials and landfill personnel.

##### **4.1 Baseline study**

For commercial recovery of generated LFG, a landfill should receive at least 200 tonnes/day of waste, be designed for a minimum total capacity of 500,000 tonnes, and have a minimum filling height of 10 meters. The waste should not have been deposited for more than 5 -10 years before LFG recovery is attempted.

Before considering commercial recovery of LFG, a baseline feasibility study should:

- Assess the waste composition, with an indication of the expected proportion of organic components, their biological half-life,<sup>5</sup> moisture content, and concentrations of hazardous materials. It is important to determine the amount and type of materials that could be hazardous, or those that will inhibit biological activity in the waste (e.g., large quantities of gypsum).
- Compute and predict the annual LFG yield and the reduction over time, using the organic half-life determined above. Predictions of LFG generation should also take into consideration the total amount of waste disposed of over time. If the computed LFG generation proves feasible<sup>6</sup> for existing landfills, the results may be verified by test pumping from several wells on-site over an appropriate time period (at least 2 months) to level out natural fluctuations such as atmospheric pressure.
- Determine the anticipated methane content in the LFG and the LFG calorific value and calculate the potential power to be produced.<sup>7</sup>
- Identify potential buyers of the power (or heat) produced and the distance to distribution net works, whether an electric power grid or heating facility (industry or district heating). After refinement, the LFG could potentially be converted to natural gas and sold to a gas utility.
- Assess the potential energy buyers' willingness to enter into a long-term contract (not shorter than 10 years) for buying power.
- Determine the sales price for the energy to be sold, the conditions for selling energy, and the means for securing selling prices.
- Assess private partnerships' involvement in commercial recovery of the LFG.
- Calculate the feasibility of LFG recovery, where environmental benefits (e.g., reduction of green house gases, replacement of fossil fuel) may be included.
- Review the socioeconomic implications of removing scavengers from the landfill. A bioreactor landfill cannot operate with scavengers on the landfill site, since extensive waste compaction is required and fires on the landfill will interfere with the bioreactions.

#### 4.2 Regulatory requirements

Many countries have regulatory requirements or guidelines with regards to the design and operation of landfills. Some of these regulatory requirements, however, may interfere with the optimal

<sup>5</sup> The time it takes through biodegradation to reduce the organic content of a material to half of its original organic content.

<sup>6</sup> i.e., there is potential for generation of a minimum of 250 kW electricity (see also Section 6.1.2).

<sup>7</sup> Methane content should on average be higher than 40-45% and thus the LFG should have a lower heating value of 14-16 MJ/Nm<sup>3</sup> to be feasible for utilization.

biodegradation of the landfill waste. During project preparation, these limitations should be revealed. The limitations could include:

*Daily soil cover* of a thickness of 15 cm is often required. If this requirement cannot be exempted for enhanced bioreactor landfills, operators should negotiate to apply only a minimal layer. Furthermore, the daily soil cover should consist only of highly permeable materials. If none of this is achievable, the daily soil cover should, to the extent possible, be removed at the beginning of each work day.

*Recirculation of leachate* may not be widely accepted. In this case, landfill operators should prepare a justification of recirculation and present it in the Environmental Assessment.

*Emission standards* for combustion of LFG in a gas engine may exist. This may lead to requirements for fluegas control at the gas engine (*see Section 3.1.1 for LFG emissions*).

*An impermeable or low permeable topcover* may be required when the landfill reaches its final capacity. Where this is the case, provisions should be made to maintain a high-moisture content inside the waste matrix, e.g., through leachate recirculation.

*Sales of energy* from independent power producers may not be possible due to local regulations.

#### **4.3 Construction requirements**

The basic construction requirements for a landfill equipped to recover LFG are similar to those of a normal landfill. To ensure optimal LFG recovery, landfill operators should consider the following additional construction requirements:

- i) Operation cells of about 2.5 ha, with separate liner and leachate collection, to ensure rapid infilling and the possibility of individually controlled leachate collection and recirculation. The design capacity for the leachate collection system should include the anticipated recirculation rates.
- ii) A leachate recirculation system with pumps, designed to ensure a relatively even distribution of leachate injected back into the waste matrix.
- iii) An LFG extraction system, with vacuum pumps, to be installed during operation of each landfill cell or after final infilling of waste in a cell. If installed during infilling of waste, the LFG collection system often consists of horizontal drains combined with collection wells. When installed during infilling of waste, higher LFG yields may be recovered. However, operational difficulties may arise, including problems maneuvering waste collection trucks at the tipping face; difficulties compacting the waste near LFG collection wells; and uneven settlements around the LFG collection wells. If installed when infilling of waste is completed, the LFG collection system consists of drilled wells. This makes installation and operation of the equipment easier, but reduces the total volume of LFG extracted. The suction capacity for vacuum pumps is critical for optimal extraction of the LFG. The vacuum pumps should therefore be designed for a peak LFG flow arising some 2-7 years after infilling is completed. Monitoring and control

systems can be installed to avoid the intrusion of ambient air into extraction wells and other problems, and thereby optimize the extraction of gas at all times.

- iv) Installation of an LFG utilization system. Utilization ranges from direct discharge of LFG into an existing urban gas system, to generation of electric power alone, process steam generation, or combined heat and power generation (CHP). Direct use of LFG in the urban gas system may require a sophisticated cleaning and enrichment process for the relatively less pure LFG compared to natural gas. Using LFG to fuel vehicles would also require extensive cleaning, and therefore is rarely applied. Hot water or steam production may be relevant in cases where a nearby industry can use these outputs. Where district heating is used, a CHP plant may be relevant. However, the production of electric power in gas engines or generators is most commonly used for connection to (1) the nearest electrical power grid capable of receiving the generated power, or (2) the nearest other energy consumer.
- v) Installation of a gas-impermeable top cover may increase the LFG recovery rate by 20-30% by volume, provided that the optimal flow of liquid (water and recirculated leachate) through the waste matrix is maintained. The biodegradation and the bioreactor will slowly stall if the waste matrix contains insufficient moisture content.

#### 4.4 Operation requirements

A landfill where LFG is commercially recovered, in principle, will operate as any conventional landfill, with gate control, a limited tipping front, and compaction of waste. However, a few important measures should be taken to enhance the stabilization of the waste and the generation of LFG:

- i) The first layer of waste in every cell should be pre-composted. This is achieved by using a compactor to grind and homogenize the waste prior to infilling. The waste should thereafter be placed (by a bulldozer) in the cell in layers approximately 1 meter thick;
- ii) a compactor should be used to place the subsequent waste in layers a maximum of 0.3-0.5 meters thick to achieve high compacting rates;
- iii) daily soil cover should be avoided to ensure optimal downflow and even distribution of precipitation and recirculated leachate through the waste matrix, and to ensure optimal flow of LFG to extraction points;
- iv) leachate from a cell in the acidic phase (Phase I or II)<sup>8</sup>—determined through analysis of leachate quality (see *Table 3 and Annex B*)—should always be recirculated onto cells in the methanogenic phase (Phase III or IV)<sup>9</sup>. To add moisture to a cell in the acidic phase, leachate from any cell may be applied;
- v) high compaction rates of the waste should be achieved by using a compactor and following ii) above; and

<sup>8</sup> See Section 3.1.

<sup>9</sup> See Section 3.1.

- vi) to reduce ammonia and other salt levels in the leachate, flush with clean water or apply treated leachate when the waste matrix is organically stabilized. Flushing is, in principle, high-flow recirculation with clean water and/or treated leachate.

#### **4.5 Training needs**

It is important to provide training and raise awareness about the concept of LFG recovery. In the assessment of whom to target for such training, the following individuals should be considered:

- Regulatory authorities, in order for them to understand the need to adjust regulations to facilitate LFG management and recovery;
- Supervisory authorities, in order for them to properly supervise the operation of the landfill and monitor the biodegradation processes in the waste;
- Landfill managers/operators, in order to ensure optimal operation of the landfill for LFG recovery and organic stabilization. This task requires knowledge and understanding of: i) on-site placement of the waste; ii) the consequences of recirculation of leachate, and when and where to recirculate leachate and how to act in accordance with the results of leachate analysis; iii) operation of gas engines and understanding of maintenance requirements; and iv) monitoring procedures for LFG and for leachate. The landfill operator should be able to provide instructions to equipment operators at the landfill.

### **5. THE ENHANCED BIOREACTOR LANDFILL**

The enhanced bioreactor landfill represents a new approach for rapidly generating LFG from a landfill. However, the technology is not yet widely proven. And, an enhanced bioreactor landfill can only be developed when new cells in a landfill are being constructed. The overall philosophy behind the concept of an enhanced bioreactor landfill is to optimize the formation of methane for recovery through rapid biodegradation of organic waste and through transformation of the organic load in leachate (*see Table 3*).



|                     |  |
|---------------------|--|
| <b>Application</b>  | The enhanced bioreactor approach applies to every newly designed landfill with containment that receives MSW and existing landfills that need improved management and operation.   |
| <b>Objective</b>    | The objective of developing an enhanced bioreactor landfill is to achieve faster degradation and stabilization of the organic waste in the landfill, and to enhance landfill gas production and thus reduce the organic load in the leachate.  |
| <b>Stakeholders</b> | <ul style="list-style-type: none"> <li>• Competent authorities and monitoring agency</li> <li>• Landfill owners and operators</li> </ul>   |
| <b>Outputs</b>      | <p>The enhanced bioreactor landfill will achieve:</p> <ol style="list-style-type: none"> <li>1. Rapid stabilization of the organic components within the disposed of waste</li> <li>2. High yield of LFG to be recovered and utilized</li> <li>3. Revenue from energy production of LFG</li> <li>4. Awareness about environmental and operational issues raised among authorities and landfill operators</li> <li>5. Potential developed for future mining of the landfill<sup>10</sup></li> </ol> <p>Note: Ammonia and salts will not be affected by an enhanced bioreactor landfill design.</p>  |
| <b>Activities</b>   | <ol style="list-style-type: none"> <li>1. Develop a containment site prepared with leachate collection and recirculation and LFG recovery.</li> <li>2. Pre-compost the first waste layer in each landfill cell.</li> <li>3. Compact the subsequent waste into thin (less than 0.5 m) layers.</li> <li>4. Avoid using daily soil cover.</li> <li>5. Limit the content of sewage sludge in the landfill to &lt;10% (w/w) of the total waste quantity.</li> <li>6. Recirculate fresh leachate into cells in the methanogenic stage.</li> <li>7. Recover and utilize the generated LFG.</li> <li>8. Excavate the landfill when stabilized, and reuse the cleared area again for landfilling.</li> </ol> <p>Note: After organic stabilization, ammonia and salts may be flushed by water. However, this is not yet a widely proven remediation technology and does not apply if the landfill is mined (see #8 above).</p> |
| <b>Inputs</b>       | <p>Apart from investment in a containment landfill, the enhanced bioreactor landfill requires investment in:</p> <ul style="list-style-type: none"> <li>• Compactor(s);</li> <li>• A recirculation system;</li> <li>• An LFG recovery system with connections to the electrical power grid or other energy consumer.</li> </ul> <p>The following additional operation costs are required:</p> <ul style="list-style-type: none"> <li>• Power for recirculation pumps and gas extraction pumps;</li> <li>• Maintenance of additional equipment (recirculation pumps and LFG recovery equipment).</li> </ul>   |

**Table 3:** The Requirements and Composition of an Enhanced Bioreactor Landfill

<sup>10</sup> See Annex C for a description of landfill mining.

### 5.1 Advantages and disadvantages of an enhanced bioreactor landfill

An enhanced bioreactor landfill has several advantages over a sanitary landfill, and it also has certain disadvantages:

#### Advantages of an enhanced bioreactor landfill:

1. It rapidly generates higher gas yield (the total theoretical quantity of LFG to be generated remains the same for all landfills) with a shorter LFG recovery time.
2. Recovery of LFG for energy purposes displaces a certain quantity of fossil fuel. Apart from the environmental benefits, for some countries this feature may also contribute to foreign exchange savings.
3. Selling energy generated from recovered LFG generates revenue for the landfill.
4. Combustion of LFG converts methane into carbon dioxide and water and thereby reduces the landfill's impact on the greenhouse effect by a factor of 3 to 6.<sup>11</sup>
5. Enhanced biodegradation and stabilization of the organic parts of the disposed waste reduces the organic load in the leachate and helps minimize the long-term potential environmental impact to groundwater.
6. Landfill operators gain a greater awareness of optimal landfill operation techniques and a better understanding of the biological processes within the landfill.
7. The rapid settlement in the disposed of waste may provide better options for future use of the area.
8. Landfill mining may be possible when the waste is stabilized (*see Annex C for more details*).

#### Disadvantages of an enhanced bioreactor landfill:

1. Operating and monitoring an enhanced bioreactor landfill requires a more sophisticated process than the requirements for a sanitary landfill. Landfill operators need more advanced operational skills and technical know-how. If the operator does not have the necessary skills, the full benefits of the bioreactor landfill may not be achieved.
2. Recirculation of leachate may generate a build-up of leachate within the landfill matrix. If the landfill is developed on a slope or as a "hill," this may result in leachate emanating from the side of the landfill and, in the worst-case scenario, may result in landfill collapse or a waste slide (e.g., Bogota, Colombia and Durban, South Africa).<sup>12</sup>

<sup>11</sup> Not all methane will be converted into carbon dioxide, and carbon dioxide from the landfill still contributes to the greenhouse effect.

<sup>12</sup> Refer to Johanessen, LM, et al. "Observations of Solid Waste Landfills in Developing Countries: Africa, Asia, and Latin America," The World Bank, Urban and Local Government Working Paper Series, June 1999.

3. Additional investments and higher operation costs are necessary to achieve the full benefits of the enhanced bioreactor landfill. If a satisfactory long-term contract for selling the generated energy (e.g., electrical power) cannot be agreed upon, it may not be possible to generate the revenues to cover the costs of the additional investments.

## **6. COSTS AND BENEFITS**

LFG recovery requires investments in both extraction and utilization systems. The economics of LFG recovery depends on several factors, as described in earlier chapters. Two of the most important economic factors are the possibility of selling the produced energy and the determination of price. The available data on the economic balance are scarce, particularly from developing countries, partly because few LFG recovery plants exist in these countries and partly because there are few incentives to reveal costs from LFG recovery. However, private companies are investing in LFG recovery systems at large landfills, which provides some proof of a believed profit margin. This chapter discusses costs for a pre-feasibility study, investment costs, operation and maintenance costs, and economic benefits from selling energy and global environmental benefits from replacing fossil fuel. At the end of this chapter, the economics of LFG recovery from a traditional landfill are compared with LFG recovery from an enhanced bioreactor landfill.

### **6.1 Costs**

The following broad cost estimates are all based on 1998 values, where nothing else is indicated.

#### ***6.1.1 Baseline study***

A baseline study or pre-feasibility study should follow the recommendations given in Section 5.1. Predictions of LFG production in new landfills vary significantly in terms of costs, depending to a large degree upon the availability of data, especially on the expected waste composition. Such a study may cost between US\$7,000-US\$20,000. In cases where the landfill already exists and the waste is in place, test pumping may be used to verify or update computed predictions. Costs for test pumping may range from US\$20,000-US\$70,000, depending largely upon the availability of equipment in the area. Including other consulting fees, a baseline and pre-feasibility study, including test pumping, thus may range from US\$30,000-US\$100,000.

#### ***6.1.2 Investment costs in LFG recovery system***

The baseline study will indicate the level of investment required to utilize the LFG generated. The level of investment depends primarily upon the type of power to be generated and the distance over which the power can be delivered.

The LFG extraction system consists of the collection system (in the waste) and a suction system (of pumps, valves, etc.):

- The LFG collection system utilizes either vertical wells (placed after infilling of waste) or horizontal drains (placed during infilling of waste). On average, the two systems require the same level of investment; however, horizontal drains tend to fall at the higher end of the cost range. The advantages and disadvantages of the two systems are described in Section 4.3 (iii). For an average 10-meter-deep landfill, the investment in the collection system will range from US\$20,000-US\$40,000 per hectare.
- The LFG suction system consists of vacuum pumps, monitoring equipment, and control systems. The investment depends largely upon the sophistication of the monitoring and control system and upon the volume of LFG to be extracted. Investments in LFG suction systems range from US\$100-US\$450 per m<sup>3</sup> of LFG extraction capacity per hour. For an average 10-meter-deep landfill, the LFG suction system requires investments ranging from US\$10,000-US\$45,000 per hectare. Many developing countries may not need equipment of the highest level of sophistication, and the investment range for these countries may therefore be from US\$10,000-US\$25,000 per hectare.

Utilization of LFG is most commonly achieved through the production of electric power. This is the most dependable and applicable method for utilization of LFG in lower- and middle-income countries. The investment in gas engines normally ranges between US\$850-US\$1,200 per kW<sub>e</sub> installed, depending on the level of sophistication of the power generator (which ranges from gas-fueled engines to gas turbines). The smallest feasible engines to install generate from 250-500 kW<sub>e</sub>, and represent a minimum investment of US\$200,000-US\$600,000.

The average range of investment costs per kW<sub>e</sub> power installed for an entire LFG recovery system is summarized in Table 4.

| <b>Component</b>    | <b>Costs in US\$/kW<sub>e</sub></b> |
|---------------------|-------------------------------------|
| Collection system   | 200-400                             |
| Suction system      | 200-300                             |
| Utilization system  | 850-1,200                           |
| Planning and design | 250-350                             |
| Total               | 1,550-2,250                         |

**Table 4:** Average Range of Investment Costs for LFG Recovery per kW<sub>e</sub> Power Installed

### **6.1.3 Operation and maintenance costs**

The annual operational and maintenance costs for an enhanced bioreactor are higher than those of well-operated and managed landfills. The additional costs reflect the operation of pumps to circulate leachate and the cost of extracting and utilizing LFG in larger plants, which have higher annual yields of LFG. The additional annual operation costs for an enhanced bioreactor landfill may therefore be from 40-60% higher than operation and management costs of conventional landfill gas project. This cost increase is offset by higher annual energy revenues.

## **6.2 Benefits**

### **6.2.1 Revenues from LFG recovery**

Revenues from LFG recovery will depend significantly upon the type of energy produced, price fluctuations over the course of the day, and on country-specific regulations regarding the subsidy of renewable energy sources (to promote CO<sub>2</sub> reduction). Subsidies for selling electric power range from US\$0.004/kWh in the United States to US\$0.04/kWh in Denmark; Java and Bali, Indonesia (before 1998) fell between the United States and Denmark with a subsidy of US\$0.016/kWh.

The price for electric power sold to the local power grid varies from one country to another. Typically, however, prices will range between US\$0.01/kWh (off-peak hour) to US\$0.08/kWh (peak hour), with an average price of US\$0.04/kWh.

To make LFG recovery feasible without subsidies, the produced electricity in the United States and United Kingdom should be sold at a price of US\$0.03/kWh or higher. For small landfills (fewer than 500,000 tonnes), as is the case in Denmark, the produced electricity should be sold at US\$0.055/kWh or higher to make LFG recovery feasible.

### **6.2.2 Global environmental benefits**

Any combustion of LFG will reduce emissions of methane, the powerful greenhouse gas (*see Section 3.1.2*). Utilizing LFG in controlled combustion for the purpose of producing energy and thereby displacing fossil fuel (and abating carbon emissions) is an added global environmental benefit. The global environmental benefits as unit abatement costs can be calculated as shown in the example in Table 5.

The calculations show unit abatement costs of about US\$4 per tonne of abated carbon. These calculations may be of interest in order for the Global Environment Facility to provide financial support for the project's incremental costs. At present, the GEF ceiling for supporting projects is a unit abatement cost of US\$10 per tonne of carbon equivalent.

Where the calculations show negative unit abatement costs, the project may be economically beneficial with positive environmental benefits. Projects of this nature may encourage a high level of inter-

|  |             |                                 |
|--|-------------|---------------------------------|
| Total amount of waste  | 550,000     | Tonnes                          |
| Total potential LFG production for recovery  | 110,000,000 | Nm <sup>3</sup>                 |
| Total CH <sub>4</sub> (50% of total LFG)   | 55,000,000  | Nm <sup>3</sup>                 |
| Total weight of CH <sub>4</sub> released in tonne (Density 0.7 kg/m <sup>3</sup> ) | 38,500      | Tonnes                          |
| Total CO <sub>2</sub> equivalent as greenhouse gas <sup>13</sup>                   | 808,500     | Tonnes                          |
| Total carbon equivalent  | 220,500     | Tonnes                          |
| Total potential electric power production  | 181,500,000 | kWh(e)                          |
| Anticipated time for recovery of CH <sub>4</sub>                                   | 20          | Years                           |
| Required size of power generator   | 1,134       | kW(e)                           |
| Investments required   | 1,700       | US\$/kW(e)                      |
| Total investment   | 1,928,000   | US\$                            |
| Interest rate of investments   | 5           | %                               |
| Operation and maintenance costs per year (10% of investments)                      | 192,000     | US\$/year                       |
| Unit price for sold electric power   | 0.034       | US\$/kWh                        |
| Total income per year  | 308,500     | US\$/year                       |
| Net incremental costs over 20 years Net Present Value <sub>20</sub> (NPV)          | 504,848     | US\$                            |
| <b>NPV<sub>20</sub> of unit abatement costs</b>                                    | <b>3.98</b> | <b>US\$/tonne<br/>of carbon</b> |

**Table 5:** Unit Cost for Abating Carbon--An Example

est in terms of private sector involvement. However, for a national program, GEF may provide financial assistance to promote the adoption of renewable energy by removing barriers and reducing implementation costs (GEF operational program number 6).

### 6.3 Compared economies for an enhanced bioreactor landfill--an example

The enhanced bioreactor landfill produces a higher annual yield of LFG than a landfill without an enhanced bioreactor. The initial investment costs in LFG recovery are higher for an enhanced bioreactor landfill. The example in Table 6 illustrates the economic differences between an enhanced bioreactor landfill and a well-operated landfill without an enhanced bioreactor. The example assumes a landfill where 1 million tonnes of MSW has been disposed of, and assumes that the enhanced bioreactor landfill generates an average 8 m<sup>3</sup> of LFG/tonne of waste per year for a period of 10 years, while the other landfill generates an average of 4 m<sup>3</sup> of LFG per year for 20 years.

<sup>13</sup> Methane is anticipated to be a 21 times more powerful greenhouse gas than CO<sub>2</sub> over a 100-year period.

|  | Enhanced bioreactor     |             | Nonenhanced bioreactor |             |
|--|-------------------------|-------------|------------------------|-------------|
|  | US\$                    | US\$/tonne  | US\$                   | US\$/tonne  |
| <b>Investments</b>                             |                         |             |                        |             |
| Collection system                              | 400,000                 | 0.40        | 200,000                | 0.20        |
| Pumps, monitoring, regulators                  | 300,000 <sup>1)</sup>   | 0.30        | 200,000                | 0.20        |
| Utilization system, gas engine                 | 1,500,000               | 1.50        | 800,000                | 0.80        |
| Planning, design, engineering                  | 400,000 <sup>1)</sup>   | 0.40        | 240,000                | 0.24        |
| Total investments                              | 2,400,000 <sup>1)</sup> | 2.80        | 1,440,000              | 1.44        |
| <b>Operation and maintenance</b>               |                         |             |                        |             |
| Annual operation and maintenance costs         | 210,000                 | 0.21        | 140,000                | 0.14        |
| Total operation and maintenance costs          | 2,100,000               | 2.10        | 2,800,000              | 2.80        |
| <b>Revenue</b>                                 |                         |             |                        |             |
| Scrap value after 10 years <sup>2)</sup>       | 1,200,000               |             | 0                      |             |
| Total revenue for sold power (0.055 US\$/kWh.) | 7,150,000               | 7.15        | 7,150,000              | 7.15        |
| <b>Balance of revenue</b>                      | <b>3,850,000</b>        | <b>3.85</b> | <b>2,910,000</b>       | <b>2.91</b> |

<sup>1)</sup>This includes leachate recirculation costs.  
<sup>2)</sup>The system for an enhanced bioreactor landfill has only been used for 10 years and can be used for another 10 years.

**Table 6:** Economics of an Enhanced Bioreactor Landfill and a Well-Operated Landfill without any Enhancement Measures Taken

The investment in the LFG recovery system depends primarily upon the depth of fill (e.g., the volume disposed divided by the disposal area). The unit investment costs for a 10 ha, 1 million tonne landfill will be in the range of US\$6.6-US\$8.5 per tonne of waste, depending on local conditions. With an investment in an LFG recovery system of US\$1.4-US\$2.8 per tonne of waste, the LFG system will constitute some 18-25 % of the total investment costs.

If it is assumed that a landfill can be left unattended for 30 years after closure, the total landfill costs (investment and operation and maintenance costs) will range from US\$10-US\$15/tonne of waste disposed of without LFG recovery. Table 6 indicates that the total LFG recovery costs (investment, operation, and maintenance costs) range from US\$4.2/tonne for a conventional landfill to US\$4.8/tonne for an enhanced bioreactor landfill. Taking into account the cost recovery from sold power, the total landfill costs may be reduced from US\$15-US\$20/tonne to US\$8-US\$13/tonne, which is the equivalent of reducing the total landfill costs by 35-47%.

If it is assumed that the leachate would be treated until the pollution potential in the leachate is at a level where it can be released into the environment with no adverse impacts, treatment may be required for several decades. The total landfilling costs without LFG recovery may then range from US\$21-US\$37 per tonne of waste.<sup>14</sup> If we add the costs and benefits from LFG recovery to these costs, the total landfill costs will be reduced between US\$18-US\$35/tonne, which is equivalent to reducing the total landfill costs by 17-27%.

Energy prices are also crucial to the economies of LFG projects. With an energy sales price reduced from US\$0.055/kWh. to US\$0.025/kWh., the total landfill costs will be reduced by 18-24%, with an aftercare period of 30 years. In this scenario, costs will be reduced by 8-14% if the landfill is operated until the leachate can be safely released into the environment. The sales price therefore becomes crucial for making decisions regarding LFG recovery.

Annex D gives four cost examples of LFG recovery from Denmark, Poland, Latvia, and Indonesia, respectively.

---

<sup>14</sup> See Johannessen, L.M., "Guidance Note on Leachate Management for Municipal Solid Waste Landfills," The World Bank, Urban and Local Government Working Paper Series, 1999.



## ANNEX A: FUNDAMENTAL MECHANISMS FOR BIODEGRADATION OF ORGANIC WASTE IN A LANDFILL

The biodegradation of organic waste in a landfill has five distinct phases, all of which influence the leachate composition and the development of LFG. In an enhanced bioreactor landfill, the time that elapses between these phases may be reduced.

The five phases are illustrated in Figure 1. They are as follows:

**Phase I:** This is an aerobic phase that takes place immediately after the waste is disposed of. Easily biodegradable substances are broken down by the presence of oxygen. In fact, this is a composting process where carbon dioxide is produced and the temperature rises. This phase may be very short-lived.

**Phase II:** This is an aerobic phase, with the development of anaerobic conditions. A fermentation process occurs, developing acids in the leachate and a significant drop in pH. This process may lead to the release of metals in the waste matrix. The LFG generated consists primarily of carbon dioxide.

**Phase III:** Anaerobic conditions are now established. Within the right microbial environment, methanogenic conditions will emerge. The LFG will start to contain increasing quantities of methane, and the concentration of carbon dioxide will decrease. Sulfate will be reduced to sulfites and will be capable of precipitating metals from the leachate. As the organic acids are converted into LFG, the pH levels rise in the leachate. The organic load in the leachate will decrease, and ammonia will increase since ammonia is not converted under anaerobic conditions.

**Phase IV:** This is the so-called stable *methanogenic phase*. This is also the anaerobic phase, where methane production is at its highest, with a stable concentration of 40-60% CH<sub>4</sub> by volume. Acidic organic components in the leachate are immediately decomposed into LFG. The organic load in the leachate is low and consists primarily of heavy biodegradable organic components. As the conditions are strictly anaerobic, the leachate will still have a high concentration of ammonia.

**Phase V:** During this stabilizing phase, methane production will begin to decrease and the presence of atmospheric air will reintroduce aerobic conditions. This condition may occur only after several decades in shallower landfills. In deeper landfills, this stage may be reached only after many decades.

## ANNEX B: MONITORING PROGRAM FOR ENHANCED BIOREACTOR LANDFILLS

To monitor the development of the enhanced bioreactor landfill, operators must follow a specific schedule to check these leachate parameters from each landfill cell developed:

Monitoring these parameters will give valuable information about the level of biodegradation in each landfill cell and will indicate when the cell reaches the methanogenic stage, when it may be feasible to recover and utilize LFG.

To monitor LFG during infilling of waste, the LFG composition may be monitored by using a portable instrument and a probe to dig approximately 2 meters into the waste, though field measures are generally not accurate and should periodically be confirmed by laboratory analysis. The LFG monitoring should start when the leachate monitoring results indicate the development of methanogenic conditions. The results should only be used as an indicator of the methane content of the LFG to assess the potential for commercial utilization. During utilization, constant monitoring of the LFG should take place. At this time, the means of LFG utilization will dictate the monitoring parameters.

| <b>Parameter</b>       | <b>Acidic phase</b> | <b>Methanogenic phase</b> |
|------------------------|---------------------|---------------------------|
| pH                     | daily               | daily                     |
| COD                    | every month         | every 6 months            |
| BOD <sub>5</sub>       | every month         | every 6 months            |
| Iron                   | every month         | every 6 months            |
| Chloride               | every 6 months      | every 6 months            |
| Ammonia N (or total-N) | every 6 months      | every 6 months            |

| <b>Parameter</b>    | <b>Frequency</b>  |
|---------------------|-------------------|
| Methane             | every other month |
| Carbon dioxide      | every other month |
| Oxygen              | every other month |
| Nitrogen            | every other month |
| Barometric pressure | every other month |

## ANNEX C: LANDFILL MINING

The main objective of landfill mining, in most cases, is to remove an environmental impact (e.g., remediate an old dump), reclaim highly valuable real estate area (for building purposes), or recover new landfill volume (to extend the lifetime of a landfill).

Landfill mining can be carried out at a landfill when the disposed of waste reaches a good level of biodegradation and is stabilized (*see Annex A, Phase IV*). Exactly when this level is reached depends to a large extent upon the chemical and biological processes (e.g., moisture content, temperature, microflora, and compaction rate) in the landfill waste. The time period may range from 10 years for an enhanced bioreactor landfill to 50-100 years, or even longer for an open dump in semi-arid conditions.

After landfill mining, the reclaimed area may be used for the planned purpose. If the purpose of the landfill mining is to remediate an environmental impact, further groundwater remediation may be required, if contamination is still present.

Landfill mining is carried out by excavating the disposed of waste and mechanically segregating the different types of waste by tumble screening, ballistic screening, using magnetic separators, and other processes. The segregation often produces the following waste products: ferro-metals; demolition and construction debris; soil and ash; nondegraded (or incompletely degraded) organic material; plastics; and hazardous materials.

Metals and demolition and construction debris may be reused after contaminants are removed. Soil and ash will often be contaminated with waste residuals and will need to be re-landfilled.

Nondegraded organic (or partly degraded) materials and plastics may be combusted if appropriate incineration facilities are available, or otherwise, they may be re-landfilled. The nondegraded organic waste together with soil and ashes may be used as soil cover at a landfill. Hazardous materials should be treated in accordance with hazardous waste regulations.

Depending upon the level of recycling and other treatment, landfill mining may reduce the landfill's volume by 30-60%. In an ideal scenario, where the original waste was pre-segregated and hazardous waste is kept out of the landfill, it is possible to apply the soil, ash, and non-degraded organic material as growth media (e.g., as topsoil for a landfill) if they meet national standards for the use of compost materials. The amount of waste to be redispersed may then be reduced to as little as 10-20% of the original waste volume. (This is the philosophy behind some of the enhanced bioreactor landfill concepts).

Landfill mining has some direct environmental impacts, particularly those related to noise, odor, and dust and from the potentially higher generation of leachate at the open excavation areas. The degree to which leachate is generated during landfill mining depends largely upon the season for landfill

mining and the climactic zone in which the landfill mining takes place. The amount of time the landfill mining process exposes the locality to increased environmental impacts depends on the quality of excavation equipment and treatment facilities, degree of waste segregation, and the availability of new landfill space. For large landfills, the landfill mining process may take several years to complete, thus extending the period during which adverse environmental impacts can have effect. If the purpose of landfill mining is to remediate a dump, it is important to assess the environmental and health impacts from landfill mining versus the environmental impacts from other remedial actions.

It is also important that landfill mining always takes place under safe working conditions. Occupational health hazards associated with landfill mining are primarily airborne in nature and may range from instant dysentery-like (and highly epidemic) diseases to chronic respiratory diseases.

The costs involved in landfill mining vary significantly, depending largely upon the level of segregation and volume of waste to be mined. Investment and operation costs from Germany indicate a range of US\$60-US\$177 per m<sup>3</sup> of recovered landfill volume. Prices from a single landfill project in the United States show the cost for excavating and waste processing to be about US\$6/m<sup>3</sup>.

#### **ANNEX D: EXAMPLES OF COSTS AND BENEFITS FROM LFG RECOVERY**

Example 1--Denmark: A small LFG recovery plant was installed in 1990. Waste disposal stopped at the area with LFG extraction in 1989. The LFG utilization plant produces combined heat and power (CHP) at three smaller plants. The plants are highly sophisticated and fully automated, situated in different directions some 8km from the landfill. The Danish government has provided financial support to the project.

Example 2--Poland: This LFG recovery plant was established in 1996-97 with support from the European Commission. This plant is also an automated CHP facility, with the heat utilized in a nearby city's district heating system.

Example 3--Indonesia: This project is under preparation by a private consortium. The LFG recovery system planned for the landfill includes a manual monitoring and control system. The LFG recovery plant is expected to produce electricity for delivery to the public power grid.

Example 4--Latvia: This is a World Bank project under implementation. The landfill is planned as an enhanced bioreactor landfill with "energy cells." The initial project calls for generation of electric power, though later plans include a CHP plant to enhance a nearby district heating system.

|   | Units              | Example 1<br>Denmark <sup>4)</sup> | Example 2<br>Poland <sup>4)</sup> | Example 3<br>Indonesia <sup>5)</sup> | Example 4<br>Latvia <sup>5)</sup> |
|---|--------------------|------------------------------------|-----------------------------------|--------------------------------------|-----------------------------------|
| Amount of waste per year  | tonnes/year        | 70,000                             | 100,000                           | 700,000                              | 205,000                           |
| Total amount of waste (a)   | tonnes             | 800,000                            | 800,000                           | 5,700,000                            | 5,000,000                         |
| Annual gas production   | m <sup>3</sup> LFG | 4,000,000                          | 3,335,000                         | 22,000,000                           | 32,000,000                        |
| Power generator effect (b)  | kW                 | 825                                | 730                               | 4,500                                | 6,500                             |
| Annual predicted power production (c)                                     | kWh                | 6,600,000                          | 5,800,000                         | 36,000,000                           | 52,000,000                        |
| Annual heat production  | kWh                | 8,200,000                          | 7,300,000                         | 0                                    | 0                                 |
| Investment: Collection system   | US\$               | 295,000                            | 260,000                           | 410,000                              | 2,230,000                         |
| Investment: Extraction system   | US\$               | 735,000                            | 440,000                           | 1,300,000                            | 738,000                           |
| Investment: Transmission pipe   | US\$               | 355,000                            | 75,000                            | 0                                    | 0                                 |
| Investment: Gas engine/generator  | US\$               | 925,000                            | 690,000                           | 3,600,000                            | 4,157,000                         |
| Planning, design, engineering   | US\$               | 365,000                            | 365,000                           | 1,300,000                            | 160,000                           |
| Total investments (d)   | US\$               | 2,675,000                          | 1,840,000                         | 6,660,000                            | 7,285,000                         |
| Investment support for other source <sup>1); 2); 3)</sup> (e)             | US\$               | 295,000 <sup>1)</sup>              | 500,000 <sup>2)</sup>             | 0                                    | 5,120,000 <sup>3)</sup>           |
| Total costs for investor (f) = (d) - (e)                                  | US\$               | 2,380,000                          | 1,340,000                         | 6,660,000                            | 2,165,000                         |
| Investment costs per kW. installed<br>Exclusive economic support (d)/(b)  | US\$/kW.           | 3,200                              | 2,500                             | 1,480                                | 1,120                             |
| Investment costs per tonne of waste<br>Exclusive economic support (d)/(a) | US\$/tonne         | 2.45                               | 2.30                              | 1.17                                 | 1.46                              |
| Annual operation and maintenance costs                                    | US\$               | 125,000                            | 100,000                           | 500,000                              | 300,000                           |
| Total operation and maintenance costs<br>(20 years) (g)                   | US\$               | 2,500,000                          | 2,000,000                         | 10,000,000                           | 6,000,000                         |
| Sales price for electricity (h)   | US\$/kWh           | 0.080                              | 0.061                             | 0.054                                | 0.048                             |
| Annual revenue from energy sale (i) = (c)* (h)                            | US\$/year          | 925,000                            | 465,000                           | 1,900,000                            | 2,496,000                         |
| Total revenue per tonne of waste (k) = (20*(i))/(a)                       | US\$/tonne         | 13.2                               | 8.84                              | 6.82                                 | 9.98                              |
| Revenue balance with support (k) - (((f)+(g))/(a))                        | US\$/tonne         | 7.10                               | 4.66                              |                                      | 8.35                              |
| Revenue balance w/o support (k) - (((d)+(g))/(a))                         | US\$/tonne         | 6.73                               | 4.04                              | 3.89                                 | 7.32                              |

<sup>1)</sup> Supported financially by Danish Government

<sup>2)</sup> Investment supported by European Commission

<sup>3)</sup> Grant from GEF

<sup>4)</sup> In operation

<sup>5)</sup> Under preparation