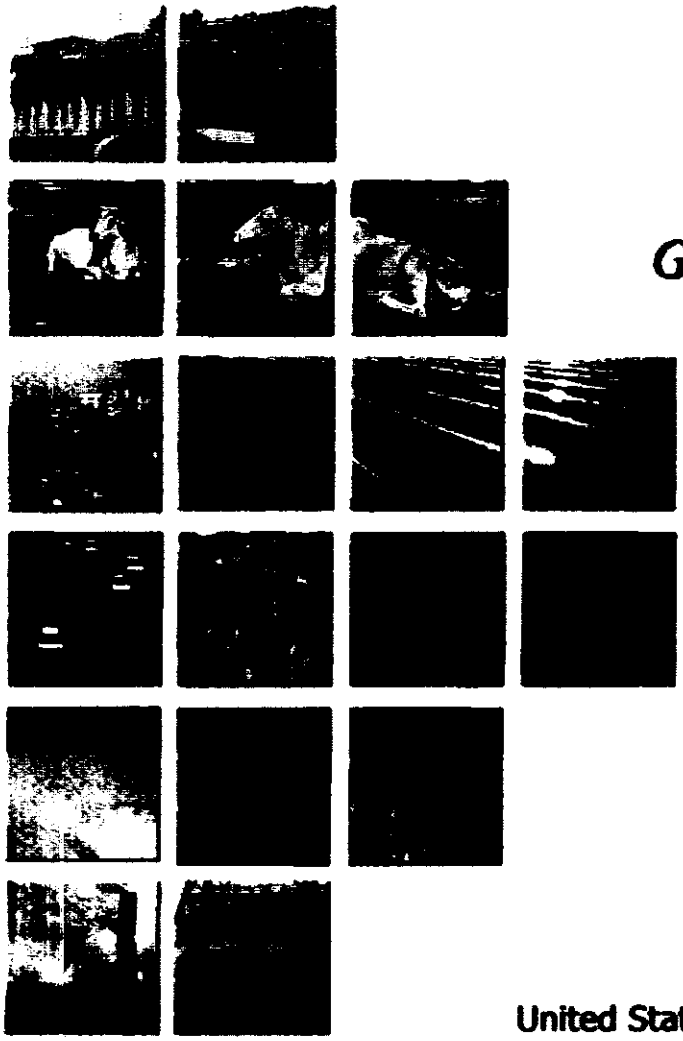
PN-ACY-135

CLIN 8: Methane Emissions and Re-Use Potential in Cities

Subtask 8.D Project Site Selected and Project Design Submitted to CTO



Greenhouse Gas Pollution Prevention Project - Climate Change Supplement

A Program of the:

United States Agency for International Development / India Mission

Implemented by:

The Louis Berger Group, Inc.
Global Environment Team

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B

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EXECUTIVE SUMMARY

I. Background

The Greenhouse Gas Pollution Prevention Project – Climate Change Supplement (GEP-CCS) was initiated in May 2000. Funded by the United States Agency for International Development/India Mission (USAID/INDIA), the project is being implemented by the Louis Berger Group Inc. (LBG) Global Environment Team. The main purpose of the project is to provide technical assistance to build capacity and facilitate demonstration projects that result in the reduction of greenhouse gas (GHG) emissions. The project has six components covering emission reduction initiatives in various sectors including industry, utilities, transport and municipal solid waste management.

This report focuses on the adoption of improved solid waste management practices by municipalities, which would lead to a reduction of methane emissions from landfills. Specifically, the report addresses the planning and design of a sanitary landfill project in a select city involving proper management of municipal solid waste for the reduction of methane gas, a major contributor to climate change. The report looks at methane recovery, flaring and reuse, among other options.

This report is the third in a series of four reports on the reduction and reuse of methane emissions from municipal solid waste.

a. Training Needs Assessment

As part of the first activities, a training needs assessment (TNA) was conducted in February 2001 by LBG/GEP-CCS with the support of Global Energy Partners (Global). It was aimed at enabling the development of a detailed training plan for municipal authorities and other organizations engaged in solid waste management activities. The TNA was conducted at five cities, namely Pune, Chennai, Bangalore, Guntur and Jaipur. The choice of cities was determined by the potential for methane recovery and reuse in these cities, and level of interest demonstrated by the city authorities to USAID/INDIA, in connection with various urban infrastructure and environmental initiatives.

The interactions with the city authorities revealed a significant lack of understanding about composting and waste-to-energy (WTE) projects, including landfill methane recovery and reuse and biomethanation. Moreover, there appeared to be concerns about ways to comply with the then recently released "*Municipal Solid Wastes (Management and Handling) Rules, 2000*" by Ministry of Environment and Forests (MOEF). Subsequent consultations with a variety of officials at the GOI, state and local levels, as well as program experts from USAID/India confirmed these information and knowledge gaps amongst municipal authorities. Accordingly, it was decided that the training content would provide more emphasis on the fundamentals of integrated solid waste planning and management; this would serve as a prerequisite to capturing benefit from utilizing solid waste for productive purposes, including methane gas recovery and reuse.

b. Training of Municipal Authorities/Urban Local Bodies Across India

Based on the TNA conducted in February 2001 and subsequent discussions, LBG/GEP-CCS designed and conducted a series of trainings entitled *"Tools for Improved Solid Waste Management and Treatment"*. The trainings were held at Chennai, Jaipur and Ahmedabad in December 2001, in partnership with the Tamil Nadu Urban Development Project (TNUDP), HCM Rajasthan Institute of Public Administration (RIPA), and City Managers Association of Gujarat (CMAG) respectively (all three of which have strong linkages with the USAID RUDO and FIRE projects).

The training plan encompassed several components relating to the fundamentals of MSW management, MoEF guideline compliance, waste treatment options with a focus on landfill methane mitigation/ recovery and approaches to project development with private sector participation. Apart from international experiences, studies were also presented by project developers working to implement WTE technologies in India. The perspectives of MNES, CPCB and state PCB's were included through presentations made by their respective representatives.

Concurrently with the trainings, GEP-CCS organized a National Roundtable on solid waste management and disposal practices which was attended by over 200 delegates from cities all over India.

As an outcome of these activities, MSW management officials are now much better informed and positioned to develop and implement strategies for MSW management that meet MOEF requirements while simultaneously mitigating methane emissions from MSW. In addition, participant input helped GEP-CCS identify opportunities for high impact, technical assistance in the subsequent subtasks of the project's methane mitigation component.

II. This Report: *Planning and Design of a Demonstration Project*

Following the training series, a representative project was required to be developed for methane recovery and reuse, including specific design aspects related to measurement, monitoring and verification of methane emissions from a selected landfill/ municipal waste site. The project was also required to explore potential funding options for the GHG emission reductions achieved.

The feedback received in the course of the training activities, the roundtable and the interactions with other institutional players had, however, revealed that the solid waste management (SWM) practices currently prevalent in most cities were incapable of ensuring systematic collection of waste, its transportation and disposal/treatment in a manner that is financially or environmentally sustainable. This was attributable to several lacunae, some of the more significant of which were as follows:

- Information gaps on appropriate landfill designs/ specifications and associated costs for Indian conditions
- Lack of regulatory clarity, specifically with respect to the MOEF guidelines on SWM

- Ambiguities in institutional responsibilities for solid waste management between various agencies at the local, state and national levels
- Inadequate funding sources
- Constraints on land availability

Development of a methane recovery and reuse project from nascence, in such a context, was considered premature, more so given that first time landfill-gas related transactions require a significant amount of organizational learning on technical, logistical and commercial aspects.

Accordingly, discussions were held between the LBG/GEP-CCS team and USAID/India, and it was agreed that the focus of the demonstration project assignment needed to be reoriented to suit the ground reality so as to create the most impact for urban managers in India. The consensus that emerged was that the demonstration project would take a holistic approach looking at integrated solid waste management, with nonetheless, a clear introduction to the GHG emission reduction aspects of a MSW project.

The overall aim of this phase was therefore to take the training implemented in the preceding stages to the next level by actually working with one city (a) to build the capacity for and to provide the technical assistance to complete an integrated SWM project, and (b) to provide guidance on incorporating GHG emissions reduction planning into municipal landfills.

a. Site Selection: Municipal Corporation of Bangalore

Subsequent to consultations with key stakeholders, and other program experts in the USAID/India Regional Urban Development Office, the city of Bangalore was selected by the LBG/GEP-CCS Project for implementation and technical assistance of this phase. The choice of the city was determined by the following factors:

- The city authorities were seen to be proactive and working with a local project developer in designing a sanitary landfill
- Landfill gas recovery/ reuse options were already being explored for the new sanitary landfill
- Preliminary GHG emission reductions were being incorporated into landfill planning strategies and design
- Involvement of key municipal stakeholder representatives namely, Bangalore Action Task Force and iDECK[1]
- Full adoption and response to the MOEF's municipal waste management directives of 2000

Most important however, was the on-going initiative on the part of the Bangalore Municipal Corporation, in partnership with BATF and iDECK, to develop two composting sanitary landfill projects that would properly treat and dispose of the city's municipal solid waste. The landfills

[1] A joint venture between IDFC, HDFC and the Govt of Karnataka, with a mandate to develop infrastructure projects through private participation, assist in project development and undertake investments in projects.

were to be developed at the sites, Kannahalli and Kyalasonahalli, with a capacity of 800 and 600 MT mixed MSW / day respectively. An independent project consultant – Mahindra Acres Consulting Engineers (MACE) - had been appointed, and had carried out detailed technical feasibility studies for the two sites. As part of the same, processing technologies had been evaluated along with detailed costing and design. The financial viability analysis had been performed by iDECK, and was being followed up by preparation of the project documentation for private participation. The two project proposals were therefore seen to be at an advanced stage of planning and potential financing.

An association with the GEP-CCS project with the above initiative was considered desirable for two reasons. Firstly, it would enable the technical assistance to be directed to a project(s) with a greater probability of being implemented, thereby reducing the risk of the TA investments getting lost due to the inability of the targeted local urban body, and/ or project promoter to carry an initiative through to implementation. Secondly, the involvement of iDECK, a financial intermediary, would help address a serious constraint in the Indian context, namely that of project funding. Given that one of the objectives of this phase was to explore funding options for the project, the involvement of a potential investor – iDECK - from the inception of the proposal, greatly added to the attractiveness of the initiative. As a further step, discussions were also initiated with IDFC (iDECK's promoter) to explore possibilities of earning carbon credit revenues for the project. In addition to these reasons, the fact that the projects were to be based on private sector participation suggested an approach/ model with greater potential for being replicated in other cities.

b. LBG/GEP-CSS Technical Assistance to IDECK and BMC

Through consultation and discussions with iDECK the LBG/GEP-CCS team assistance on the project design was defined:

- To provide TA to BMC in the design phase of the project.
- To review and identify information gaps with respect to GHG mitigation, in the detailed project reports prepared by MACE. These project reports would be the basis for developing the bid documents.
- To provide a discussion of "best practice" for GHG mitigation, including measurement, monitoring and verification, and technologies that could be applied to these and other landfill sites in India.

The TA on the project was ongoing during 2002 in various inter-actions with IDECK, including providing IDECK with opportunities to increase its knowledge on the various aspects of GHG emissions, greenhouse gas mitigation project development and carbon accounting. The review of the project documents was performed in July-August, 2002 by the LBG/GEP-CCS team which consisted of the LBG/GEP-CCS technical team, in association with Global Energy Partners, LLC (Global).

The review yielded several insights on GHG related issues required to be addressed as part of the landfill design, and highlighted specific information gaps that needed to be addressed in future planning exercises. The experience also generated inputs that would enable the preparation of appropriate toolkits/ manuals for use by municipalities/ other stakeholders to incorporate GHG mitigation into landfill projects.

The draft report prepared was then presented to IDECK and BMC for comments from their technical team, so that these comments could be taken into consideration before the final report was submitted. The final report then served as a guide and a reference to inform the BMC and IDECK as they prepared the project for the GoI approval process and the project bid documents were developed.

Importantly, this assistance provided an opportunity to sharpen the understanding of the key elements required to be addressed by future technical assistance for improving waste and landfill design and management in India – a prerequisite to any subsequent value added use of municipal waste, including that of methane emissions recovery and reuse.

c. *Demonstration Project Report: Project Review and Resource Guide*

The overall report and findings, included in the following sections, have been organized to cover and address the following:

- **General Review of IDECK Detailed Project Report**
  The General Review includes the observations and identification of technical information gaps in the IDECK Project Reports, in regard to greenhouse gas (GHG) mitigation. The review section also provides a discussion of "best practice" for GHG mitigation, including measurement, monitoring and verification, and technologies that could be applied to these and other landfill sites in India. The review was done based on "Detailed Project Reports" completed for the Kannahalli and Kyalasonahalli sites in Bangalore by Mahindra Acres Consulting Engineers (MACE). The MACE Report may form the basis for developing a tender for the future implementation of these projects.

- **Landfill Design, Gas Collection and GHG Emissions**
  An illustrative recommendation and general practices are included in this section discussing sanitary landfill design, gas collection systems and energy project or methane recovery and reuse project.

- **Best Practices for LFG Recovery and GHG Mitigation**
  The Best Practices section provides a brief supplement LFG Recovery and GHG Mitigation and recommends suitable practices for GHG mitigation efforts at these landfills with a guide to additional international resources and information. These include:

  1. Measurements of methane emissions for monitoring, verification and modeling purposes;
  2. Expected gas emissions based on applicable models to the Indian situation;
  3. Gas recovery from the landfill, flaring equipment, potential for utilization;
  4. Microbial methane oxidation as an alternative to gas collection for GHG abatement oxidation.

- **Resource Guide for Future Operations**
  This resource guide is intended to provide some insights into the GHG mitigation process for MSW and landfill to gas operations. First a guide is provided for the typical steps that can be followed for the project development process. A calculational tool is provided based on the review conducted for the Bangalore projects. Several examples of LFG case studies from developing countries and the US are then supplied. Lastly, suggestions are provided for future MSW and LFG training activities along with recommendations for Indian municipalities. Annex A provides a listing of background information that is highly recommended for reference use as municipal officials initiate the process of developing landfills for compliance and GHG mitigation.

III. Demonstration Project Status: *Results of the LBG/GEP-CCS Interventions*

After receiving the final required GoI approval for the project, on March 7, 2003, the Bangalore Municipal Corporation issued the tender notification inviting interested parties to purchase/submit qualification documents for the landfill project. A copy of the notice that appeared in the "Times of India" is attached under Appendix: 1

Appendix 1.

Tender Notification

BANGALORE MAHANAGARA PALIKE
TENDER NOTIFICATION

No. EE/SWM/PR/518/2002-03 Dated : 06-03-2003

DEVELOPMENT OF WASTE PROCESSING & ENGINEERED SANITARY LANDFILL FACILITIES

Bangalore Mahanagara Palike (BMP), invites applications from interested parties in accordance with the Request for Qualification (RFQ) Document in order to shortlist competent parties who could subsequently bid to develop, operate and maintain a municipal solid waste processing and engineered sanitary landfill facility (the Project) under a long term Build, Operate and Transfer (BOT) Concession.

The RFQ Document containing the project profile, instructions to applicants and criteria for evaluation may be obtained from the office of :

V.P. Ikkeri, Deputy Commissioner (Health),
Bangalore Mahanagara Palike, N.R. Square,
Bangalore - 560 002, India Phone : 2248364,
Fax : 91-80-2128531 E-mail : commissioner@blrbmp.com

Cost of RFQ Document (Inclusive of taxes) :	**Rs. 5000/-** (Rupees Five Thousand only for US $110/- (USD One Hundred and Ten only) in the form of a crossed demand draft (non-refundable) drawn in favour of The Commissioner, Bangalore Mahanagara Palike, payable at Bangalore, India.
Date of issue of RFQ Documents :	From **10th March-2003** upto **31st March - 2003** between 10.00 AM to 5.30 PM on all working days.
Pre-bid conference meeting :	**At Mayohall**, Residency Road, Bangalore on **16th April 2003** at 11.00 AM IST.
Last date for submission of Application (Application Due Date)	**April 30, 2003 upto 1700 hrs IST**

The RFQ Document can be obtained by post / courier upon a written request addressed to **V.P. Ikkeri, Deputy Commissioner (Health), BMP** from the above mentioned address along with a demand draft for the total amount payable towards the cost of the document and additional postal expenses of **Rs. 150/-** (Rupees One Hundred and Fifty Only) for delivery within India, and US $44/- (USD Forty Four Only) or **Rs. 2000/-** (Rupees Two Thousand only) for delivery outside India. BMP will not be responsible for any delay, loss or non-receipt of RFQ Document sent by Post / Courier.

Sd/-
V.P. Ikkeri,
Deputy Commissioner (Health)

1.0

Introduction

1.0 INTRODUCTION

The overall objective of this project is to provide guidance to municipalities who wish to incorporate GHG emissions reduction planning into municipal landfills. While current estimated methane emissions from MSW sources in India are relatively low, there is an opportunity for addressing future growth in emissions at an early stage. Using the IPCC (1996) default values of 45 kg methane / MT of waste (65 m3/MT), and 0.35 kg MSW/head/day gives an annual emission of some 5.7 kg CH_4/head (for 1995). Stated differently, annual India-wide production of 30.5 million tons of MSW by the urban population yields about 1.4 million tons (Tg) of methane, or, at conversion of CH_4 to CO_2 of 21 on a weight basis, about 30 milion tons of CO_2 equivalent. Garg et al., 2001, using these default values and estimates, calculated 1.8 Tg of methane from MSW (probably based on a higher MSW generation figure). This estimate (1.8 Tg methane) is currently some 10% of total projected Indian anthropogenic methane emissions, and is equivalent to almost 40 million tonnes of CO_2 emissions, or 3% of total Indian GHG emissions, however, given the current method of disposal for Indian MSW, which is mostly disposed of using open dumps and burning, rather than anaerobic landfills actual greenhouse gas emissions would likely be much higher than presently estimated. With rapidly growing MSW generation (some 50 million tonnes are estimated to be produced currently), waste composition changes, and increasing efforts at MSW collection and disposal, GHG emissions from MSW could increase significantly in the future.

Most importantly, however, the rapid development of this sector due to new MSW disposal regulations coming into force, provides opportunities for timely technological and market intervention to reduce GHG emissions modest costs. Indeed, large capital investments are being contemplated for MSW disposal, and in some cases, advanced technologies are being considered that are not yet used in more developed countries. Thus, this is an opportune time to develop projects that have potential for GHG mitigation.

Bangalore, one of the top ten cities in India in terms of population, has identified five potential landfill sites. At two of these sites, Kannahalli and Kyalasonahalli, iDECK and MACE propose to establish sanitary landfills (of 800 and 600 MT mixed MSW/day capacity). These landfills will incorporate sorting, composting, and landfill operations. Two "Detailed Project Reports" were prepared for these sites, and these reports are the subject of the present review. The two projects and reports are essentially identical, except for the smaller size of the compost plant at the second site and the lower level of detail of that (Kyalasonahalli) Report. **Thus, herein only the first, the Kannahalli, Report is addressed, except as otherwise stated.** The present review provides "expert opinion" on these Detailed Project Reports, specifically as these relate to GHG emissions.

As all aspects of the design and operations of the proposed MSW composting and landfilling operations can potentially impact GHG emissions, either positively or negatively, these are reviewed in some detail. In Section 2, general issues and comments related to the technical aspects of the projects are covered, while Section 3 deals more specifically with GHG related issues, including collection and abatement methods.

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Section 4 discusses current "best practices", including modeling, measurement, monitoring, and verification of GHG emissions from both the landfills and composting operations, as well as innovative approaches, specifically the use of MSW compost to promote microbial oxidation of methane in the landfill cover prior to landfill closure and, for longer-term GHG mitigation.

2.0

GENERAL REVIEW OF THE DETAIL PROJECT REPORTS

GENERAL REVIEW OF THE DETAILED PROJECT REPORTS

2.1 Waste Quantities and Composition

The Report states that Bangalore, with a population of 4.3 million, produces some 2,425 MT MSW/day, or 920,000 MT MSW /yr, or almost 0.6 kg/person/day. However, Moulik (2000) quoting a CPCB (Central Pollution Control Board) survey of 1997, gives a waste collection for Bangalore of 2000 tons (800,000 MT/yr), or about 0.5 kg/person, the general figure given for cities of this size. The Hindu Times (January 2, 2002) reports a current waste collection of 2,200 tonnes daily. Overall these figures are reasonably close and need not be further discussed.

The Kyalasonahalli site is to collect garbage from about 1.75 million people, for a total of 600 MT per day (some 0.34 kg person/day), and the Kannahalli site, about 800 MT/day from about 2.54 million people (0.315 kg/ person/day). Looking at the individual ward data provided in the reports, MSW generation rates range from as little over 0.1 to almost 1 kg/person/day. Some variation in collections would be expected depending on neighborhood (e.g. settlements, commercial districts, etc.), but overall this seems to be rather a large range in volume. Demolition debris, hospital wastes and industrial wastes from organized collection will not be included in the MSW delivered to these plants. Both rapid population growth and increasing per capita MSW generation is foreseen, with an annual increment of 4% in MSW collection. The municipality is in process of adding additional landfill sites and it is anticipated that one or more of the additional sites will be online to handle the growing volume. Thus, the design of these systems is based on receiving only the above stated initial levels of wastes, 600 and 800 tons /day respectively, for the entire duration of the projects (e.g. the life-time of the compost plants), and any additional wastes being produced should not affect the conclusions set forth in this report.

The composition of MSW is critical to determining potential GHG emissions. One gap in the report documents identified is the lack of specific information for Bangalore MSW; only generic information is provided.

1. Page 2-2 (also 4-8) states "India waste has 30 to 40% organic matter on a dry weight basis, which along with a moisture content of 50%, makes it some 60 – 80% component of the wet waste stream". We believe this calculation could be in error and should be reexamined and potentially reversed.
2. Composition Table 2.3, from a NEERI (1995) study, provides data on the "physical characteristics" MSW as a function of the population sizes. Although the numbers are given with a precision of two decimal places, statistical information is not provided, the data appears variable, is not normalized (e.g. to 100%), and no trends are apparent when going from smaller to larger population centers. The largest differences are between the population centers of from 2 to 5 million (n =3) and over 5 million population (n= 4), with "compostable matter" of some 57% and 31% (wet weight basis) respectively, which is almost a two-fold difference.

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3. Table 2.3 provides data on "waste as physically seen", with "organic matter" at 78% (comprising leafy biomass, fruits, vegetables, lawn clippings, fodder, food residues, animal wastes), with paper at 3%, textiles at 2%, "coconut" at almost 3%, leather about 3% and plastics listed at almost 4%. The remaining "non-biodegradables" were only 6%. In our opinion, the latter is a rather low figure for Indian MSW, which typically has inerts of over 25%.
4. Table 2.7 presents "composition of Indian MSW", which lists "biodegradables" at 52%, earth (stones, rubble, sand, etc.) at 31% and paper at 5%. No moisture content is provided.
5. Table 3.16 provides a "Profile of Solid Wastes", based on other data, and gives some ranges: organic matter 60–75%, mud, dust ash, 15 –20%, paper 5 –10%, plastic 5 – 10%, glass 3-6% and others at 2-5% (ranges total to 90 – 126%). "The waste also has high moisture content".
6. Table 4.3 provides "physical composition" ranges, lists additional categories, such as "garbage" at 16 –20%, leaves 14-16%, coconut shell 5-6%, paper 5-6%, plastic and rags 10-12%, textiles 2-3%, ash and silt 25-30%, stone 1-2%, earthenware 8 –10%, and ignited coal 5-6%.
7. Other data, this time from CPCB for Indian MSW, suggests a composition of some 40% vegetable wastes/leaves, 4% grass, 1% paper, 1% plastic, 1% metals, 1% glass, 42% stones and ash, and 12% miscellany (add to over 100% due to rounding up to 1% the minor constituents).
8. Ramin Yazdani, in his TNA Report on Bangalore, gives the following composition: Combustible 30%, paper 3%, plastic 3%, metal 2%, glass 2%, "recyclables" 20%, rock and dirt 30%, and miscellaneous 10%. The moisture content is given as 40% and the density as 420 kg/m3. This is, again, not Bangalore–specific waste but a generic Indian waste composition. (He also mentions other data, including a "rock and dirt" content of almost 40%).
9. Chemical composition in Table 4.2 gives a moisture range of 40 –50% and organic matter of 30-35%, a C content of 15 – 20% and C/N ratio of 25 – 40. Elsewhere (pages 4-22 and 6-77) the refuse composition is given as 50% organic fraction, with 50-55% carbohydrates and 5% protein.
10. Bulk density is variously given as 400 to 600 Kg/m3 (Table 4.2) or 1,000 Kg/m3 (in situ) (page 4-22, 6-76) or as 400 Kg /m3 on page 7-23, which details the composting operation. Bulk density of composted material going to the landfill is stated as 700 Kg /m3, while MSW going directly to the landfills (presumably demolition debris and such) has a density of 1,200 kg/m3.
11. The calorific value for MSW is quoted as "only 800 to 1,400 Kj/kg". This is a wide range. Table 2.5 quotes a range of 800 Kj/Kg (for the largest cities) to 1000 Kj/Kg (for small municipalities). This is a more plausible range, and a 900 Kj/Kg average is probably appropriate.
12. There is little quantitative information to support the moisture content, which is perhaps even more site- specific than composition. Both reports indicate that "the waste generated in Bangalore has high moisture content." The average annual precipitation is some 97 cm (38 inches), which puts this location at a moderately wet climate. However, more detailed information in this regard would be appropriate and necessary for more accurate GHG emission calculations.

In conclusion, there is limited information available on Bangalore, or even of generic Indian MSW composition on which a quantitative analysis of GHG emissions should be based. Comparing data from different studies is not possible in this instance as each data set uses different terminology, and provides no information about methodology or statistical significance, which make comparisons highly challenging. One of the important issues for future work would be to gather data on actual MSW composition. We do know that that Indian MSW has lower heat of combustion, less paper, less metals, less plastic, less glass, but more food wastes, higher moisture content, and more inerts (soil, dirt, etc.) than U.S. garbage. It will be difficult, therefore, to project GHG emissions from this and similar projects without gathering more specific information.

2.2 Waste Composition

For the task at hand, we assumed the waste composition for Indian MSW, as identified in Table 1. It should be noted that this is not meant to be an actual or even as a representative example, only our best estimate of what type of waste may be present in Bangalore. Note that we do not consider the effect of monsoons on the waste composition, when it would be wetter. One recommendation is to measure Bangalore MSW during the operation of the compost plants. However, for the present "first cut" analysis the data in Table 1 should be adequate. It should be noted that MSW composition data for the U.S. can also be rather variable and uncertain.

TABLE 1:
ASSUMED MSW COMPOSITION FOR BANGALORE

COMPONENT	% Total MSW	% Moisture Component	Dry % Total MSW	H_2O % Total MSW	% Dry Basis of MSW
Food Waste	40	66	13.6	26.4	23.8
Garden Waste	15	60	6	9.0	10.5
Paper Waste	5	25	4	1	7.0
Plastic	4	0	4	0	7.0
Textiles	3	20	2.4	0.6	4.2
Wood	4	25	3	1	5.3
Metals	2	0	2	0	3.5
Glass/Ceramics	2	0	2	0	3.5
Ash, Soil, Dirt	25	25	20	5	35
Other Inerts	none	0	0	0	0
TOTAL	100	--	57	43	100

TABLE NOTES:

1. The above compositions are somewhat low on moisture (typical moisture may be closer to 50% and would be even higher in the monsoon season)
2. For comparison: U.S. waste has some 9% food wastes, 19% garden wastes (though these are probably less degradable than Indian garden wastes), 33% paper, and 7% other organics.
3. Ultimate methane production yields for this waste composition is about 35 m3 of methane /MT, approximately 40% of the ultimate methane yield of U.S. wastes.

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2.3 Composting Operations

The Bangalore MSW projects contain composting operations and attached landfills to handle the initial rejects and post-composting remnants. The composting process determines the amounts and biodegradability of the wastes landfilled and their GHG emissions potential. Also, composting itself is potentially a source of methane emissions (see Section V). Due to the central nature of the composting systems to these Projects, they are addressed in some detail and discussed in terms of their potential impacts on GHG emissions. (See also Ramin Yazdani, TNA Report of his site visit of February 14, 2001 to Bangalore).

The Karnataka Compost Development Corporation (KCDC) has almost 25 years experience in composting MSW in Bangalore, and thus the technical and commercial viability of this operation is well established. However, we noted that the windrows described in the MACF document seem to be somewhat larger than those observed during the February 2001 site visit by Ramin Yazdani. A minor point: Chapters 4 and 5, describe using bacteria for "bio augmentation" with "specially developed innocullam [sic]" (pages 4-88, 4-89, for examples). Herbal extracts are also to be used for odor control. We are not aware of any scientific evidence for the efficacy of adding any bacterial cultures or herbal extract to improve composting processes and thus might recommend against their use. One issue is the fraction of MSW handled by the compost operations. Page 5-2: "....composting can handle up to 30 to 60 percent of a city's MSW stream..." The fraction of MSW landfilled, out of the 800 MT/day handled by this facility (Kannahalli) is given as 15% (120 MT, Option 1) to 30% (240 MT, Option 2), with a density of 1.2 MT/m^3. To this is added the composted MSW rejected during final processing of the compost, given as 105 MT (Option 1) and 70 tons (Option 2), with a density of 0.7 MT/m^3. The daily total loading on the landfills would then be some 225 MT (250 m3)/day for Option 1 and 310 tons (300 m^3) /day for Option 2, summarized in Table 2:

TABLE 2:
COMPOSTING AND LANDFILL FLOWS AT KANNAHALLI

Option	MSW	Total MSW	To Landfill	To Compost	To Landfill	Compost Remnants	Compost Remnants	Total Landfill	Total Landfill
	TPD	TPY	TPD	TPD	TPY	TPD	TPY	TPY	m3/yr
1	800	292000	120	680	43800	105	38325	82125	91250
2	800	292000	240	560	87600	70	25550	113150	109500

It should be noted that the fractions of MSW actually composted (as documented in the Reports) is some 85% to 70% of the incoming MSW, which appears on the high end and perhaps higher than stated current experience and practice. Composting reduces the weight of MSW by some 50%, though perhaps the remnants are less reduced in weight. The lack of information on the composition of the rejects or remnants is a gap identified in the report. Overall the design assumptions appear to tend towards a "best case

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scenario". The experience of the KCDC in composting Bangalore MSW should be reviewed for an 'everyday' scenario.

"The performance of composting units in Bangalore has been a mixed bag" (Page 3-31). Although not amplified in the Report, we understand this to be due to problems with compost quality, inherent with MSW, due to lack of initial segregation or separation, which results in plastic, glass and metal in the compost. Marketing has also been difficult with MSW compost with prices (page 3-31 to 3-33) being about 1,000 Rupees/MT (see also Yazdani Report). However, the Reports (e.g. Chapter 9, elsewhere) states sales price of some 1,550 (US $31/MT), escalating some 12% every two years. However, these matters are not further addressed here. There is not discussed the type of waste that would be landfilled, in either option. The plant design and process economics (Chapter 9 "Estimated Cost of Operations") are based only on Option 2.

The compost process is assumed to be completed after 6 weeks (42 days), and there is little provision for curing and storage of compost on-site. More land is being acquired, which is needed to expand the compost operation to the full 680 TPD, as the present Kannahalli site only accommodates some 500 TPD. The plan is not to increase the flows to these sites over time. The calculations for the volume of windrows, in our opinion, appear to have been overestimated by almost two-fold in the Reports (the actual number is about 12 m3/linear meters, rather than the 23.5 m3/m stated on page 7-23, line 6). The exact value depends on the actual shape of the windrow (e.g. hemispherical or straight side with dome, as shown schematically on page 7-23). Thus the composting operation may require about twice the area anticipated. This calculation should be checked. (Yazdani reports that KCDC operates a 350 MT/day composting plant on 15 acres now). Also the windrows appear to be rather large in comparison to best practice windrow size.

The stated quantity of the "Digested Garbage" produced is given 364 TPD, at some 900 Kg/m^3, an almost 50% by weight and 70% by volume reduction. In our opinion, this result seems to be significantly overstated. The digested garbage is then processed by two stages of trommel screens to separate recyclables, producing 336 TPD of "Semifinished Goods" and finally 280 TDP "Finished Goods". The loss fractions are re-digestables (to be ground and returned to composting) and "remnants", which are landfilled. From this basis 80% of the MSW is "biodegradable" and composting will reduce the total weight of that fraction by 50% (Chapter 9). This calculates as a decrease in some 84 tons due to the processing of the "Digested Garbage". However, the Report (Table 8.4) states that the "remnants" from the composting plant that are to be landfilled amount to 105 TPD (year one, Option 1) or 70 TPD for Option 2. These mass balances appear inconsistent and should be rechecked.

From a GHG perspective, these are passive windrow composting operations, which apparently are only turned once a week. The large size of the windrows, their compaction, and infrequent turning, suggests that passive air diffusion will be the limiting factor (as it always is for passive systems), and there will be problems with odors and time to completion. The greatest impact, however, may be on compost quality, which is critical for its marketing. Sufficient experience exists in India, and Bangalore, to allow

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an in-depth discussion of these processes. From a GHG perspective, the major issue is the amount of methane gas that would be generated from the compost piles, as well as the fraction and methane potential of MSW that will be landfilled, both unknowns and further discussed in the next section of this report.

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3.0

Landfill Design, Gas Collection and GHG Emission

3.0 LANDFILL DESIGN, GAS COLLECTION AND GHG EMISSIONS

3.1 Landfill Design: Size and Longevity of the Landfills

As was the case for composting, the background discussion of the landfill designs (Chapter 6, 100 pages) is generic and lacks practical detail that will be essential as the projects proceed. One statement, on page 6-76, proffers that: "It has been estimated that 150- 250 m^3 of landfill gas is produced per ton of MSW". Actually, we believe that this generic value is applicable for U.S. MSW. Based on a detailed review of the literature and on LFG production data for 19 U.S. landfills, Vogt and Augenstein (1997) estimated about 175 (150 – 200) m^3/MT of LFG produced per ton of MSW. We estimate (see also Table 1) that Indian MSW would produce less than half as much LFG, some 70 (50 to 90) m^3 LFG/MT, or 35 m3/CH_4/MT waste (LFG is 50/50 CH_4/CO_2).

In Chapter 8 the landfill volumes are given as 41,634 m^2 (about 10 acres) plus another 22,673 m3 for infrastructure (road, leachate pond, dirt piles, etc.). The excavation depth is 5 meters below grade and the average embankment height 13 m above grade (5 to 21 m range). The available volume for waste deposition is given as 678,722 m^3 (after allowing 10% for soil cover and 10% for compaction). From Table 2, a lifetime of 6.2 to 7.44 years is projected. (The Kyalasonahalli site is somewhat larger and with less MSW composted its life expectancy is longer). The daily cells would be a paralled piped some 25 m long x 5 m wide and 2.5 m high with a 3:1 slope at the face, or some 124 m2/day (for 310 m3/ day of waste as received, page 8-14, vs. 300 m^3/d calculated above for Option 2 – this is a small discrepancy).

At 10% of the total volume, the soil cover is rather modest. A rule of thumb is that daily soil covers require closer to 25% of the landfill air space, plus intermediate, pre-monsoon and final soil covers. Another point is the expected density of the waste, which appears high for the rejects and even for the remnants. There is no discussion of the compaction required, for which several passes of heavy equipment are needed. These issues should be further addressed in the final design, which should also consider increasing landfill capacity by "piling it higher and deeper". These issues are beyond the scope of the present report, but should be mentioned as they pertain to the GHG emission.

A best practice recommendation is that the daily cover should not be soil, but, rather, composted MSW remnants. The source separated /rejected MSW would be placed first in the daily cell, then compacted, followed by the compost remnants and further compaction. MSW compost is being used extensively in the U.S. (in California) for daily cover, and has been permitted by the state's solid waste regulatory authority. It is effective in preventing vectors (birds, rodents, etc.), odors and wind dispersion of waste. Perhaps most important in the present context, it is plausible that this composting cover, if provided with adequate initial moisture, will be an effective barrier to GHG (methane) emissions from the landfill. Indeed, about half of the methane from the landfill will likely be released before the final capping of the landfill. This is discussed further in

Section 4. The excess excavation dirt, most of which does not appear to be used as soil cover in any event, may need to be disposed of.

The life of the landfill calculated as 6.2 years for Option 2 (the default option for the economic calculations), could be considerably shortened if the rejects or remnants are greater than assumed or if the compost plant has down-times or problems, or if the densities are not what they are expected, or if compaction is not as efficient, or if soil covers (if used) are of greater depth, etc.

More importantly, there appears to be a discrepancy between the designs of the compost plant which is given as 700 tons, while for Option 2, the basis for economic calculations, only some 560 TPD of waste is actually to be composted. Considering the mixed success of other compost plants in India, and other available information, there is a high probability that much greater amounts of MSW would be actually diverted to the landfill. As per the MACE document, the composting plant is to produce compost at only 60% of capacity the first year, going up to 70% and 80% in years 2 and 3 (see Table 9.10), staying at that level thereafter (e.g. Chapter 9), though it is not clear from assumptions what the basis for this figure is. The excess material would need to be landfilled. Calculating the exact adjustments is not necessary, but it is clear that these factors significantly reduce landfill longevity, unless less MSW is delivered to the plants initially. The issue of landfill longevity is not further addressed.

Another issue is the density of the waste. The remnants are given as a 0.7 MT/m^3 with the other waste "unit weight of civil debris, etc." given a density of 1.2 MT/m^3. This compares to raw mixed MSW at 0.4 MT/m^3 and a final compost product at 0.9 MT/m^3. We assume that the basis for these landfilled densities are after compaction but that is not stated. These estimates also appear on the high side. Table 8.7 and Page 8.8, characterize the MSW being diverted to landfills "civil debris, etc.", but that appears not to be the case. It is reasonable to assume that the material diverted from the compost plant is not the same as that being composted. A better definition of the nature of the rejects and remnant being landfilled should be provided.

Overall the landfill configuration (160 x 260 m) is based on the top to bottom design characteristics, as indicated in Figure 1.

FIGURE 1:
SPECIFIED LANDFILL DESIGN DEPTHS

TOP OF LANDFILL (vegetated)	
450 mm	Vegetation/Surface Layer, uses excavated soil material
150 mm	Drainage Layer, Granular Soil Material hydraulic conductivity 1 x 10^{-2} cm/sec;
1.5 mm	HPDE Geo Membrane
600 mm	Barrier Layer, excavated soil with bentonite, hydraulic conductivity 1x10^{-7} cm/sec
200 mm	Gas Venting Layer, Granular soil material, hydraulic conductivity 1 x 10^{-2} cm/sec
	150 mm diameter x 10 m perforated gas collection pipe in Gas Venting Layer
MUNICIPAL SOLID WASTE LAYERS (average over whole site some 16 m deep)	
150 mm	Drainage Layer, Granular soil material, hydraulic conductivity 1 x 10^{-2} cm/sec.
1.5 mm	HDPE GeoMembrane, 2% slope with 150 mm dia. HDPE pipe for drainage.
900 mm	Composite Layer, Excavated Soil with bentonite, hydraulic conductivity 10^{-7}cm/sec
BOTTOM OF LANDFILL	

Due to the increase potential for clogging of these leachate collection pipes if they are embedded in the HDPE lining, best practice indicates that they should be buried in a layer of gravel, or some similar high porosity material. Soil, even if "granular", is not adequate for this purpose. Shredded tires can be used, if available. A clogged leachate collection system could potentially result in the whole landfill becoming water logged before final capping – and make LFG recovery (discussed below) problematic. If waste becomes fully water-saturated, waste slope stability can become a concern

Viewing the design from a GHG emission reduction context, achieving the stated low permeability (10^{-7} cm/sec) with bentonite "amended" excavation soil would require soil testing and experience. In general this is not recommended, as it is difficult to mix the bentonite well enough into the soil and results are generally not satisfactory. A best practice choice would be a GCL, "geosynthetic clay layer" which is clay layer sandwiched inside a geosynthetic liner. This is approved in the U.S. as a substitute for a 2 ft clay liner, can be easily rolled out and provides a 10^{-8}cm/sec barrier. It is cheaper than a bentonite amended soil and has a better performance. This is particularly recommended for the covers, which, due to settling, will crack, leading to fissures through which the LFG can escape and water penetrate (resulting in increased GHG emissions). A GCL layer will also save on air space (increase landfill capacity).

Best practice is also to use a LDPE, Hypalon or polypropylene liner as a top cover. LDPE has, for example, a 200% elongation rating, vs. only 50% for HPDE, which is likely to rip when the landfill settles, leading to LFG release and water penetration. Due to low tensile strength, which leads to failure during landfill setting, HPDE is not recommended as a top cover.

Good surface drainage, along with a LDPE liner GCL underlayer will be sufficient to prevent most infiltration into the landfills, the major concern. Actually, with the non-reactive nature of waste to be landfilled in this case, leachate production is much less of a problem than in more conventional landfills. The "gas venting layer" is discussed further in the next section.

The discussions of the bottom liner specification and leachate drainage systems designs (pages 8-15 to 8-28) present some issues. Experience shows that a HDPE liner is likely to be penetrated and punctured during compaction of the waste placed in the landfill. A 50 to 60 cm deep protection layer is likely to be required. Alternatively, it would be possible to use selected waste materials, such as the rejects from the compost operations, as long as these do not have metal or other sharp objects.

We did not review other design issues which do not impact GHG emissions, such as slope stability, which are covered in some detail in the Report, nor the cost estimate, nor did we address the reasonableness of the designs or costs in context of the Indian situation. In brief, the total cost of the landfill construction (materials and civil engineering costs) is somewhat above US$1.6 million (80 million Rupees), of which some US$460K are for the HDPE liner, with the cost of the final soil liner and covers of similar costs (See Section 10, "Estimated Cost of Operations" spreadsheet). The leachate drainage and gas collection systems are of much more modest cost. These costs appear reasonable.

Some 310 m^3/day of waste is to be placed into the landfill (Page 8-14), based on first-year Option 2 (although that is 310 MT/day, 300 m^3/day), providing for one daily cell of some 5 m wide, 25 m long and 2.5 m high. The daily cells will be covered with 15 to 30 cm of soil. However, as suggested above, and further discussed below, recommended best practice would be to replace much or all of the daily soil cover with composted remnants, which would increase landfill capacity and also lower costs. A much thicker soil cover is to be provided before the monsoons, which appears appropriate. Overall the detailed designs of the landfills are not further addressed, only the landfill gas and GHG issues are discussed in the next section.

3.2 Landfill Gas Collection Design

The discussion of landfill gas in Chapter 6 of the Report was, as stated above, quite general, even in the section headed "Indian conditions" (page 6 -76). Chapter 8 provides a similar general discussion of landfill gas. For example, it states that a gas production of 6.3 m^3/yr/MT of waste (LFG, landfill gas, roughly 50/50 CH_4/CO_2) would be generated "in enhanced decomposition mode" in "controlled landfills" (page 8-30), but without discussion of these terms or what type of waste material is being considered, or the timing of such releases. We believe this is actually US EPA data, for active landfills. It is important to note, for reference, that these numbers are considered uncertain and variable even for U.S. conditions. At this rate of emissions, all landfill gas (some 175 m^3 LFG/MT) would be produced over about 25 years. Of course, because of the first order exponential decay assumed, about half the gas would be produced in the first ten years, and these emission rates refer to active landfills.

The Reports then state that for this site "the gas generation will be much less ... hence the gas generation has been considered at 351 standard cubic meters of gas per day". This number is actually almost exactly 10,000 standard cubic feet / day, suggesting a conversion from English units. The report does not state what the timeframe for this

emission is. Nor how this figure was derived. It must be assumed that this is to be at closure, starting at five years (see Chapter 10), when the gas vents are emplaced (as the calculation for gas vents are based on this number, and these are not placed until the final closure). However, as further discussed below, by this time most, at least half, of the gas will already have been produced. Still, assuming a full landfill, some 650,000 tons placed (the density is almost one for Option 2, see Table 3 above), this would give only some 0.2 m^3/yr/ton deposited in the landfill, roughly 30-fold lower than the quoted EPA estimate.

This appears low based on the following analysis and assumptions:

1. A lower LFG potential for Indian wastes of 70 m^3/MT (35 m^3 of CH_4/MT see Table 2),
2. A lower emission for the waste actually landfilled in this case, assumed at only ¼th of above,
3. A faster decay coefficient (due to higher temperature, moisture) during the initial placement (resulting in half of the LFG released before closure and placement of final cover); and
4. A slow-down in decay after closure (e.g. to only 10% of remaining potential per year).

In this case, for 650,000 tons of waste in place at closure, the projected LFG emissions would be:

(700,000 MT x 70 LFG/MT [for 1] x 0.25 [2] x 0.5 [3] x 0.1 [4])/365 = 1700 m3 LFG/day,

This is almost five-fold higher than the 351 m^3/day projected in the Report. There is no indication of the basis for that calculation (unlike the detailed examples in prior sections dealing with liners and leachate). This issue is at the heart of this present analysis and is further discussed below. First, however, the LFG gas collection system is addressed.

The Report further states (page 8-30) that "it is common practice to provide one vent pipe per 7500 standard cubic meters of gas per year", thus coming to an estimate of 17 vent pipes required, based on the above assumed 351 m^3/day production of LFG. In our experience there seems to be little common practice in this field. Some authorities state that vent pipes should be provided approximately every acre (or even acre and a half). Others believe that gas collection pipes should be spaced some 40 to 60 m apart (about each half acre to acre). Both single vertical and vertical pipes connected to lateral (horizontal) buried pipes are used, the horizontal pipes reducing the need for a large number of vertical pipes. The presence of a plastic membrane to seal the landfill also greatly reduces gas releases through fissures and cracks (the major, and often unrecognized, pathway for gas release from unlined systems) and also reduces the need for gas collection pipes. At the stated gas production rate (351 m^3/day) the flow through the 15 cm diameter pipes is relatively low (1.3 cm/sec gas flow) that if, indeed, the pipes are the path of least resistance these would easily collect all the gas generated under the liner. (Calculation: flow rate of 351 m^3/d, divide by 31.5 million sec/year = 4 l/sec, then divide by cross area for 17 pipes, or 17 x 176 cm^2 for the 15 cm diameter pipe). Even at

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a gas production rate that is 4½ times higher than the estimated, gas production rate of some 1600 m^3/day, a gas flow of some 7 cm/sec is still quite small in terms of any backpressure due to the piping. Thus, we don't believe this assumption presents any problems. Indeed, the number of collection pipes, at 17, may appear somewhat over designed for the task.

A key issue is if the "granular soil" with 10^{-2} cm/sec hydraulic conductivity would allow the unrestricted flow of the LFG gas to the pipes. This would be true under dry conditions. However, soil with this hydraulic conductivity typically contains fine sand which would become wet, possibly by infiltration, or while being placed, or by condensation, and, in any event, would quickly become saturated and thus blinded to gas flow. For this layer, best practices recommend pea gravel, which would drain reasonably well and maintain a very low pressure drop for gas flow. Shredded tires can also be used. If there are no such materials available locally, or if too expensive for the present design and location, another alternative would be to place the vents vertically into the landfill, penetrating to some depth, rather than horizontal collection pipes close to the surface. Some best practices recommend vertical gas wells going down at least 6 meters, penetrating through the liner and with a larger diameter pipe extending into the waste and the 15cm inside of it, to avoid breakage when the landfill settles and recommend some 10 to 12 such vents. There should be a gravel layer surrounding the pipes to prevent clogging (as shown on Page 8-32, rather then the design shown on Page 8-34, and in the attached drawings). Pipes would be placed prior to closing the landfill site. Horizontal pipes connecting to the vertical ones can be considered, but are not necessary considering the low amount of gas that will be produced in this case.

The surface cap and liner would prevent almost all gas escaping through the top, and if properly designed, also laterally. The LFG will find the path of least resistance, and thus migrate through the waste layer. It would therefore be sufficient in such a case for the gas collection pipes to be located horizontally near the surface of the landfill, as designed, rather than vertically, as above. However, in that case, even if the entire "gas venting layer" is not gravel, gravel should be used to bury the perforated pipes in the gas venting layer and the gravel should extend from the barrier layer to the waste layer below, to avoid the pipes filling with water or becoming clogged with soil. It is more likely that the gas would migrate through the waste layer than the gas-venting layer, and reach the perforated pipes through the gravel layer surrounding them.

The report indicates that the vents would be connected on top of the final cover with a network of pipes to collect the gas, with a blower and then burned in a flare. There is no further discussion or design of these items, either here or in Chapter 10, and no costs for the gas collection and flaring equipment appear to be allocated. However, the Report indicates that this strategy would be in compliance with MSW 2000 rules.

We find a significant challenge with the relatively low flow rate, some 40 standard cubic feet (scf) / min, (or even less than 10 scf/min if the lower gas production rate is considered). This requires a very low head blower, and most important, a very large turndown ratio for the flare system. Indeed, due to barometric pressure changes, there

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would be a great variation in the methane extracted from the landfill. The blower would continue to suck in gas, but this would result in entrainment of air and dilution of the methane gas with air. The standard procedure is to use a methane measuring instrument and adjust the flow to the flare by means of a throttle valve to maintain a methane composition of some 50%. When the methane concentration increases above 55%, flow (e.g. blower suction) is increased, when it drops below 45% it is decreased. The instrument of choice for measuring methane is a thermal conductivity detector, which is a simple method that can be readily read by minimally trained personnel.

Alternatively, FID detectors can be used, which are more sensitive. Almost all landfills in the U.S. use this method or variations thereof with reasonable success. For relatively large landfills and high gas production rates, the flow is relatively steady and needs only to be checked weekly initially, or even less frequently once gas production stabilizes after landfill closure.

Another major challenge is keeping the flare lit. The variability in the gas flow and the limited turndown ratio for most flares can be an operational problem for relatively small landfills. This is likely to be a more significant issue here, where smaller gas flows are collected over four hectares. Even with a low head (1 psi) blower, this would present problems. Open flares have typically only a 5 to 1 turndown ratio; a larger turndown ratio flare would be required for the present application. Another issue is that the open flares will blow out in the wind, particularly at low and variable flows, however enclosed flares are very expensive.

For the Bangalore Landfills and anticipated relatively low gas production rates, managing such a system would be challenging. Three or four of the vents can be ganged together with flexible tubing and connected to one flare to minimize the cost of these systems (and also to provide sufficient gas for the flares). In our expert opinion this option would be the optimal system for minimizing GHG production by these landfills.

One potential problem is moisture condensation in the collection pipes. Due to water saturation of the gas, the lines will quickly clog with water unless provisions are made for condensate traps and water removal. This requires that the horizontal collection lines be on a gradient, with a U-shaped tube allowing for water overflow without allowing gas escape (or sucking in air). This is relatively simple, but does require that the collection lines be designed with this in mind (a low spot is required to allow water shedding). These flares (see Appendix III) avoid the problem of active management while preventing the emissions of methane to the atmosphere, by not requiring blowers.

We also reviewed additional specific design issues for these landfills. For example, the design of the landfill should prevent lateral flow of LFG, which to our knowledge was not addressed in the Reports. From a GHG abatement perspective, the amount of gas likely to be produced, and mitigated, at this site is relatively small, however this project can serve as an example to assist other municipalities look at the incorporation of GHG reduction components as they develop sanitary landfills, as discussed in the next section.

4.0

Best Practices for LFG Recovery and GHG Mitigation

4.0 BEST PRACTICES FOR LFG RECOVERY AND GHG MITIGATION

4.1 Introduction

This Section provides a brief supplement to the above discussions for further guidance on the topics addressed in this Report and the development of suitable practices for GHG mitigation efforts at these landfills with a guide to additional resources and information.

SWANA (The Solid Waste Association of North American) has a number of practical reports, in particular the "Landfill Gas Operation& Maintenance – Manual of Practice", a detailed "How-To" manual for LFG gas management, recovery, measurements, etc. There is an enormous volume of literature on landfill gas, which cannot be reviewed in any detail, nor would be particularly useful in this context. For example, the proceedings of technical meetings for landfills, LFG, MSW and similar conferences contain many technical papers of interest, but these are generally too specific and narrow for practical purposes. For one example, the literature on modeling landfill gas emissions is extensive, but not directly applicable to the present situation, with its unique wastes and environmental conditions. For another example, the papers in "peer reviewed" journals are generally very research oriented (e.g. academic) and not practical. Appendix I provides a short listing of additional annotated reference materials that could be used in the development of a training and operations manual for India.

Application of the LFG models and practices to the present case is limited to the context, the size of the Bangalore landfills, their eventual gas production potential, and typical Indian wastes. While the Bangalore landfills are below the U.S. for fugitive emissions threshold, smaller landfills do routinely collect landfill gas. In most cases these landfills are deeper than the present one, and withdraw from deeper vents. This would result in more steady gas collection, with concentrations changing more slowly than in surface gas collection systems. Still, the design for the Bangalore Landfills, with a sealed cap, should be able to prevent LFG migrating off-site, which is the major requirement for all landfills.

From the above discussions four major issues need to be further addressed in any evaluation of these Bangalore landfill projects for GHG abatement, in the context of best practices as they may be relevant to India:

1. Measurements of methane emissions for monitoring, verification and modeling purposes;
2. Expected gas emissions based on applicable models to the Indian situation;
3. Gas recovery from the landfill, flaring equipment, potential for utilization; and
4. Microbial methane oxidation as an alternative to gas collection for GHG abatement oxidation.

These topics are addressed briefly below, concluding with a step-by-step guide for looking at GHG emissions in a MSW landfill project.

4.2 Landfill Gas Measurement, Monitoring and Modeling

Measuring LFG production from landfills is not easy and to our knowledge few methods have been tested for Indian conditions. Basically there are two types: active and passive measuring methods.

4.2.1 Active Collection, Measuring and Modeling of LFG Production

An active collection system, as designed for the Bangalore Landfills, uses perforated vertical and, sometimes, horizontal, pipes, gas collection lines, blowers, flow regulators (throttle valves), condensation water traps, etc., to collect all, or at least most, of the LFG produced. For GHG mitigation measurement of the gas mass flow and composition is needed, which requires analytical instruments for gas composition and accurate measurements of gas flows. These must be carried out over relatively long periods and integrated. This is difficult even for short periods, practically impossible for longer ones under field conditions. Most importantly, there is no assurance that the collection system actually does collect all or most of the landfill gas. Only large landfills, with good cap designs, deep gas collection systems, documented history of waste loading, and active collection systems allow collection of reasonable data on gas compositions and mass flows. Such data can realistically be collected for only brief periods.

To obtain information on actual LFG (e.g. GHG) production from landfills, Vogt and Augenstein (1997) studied 19 U.S. landfills, collecting some 300 data points on their LFG production. These data points were then plotted on various models, which included landfill size (loading), waste age (when deposited, when closed), moisture and temperature. The data fell into a reasonably close (better than anticipated) range, best represented by a simple exponential decay model. In the model the gas generation (G) from all of the tons (or cubic meters of landfill x 0.6) from the initial time of waste placement over the years is given by:

$$G = k \times Lo \times e\,(-\exp k_t)$$

Where G = methane generation per year, M^3/tonne/year
k = rate constant, (1/years)
Lo = yield (in M^3/tonne)
e = base of natural logarithm
t = time from placement of the waste in question

With suitable constants for the US, about 75% of gas recovery values will be within -30 to + 50% of this model's prediction. In other words there is site-specific variability but this model is reasonably good. (Some of the earlier LFG models were too optimistic by several-fold, overoptimistic, resulting in failure of a number of ventures). For the U.S. a k = 0.04 to 0.08 (the range dependent mainly on moisture), and with an "ultimate" gas potential low of some 175 (140 to 180) m^3 of LFG /MT of landfill gas. Collection efficiencies of 70 to 90 percent were estimated. More complex mathematical models would also fit the data, but are no more predictive than the simple first order decay model. This model results in a peak in gas production as the landfill is filled followed thereafter by a slow decay as the landfill organics decompose. At the lower k value, the landfill will remain "active" (e.g. still emitting over 5% of original gas levels) for some

40 years. One reason for this is that most of the organics in U.S. landfills are paper, which decomposes rather slowly under the typical (initially dry) moisture conditions in U.S. landfills.

For India and developing world in general we recommend:

k = 0.15 year-1 (likely to range from 0.1-0.25 – use average 0.15)
Lo = 35 liters CH_4/tonne (likely range 15-40)

The above model and input parameters can be used as a "calculational tool" to estimate GHG emissions from landfills in India.

It should be noted that the operation of an active LFG collection system with efficient gas recovery is an extensive engineering procedure. To allow flow adjustments each of the wells must be equipped with a throttle valve and ca. 1-2 cm hole allowing insertion of a Pitot Tube, for flow measurements, and otherwise stopped. The wells must be adjusted individually based on the gas composition readings (as discussed above). There is no simpler way to do this, or to avoid it. For large landfills, where there is active gas collection for power applications this is justified. Also for such systems the gas flows vary little enough that such adjustments need not be made too frequently. For small landfills and where gas is only flared, this is generally not worthwhile and the quality of the information, or of the gas collected is generally poor, but does not generally matter. For GHG applications, better data is would be required.

In brief, gas collection with short-term measurements of composition and mass flow is the only available method for measuring LFG gas emissions. This is further detailed below.

4.2.2 Passive Measuring Methods

Passive measuring methods involve measuring gases released from the landfill surface, without active collection (e.g. blowers). These can be accomplished through collection chambers or measuring gaseous plumes above the landfill. These methods are not generally appropriate to day-to-day operations and are imprecise, but can be used as a "first cut" assessment.

The static chamber method has the advantage of being far less expensive and thus appealing in the present context. This technique involves covering a section (typically 1 m^2) of ground with a plastic chamber and allowing the gas to diffuse from the ground into the chamber for a few hours, then sampling the gas and measuring CH_4 and CO_2 (even O_2 and N_2) concentrations. The difficulties are the enormous point to point variability, typically several orders of magnitude, and even day to day reproducibility for the same location is not good. The reason is that gas emissions from the cap of a landfill are not homogeneous, rather most of the gas is emitted from fissures, cracks and similar venting regions. Active chambers incorporate a slow air flow through the chamber allowing for longer-term collection of a more representative sample of vented gas. Above ground methane plume measurements can be carried out, using FTIR (Fourier transform infrared) measurements, which can be correlated with local micrometeorological measurements (mainly wind velocity and direction) in sophisticated dispersion models to produce a

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general source term for the entire landfill, or a good part of it. Aside from their sophistication, they are generally not as accurate as one would hope. (e.g. the modeling of the actual release is not good). To overcome this limitation tracer releases have been used, such as SF_6 or N_2O which can be detected at low levels. This improves the results, but increases costs and still suffers from limited accuracy. These above ground measurement techniques require rather flat ground and low wind velocities. In brief, these are considered research tools, not suitable for routine work.

Many investigators measure below-ground gas compositions, *in situ* or by sample extraction. These measurements can indicate air-intrusion into the subsurface, and are recommended as routine measurements in landfills, but have little relevance to fluxes and thus GHG emission.

Isotope analysis has been used to determine if the methane gas emitted from landfills has been oxidized by methanotrophic bacteria during its migration through the landfill cover. The methane oxidizers have a slight preference for lower weight isotopes, thus the $^{13}C/^{12}C$ ratio of CH_4 decreases in gas vented through a microbial oxidation layer, compared to that from the deeper landfill. An interesting technique, but not useful for routine measurements.

Biodegradability and methane yield potential can be used to obtain an maximum yield for CH_4 production, by placing the waste into closed containers, amending these with nutrients and water, incubating and measuring the gas released over time, weeks to months. One difficulty is that even "months" is a short interval compared to landfill time, while the contact with nutrients and bacterial inoculum is better in these bottles than in landfills. Also sampling of the waste is a problem, as well as gas leakage. In conclusion, no passive measurement techniques can be recommended as a general practice, and none are specifically applicable to the field projects, in particular under Indian conditions. The best approach would appear to use the LFG models to predict GHG emissions.

4.2.3 Representative Measurement Technique – "Bioreactor" Landfill

A number of measurements are important for a controlled or "bioreactor" landfill operation. Many, even most, of these measurements are above and beyond the measurements and practices of conventional landfills. These measurements are as shown in Table 1 (taken from Augenstein, D. and R. Yazdani, 1995, "Landfill Bioreactor Instrumentation and Monitoring" from US EPA Seminar Publication "Landfill Bioreactor Design and Operation" Wilmington DE, March.

Moisture is critical to biological activity since it is essential for biological activities of methane generation. Moisture can be measured in situ by Gypsum blocks, of the type often used in soil moisture determinations. These moisture sensors rely on the fact that the high dielectric constant of water or landfill leachate increases capacitance of a "capacitor" consisting of a gypsum block capacitor. The capacitance is indicated directly by flow of current at high frequencies (high RF current). Another method of moisture determination is that of the conductance of a porous matrix such as small packed poly

(vinylchloride) beads. Both of these moisture measurement methods are somewhat qualitative, and an elevated reading simply indicates that moisture has reached the sensor. This knowledge is, however valuable in and of itself since the same moisture level capable of elevating sensor readings appears to be closely correlated with much (severalfold) increased biological activity.

Gas composition is critical for purposes of either gas energy use, or simply flaring. Methane content must usually be above 30-40 per cent for fueling energy applications. The trouble-free burning of gas in a flare usually requires at least 25% methane content. Methane content can be measured by thermal conductivity meters sold for the purpose by companies. More accurate meters rely on infrared detection and are sold by vendors. The most accurate methods rely on gas chromatography (GC). A thermal conductivity detector can quantify all gases of interest. Vendors sell molecular sieve columns specifically adapted to landfill gas composition.

The landfill gas generated typically starts off as mostly carbon dioxide. With time (usually a few months after generation starts) the gas composition stabilizes at about 55% methane and 45% CO_2. When gas is collected by wells, the wells are "tuned" by increasing extraction rate if gas remains over 50% methane, and decreasing extraction rate if falling methane (or nitrogen over bout 15%) suggests undesirably high air entrainment.

4.3 Expected Gas Emissions

Application of the LFG models developed in the U.S. to Indian wastes and condition without modification is problematic. First, of course, the waste composition is quite different in terms of composition and biodegradability. Most of the biodegradable fraction consists of food wastes and related garden wastes that decompose quickly, with relatively little slowly decomposing materials such as paper. Also, Indian "garden waste" is different from U.S. "green waste", in terms of biodegradability. Temperature and moisture conditions are also quite different. Even for similar rainfall in Bangalore to some U.S. East Coast conditions, Bangalore landfills will be wetter due to the monsoons, and longer time until closure. Further, in the present case the waste being landfilled would be of even lower LFG potential than typical Indian wastes; we estimate at only $1/4^{th}$, than even the typical Indian MSW, which, in turn, we believe to have a LFG potential of only 40% of U.S. wastes.

Using these factors we estimated LFG production from the proposed Bangalore landfills at about $1/10^{th}$ the potential of U.S. wastes per ton, and much more rapid release of the gas. Roughly we estimate the yield potential at some 9 m3 CH_4/MT of landfilled wastes. As already discussed above, we suggest a simplified model with a fast initial decay of residual food and other easily degradable wastes, with half the LFG potential emitted before final closure, followed by a slower decay after landfill closure (k = 0.1, appx. 10% per year), giving some 850 m3 CH_4/day, initially after closure. This is, of course, a crude model.

There are few good, documented, examples of LFG recovery from landfills in LDCs. An applicable example is given from Thailand by Eam-o-pas et al. (1999)For a landfill near Bangkok they estimated that the wastes contained a much higher percentage (20%) of "readily biodegradable" waste, compared to the U.S. (14%). The Bangkok waste had also less moderately (7% vs. 28%, k=0.14) and slowly (17% vs. 26%, k =0.05) degradable materials than U.S. wastes, but more inerts (56 vs. 33%). Moisture was 50% by weight, vs. 25% for the U.S. These wastes, under the local conditions would release all their gas with a half-life of about one year (k = 0.69). The landfill was saturated with water, and LFG production required draining the leachate from it. Based on this approach, they estimated an overall decay coefficient of 0.15 wastes, with an LFG gas production rate of some 100 m^3/mt of wastes. For a half a million ton (total placement, 2.4 ha) phase of the landfill they projected that at closure they would recover some 300 m^3/hr before closure, reducing to some 45 m^3/hr within ten years of closure. Actual measurements at that site gave remarkably close results to those projected, 310 m^3/hr of LFG outputs prior to closure This is one example of LFG, modeling and actual measurement of LFG from a landfill in a developing country that can serve as an example.

4.4 Microbial Methane Oxidation in Landfill Covers and Composting Operations

A major issue identified above is that much, roughly half, of the potential LFG/GHG emissions may escape prior to landfill closure and installation of the gas collection pipes. This is less of a problem with U.S. landfills, where decay rates are much slower and thus release during filling not as much of a problem. Two solutions present themselves: installation of gas recovery systems prior to closure or operation of the landfills to maximize microbial methane oxidation. Gas collection prior to closure is not considered practical in the present case, thus techniques to promote methane oxidation are recommended.

Another major potential source of methane emissions identified above is the composting operations. There is very little data on methane emissions from compost operations, and methane emissions would be expected to vary greatly with the nature of the waste being composted and the exact operating conditions. In our correspondence with international waste expert Dr. Edelmann of Switzerland (7/19/02), he expected that for the type of compost piles being contemplated in Bangalore (3 m high, turned once weekly) a "minimum of 10 – 15% methane" would be produced in the off-gases from the compost. Assuming the balance is only CO_2, this would mean that at least as much methane is produced by the composting operations as by the landfills, perhaps more. This is, a central issue in any GHG mitigation effort from such an operation. In this case, where it would not be practical to collect the gas from the compost piles, microbial methane oxidation becomes a plausible control technology option.

Microbial methane oxidation is carried out by so-called methanotrophic bacteria, which use methane as an energy source. Such bacteria are ubiquitous in soils and all types of environments and their requirements are simple: oxygen, methane, some nutrients (N, P, etc.) and, of course, moisture. Moisture is perhaps the critical component: too little and methane oxidizers are not able to grow, too much (e.g. exceeding field capacity or

waterlogging) and gas transfer (diffusion of O2 and CH_4 to the methane oxidizers) limits methane oxidation. Microbial methane oxidation has been demonstrated and measured in landfill cover soils by a number of investigators, starting with Whalen et al. (1990) a little over a decade ago. A large number of publications have demonstrated methane oxidation in both simulated landfill covers as well as in actual landfill covers since then, although the quantification of this phenomenon, outside the laboratory or under experimental conditions, is difficult.

The most plausible approach to methane oxidation is to manage the compost cover to maximize the activity of these organisms. Composted materials are very suitable for such purposes because of high surface area, high moisture holding capacity, embedded inorganic nutrients, and limited alternative energy sources. It is much better than soil or artificial substrates. Recent work from Austria has demonstrated that well cured (aged) MSW compost can oxidize more methane than other compost (e.g. partially composted MSW, sewage sludge compost) or soils in experimental reactors (e.g. Humer and Lechner, 2001). Such compost was also used by these authors as cover over landfills, being placed in trenches or as dressing on top landfills. They measured methane emissions through the covers both enclosed chambers. The main determinants of methane oxidation were the temperature, moisture, depth, compaction and channeling in and below the compost layer.

For the climatic conditions in Bangalore, and considering the ready availability of well cured compost at this site, it should be possible to manage compost covers to, indeed, maximize methane oxidation in both the landfills and composting operations. For the landfills, as mentioned above, compost remnants would be added daily on top of source separated MSW. From the data in Table 2, the composted remnants represent about one third of the total landfill loading (by volume) which should be adequate, even if this is not a high value compost. Based on the experience quoted above, it may be best not to compact this dressing too much, though that would require some experience. Another issue would be to manage the moisture level of this compost material – this may be the critical parameter.

In brief, the daily landfilling operations thus would entail first filling the daily cell with the source separated MSW, compacting this layer, and then adding the compost remnants, and compacting this layer only moderately. The remnants would be moistened to the desired level, which would be determined by experience, but below field capacity. Rather than piling cells on top of each other on a daily basis, it would be best fill these systems in layers on, perhaps a monthly basis, to allow the initial methane emissions from the placed waste to be released through the compost cover. It may be necessary to spray some additional water on top of the compost cover occasionally. Clearly this protocol is very preliminary, and would need to be refined based on more information on the actual nature of the compost remnants as well as further information on the efficacy of the methane oxidation by these covers. This technology is, clearly, still at the early stages of development.

To determine the actual GHG mitigation effectiveness of these procedures, recommended method is to use enclosed chambers placed on top of the landfill cells and measure methane emitted. For this purpose, cells with soil cover and compost cover should be compared, as a function of different parameters (e.g. moisture, compaction, etc.). Collection of sufficient data points would likely allow a comparison of these methods.

A similar approach could be applied to the compost operations. In this case the compost piles should be dressed with a layer of cured compost, probably half a meter thick, placed on the crown of the compost piles. Airflow would be by convection through the sides to the top of the pile and, thus, move through the compost dressing. Again, the same measuring methodology as described above would need to be applied, with gas collection chambers on top of the pile to determine the amount of methane gas produced.

In both cases, gas compositions should be measured, at a minimum CH_4 and CO_2. Methane can be perhaps best be measured with a portable FID detector. CO_2 could be measured routinely through lye absorption, if the concentration is high enough (> 5%). Occasional full gas compositions (e.g. O2 and N2 also) should be measured, which would require an on-site gas chromatograph. Techniques such as isotope fractionation or microbial identification are used but usually not for projects of similar size in this context. .

Methane oxidation by compost dressings is still an experimental technique that requires considerable data collection and on-site research for validation. As a final point, the production of N_2O during the methane oxidation process must also be considered in any future analysis.

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5.0

Resource Guide For Future Operations

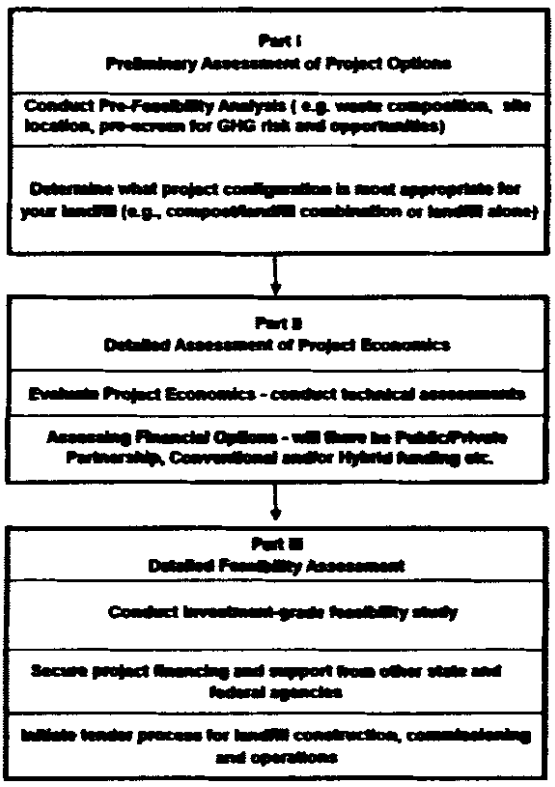
5.0 RESOURCE GUIDE FOR FUTURE OPERATIONS

This resource guide is intended to provide some insights into the GHG mitigation process for MSW and landfill to gas operations. First we provide a guide on the typical steps that can be followed for the project development process. A calculational tool is provided based on the review conducted for the Bangalore projects. Then we provide several examples of LFG case studies from developing countries and the US. Finally, suggestions are provided for future MSW and LFG training activities recommended for Indian municipalities. Annex A provides a listing of background information that is highly recommended as municipal officials initiate the process of developing landfills for compliance and GHG mitigation.

5.1 Project Development Steps

The Bangalore projects provide an opportunity for research on issues above at a field scale. Steps should form part of the procedural guide to the incorporation of GHG mitigation projects in landfills. Figure 2 provides a stylized process that can be employed for development of potential LFG projects. These steps are adapted from literature provided through the US EPA Landfill Methane Outreach Program (LMOP)[1], which would be a useful resource for Indian municipal authorities.

FIGURE 2: LFG Project Development Steps



[1] See http://es.epa.gov/partners/land/landmeth.html for further reference.

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More detailed technical steps during Part II of the project development process would include the following features:

1. Collect data on MSW Composition. Waste delivered to the sorting area could be manually classified and statistical data collected on the content of various components. Moisture contents should be determined by drying (oven, or, if not possible, sun drying can be used). Waste density is also of interest. Because the Development of techniques for GHG mitigation by composting learned projects in India (or elsewhere) is a work in progress, waste such as proposed to be landfilled should also be prepared, if possible. (It is likely that the KCDC already has such data for Bangalore.)

2. Biodegradability of the MSW. The objective is to determine both the aerobic and anaerobic biodegradability of this waste material. It is likely that KCDC has data on actual losses during composting operations, and their experience should be reviewed. Anaerobic biodegradability data could be estimated from (1) above and prior experimental work by others.

3. Carry out a Design Review for LFG Recovery/Flaring. The above discussion identified a number of significant areas. System designs should be reviewed as to applicability and effectiveness based on estimates on methane emission, from Data in 1. and 2. A figure of the recommended passive flare (solar power igniter) is provided in Figure 3.

4. Review Existing Experience on Methane Oxidation in Landfill /Compost Covers. It is possible that some half of the landfill GHG emissions may take place before LFG is actually collected, and an even greater amount may be generated from the compost operation. One practical method for reducing GHG from these sources appears to be through controlled microbial methane oxidation. This requires a more detailed review of the literature and best practices, for applicability in the Indian context and for specific site and waste composition.

5. Develop a LFG /GHG Model for the Proposed Composting/Landfill Processes. Based on the above information, and other literature data it would be possible to develop a model for LFG and GHG emissions (including N_20 and the fate of C) from the compost/landfills operations.

6. Develop a Data Collection and Analysis Plan for Bangalore Projects. As discussed above, there are not readily available methods for directly measuring GHG emissions from landfills or, for that matter, compost operations. Gas (including CH_4) concentrations measured within landfills (as discussed in the Report) are of interest only to determine if there is air intrusion, they do not have any relevance to actual emissions from the landfill. Integrated measurement of gas flows in the passive collection vents would be difficult, as these would be very variable (being affected by barometric pressures). We recommend that the GHG emissions from the landfills be

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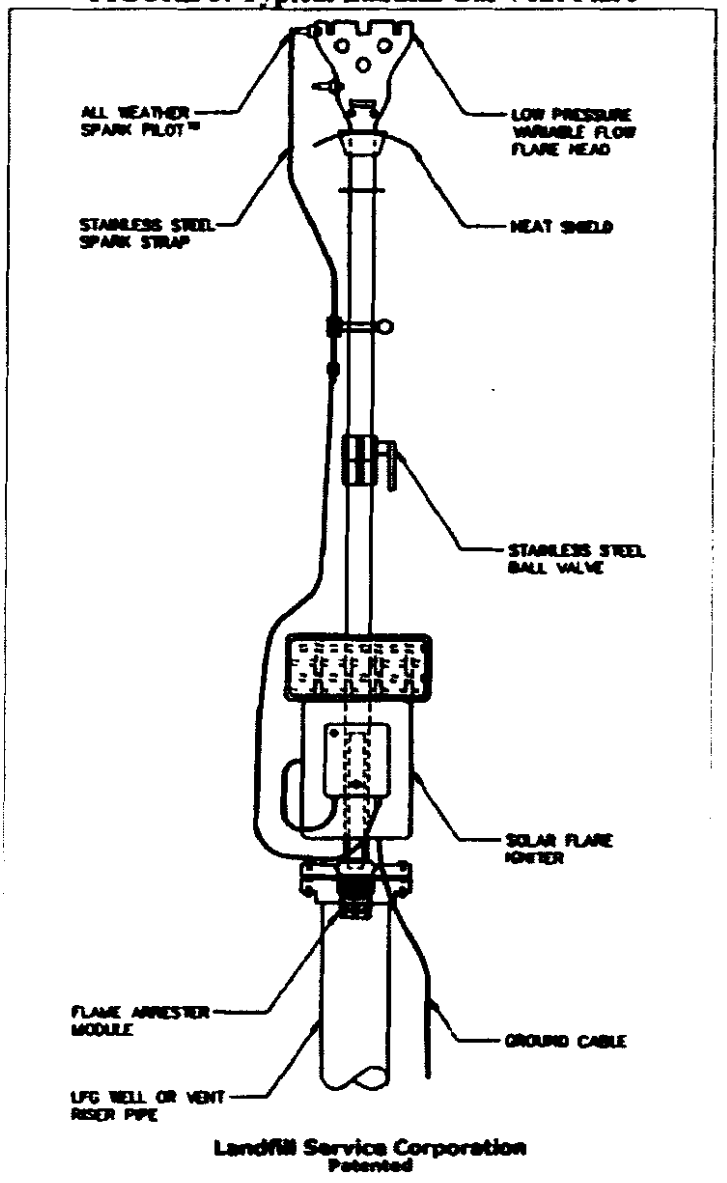
based on the LFG models and limited data collection. We recommend that any data collection effort focus on the emissions of CH_4 from the landfills during their active operation (e.g. before closure) and on the compost piles, as these are the sources of most of the GHG emissions from these systems. The actual methods (analytical instrumentation, etc.) and data collection plan should be developed after further definition of these projects.

FIGURE 3: Typical Landfill Gas Vent Flare



Source: www.posishell.com/landfilltech/diagrahm.cfm

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5.2 Calculational Tool

A formula to calculate the gas generation (G), represented in cubic meters per ton of MSW, is given by:

$$G = k \times Lo \times e\,(-\exp k_t)$$

Where G = methane generation per year, M^3/tonne/year
k = rate constant, (1/years)
Lo = yield (in M^3/tonne)
e = base of natural logarithm
t = time from placement of the waste in question

For India and developing world in general we recommend:

k = 0.15 year-1 (likely to range from 0.1-0.25 – use average 0.15)
Lo = 35 liters CH_4/tonne (likely range 15-40)

The above model and input parameters can be used as a "calculational tool" to estimate GHG emissions from landfills in India.

5.3 International Case Studies

The following six cases are provided as illustrations of LFG projects. Most of the examples are from the US, with the first two cases

1. **Landfill Gas Generation and Recovery in Thailand:** (Reference: Eam-o-Pass et al., 2000; See also discussion in Section 4.X)

This project, located outside Bangkok, attempted gas recovery from the Kangphasaen Landfill 80 km northwest of Bangkok. A test was run extracting gas from 39 wells in a small shallow section of the landfill.

The first (and probably common for the developing world) problem encountered was that monsoon rains raised the in-landfill water table to within 1-2 meters of the surface. Gas cannot be recovered from such a waterlogged landfill because gas well perforations are "blinded". The approach taken was to try gas extraction from a deeper portion of the landfill. Horizontal boreholes with drainage pipes were placed into the landfill to drain the landfill and lower the water table. Horizontal collection pipes were then placed into upper levels of the waste. It then proved possible to extract enough gas to fuel 2 x 435 kWe Waukesha engine-generators. The successful operation of the engines had led to substantial reductions in electricity costs.

One problem with gas recovery at this landfill was that heavy rains kept the landfill saturated, with water table up to within a few cm of the top of the fill. It turned out necessary to drain the fill before any gas extraction could occur. Horizontal drain pipes were put into sides of the landfill to drain the water level down so that gas extraction could occur (landfill permeability to gas, i.e., porosity, is required for most of the conventional means of gas recovery). Then a gas collection system consisting of horizontal pipes was placed over the waste and waste placed over that. Enough gas could

be extracted so that 2 x 435 kWe Waukesha Engine-generators could supply about half the electricity to a nearby university.

2. **Vietnam Landfill Project:** (Reference: Augenstein et al., 1996)

A conceptual bioreactor landfill design was carried out for a proposed project through a UNDP program in Hanoi, Vietnam. With a waste stream of 500 tonnes/day, the waste was assumed to be high organic, thus with substantial gas potential. The further assumption was that landfill containment approximated the rather stringent lining requirements of the United States. This was assumed necessary to allow the financing of a controlled landfill project by international banks and/or aid organizations.

With these assumptions, the cost of a landfill was found to range US $300,000 to $500,000 US per US acre, or from 750,000 to 1.25 million per hectare. Surprisingly, the net outlay per tonne of waste filled, at 60 ft (18M) depth was only US $5-$9 per tonne. Furthermore, the incremental cost to implement a "controlled landfill" versus a lined conventional landfill to OECD and US containment standards, was calculated to be US $1.20-1.80 / tonne. The reason for this low cost of the controlled landfill is that most containment and other costs--such as for control of leachate liquid emitted from waste--will be present whether full decomposition and gas management is practiced or not.

With all of these assumptions, the cost of gas, exclusive of cleanup, was projected to be about $0.50 US per million Btu. The electric potential for Hanoi was estimated at around 6 MWe, a very significant amount for that city. The design assumptions made were were recently confirmed by data collected at Yolo County (see below). The methane gas yield may however have been high by about a factor of two. Even with this discount, the overall project is still very attractive situation from a renewable energy standpoint. This type of project should be considered in all Developing Countries with significant MSW collection.

3. **Marina Landfill near Monterey, California:** (Reference: Augenstein and Pacey, 1996).

Pacific Gas and Electric and Monterey County commissioned and cost shared gas extraction tests between 1977 and 1981. Then Palmer Capital, after a bid process installed two Waukesha Engines (first Dec 1983-second Feb 1984) at the Marina Landfill. A switchover to Jenbacher (German) and Caterpillar Engines occurred in the late 90's. The generation is now up to (I estimate) about 2.5 Megawatts. The Monterey Regional Waste Management District (MRWMD) has had a per-kWh payment and a capacity payment which is earned by being available to generate power during the peak summer demand season. Marina now averages about 4 cents/kWh from the electrical grid.

As the result of a complex series of transactions and low power revenue, Palmer Capital gave the Waukesha Engines to Monterey County for a significant tax writeoff. The County replaced Waukesha Engines by low-emission Caterpillar 3516 and Jenbacher

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Engines in the late 1990's. About 7 million tonnes of waste now in place. Generation has grown to about 2.5 Megawatts. This may be the longest running landfill gas energy facility in the world.

4. **Yolo County, California:** (Reference: Augenstein 1999)

Yolo County initially commissioned a landfill gas recovery study in 1983, conducted by EMCON Associates. Recoverable gas projections were also made using an available model An intricate bid process followed which culminated in installation of 3 Caterpillar G399 engines at Yolo County. On startup these engines encountered a series of problems which are now straightforwardly avoidable: Combustion products of chlorinated hydrocarbons--common in the landfill gas from discarded solvents and aerosol propellants--corroded piston rings and cylinders (now seen as avoidable with alkaline engine oils) Hard groundwater resulted in deposits in the engine cooling water jacket (avoidable with softer water treatments). Insufficient landfill gas cleanup allowed excessive valve and other wear. However repairs and revised operating procedures were successful in reducing problems. The engines are in their 14th year of operation, and currently producing about 1.5 MWe.

The Yolo County operation is notable particularly for its piloting and now larger scale implementation of a "controlled landfill" approach in which biological conditions are optimized to accelerate waste decomposition to methane. This is combined with increased recovery of the resultant rapidly generated methane from the usual 65-85% to over 90%. The technology has received support from the US Department of Energy Greenhouse Gas reduction program as well as the State of California. The Department of Energy sees the technology as a waste management route with potential to ultimately lessen world greenhouse gas emissions by 3-5%. The State of California sees the technology as a way to add 1-3% to the California electricity sup[ply in the form of renewable electricity.

5. **Landfill Gas Fueled Boiler: Raleigh, North Carolina:** (Reference US EPA, Landfill Gas Energy Utilization: Technology Options and Case Studies, 1992)

In Raleigh, North Carolina, a boiler fueled by about 900 cfm of landfill gas generates steam at a rate typically near 24,000 pounds per hour to meet the needs of a pharmaceutical plant. The energy conversion system uses gas collected from a nearby municipal landfill. It consists of a pipeline system, a boiler, and the building housing it at the pharmaceutical plant. Capital investment for the pipeline, pumping station, and boiler totals approximately $900,000. Gross revenue from steam sales to the pharmaceutical plant are about $450,000 per year.

The history of this project provides another example of complexities that can be encountered in attempts to find appropriate landfill gas energy uses, and then to implement a system. Securing needed landfill gas rights was difficult; much further analysis and investigation was also involved in the selection of an energy application and user.

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6. **Prince Georges County, Maryland:** (Reference US EPA, Landfill Gas Energy Utilization: Technology Options and Case Studies, 1992)

The Brown Station Road landfill in Price Georges County about 15 miles east of downtown Washington DC. Gas from the landfill is use to supply both the electrical and the heating needs of a County building complex and also electricity for export sale to the local utility. The energy equipment comprises a landfill gas cleanup and pumping station, a 2-mile pipeline, three engine generators, and a boiler that supports the heating and hot water system for a local correctional facility.

The project produces 2.3 MW of electrical power, which has displaced nearly all of the outside electrical power needs of the facility. With the heating system in place, external fuel purchases are quite low. The resulting fiscal effect has been significant for the County.

5.4 Training Needs

Landfills are an established technology that can be readily adapted for most Indian conditions. In addition, because of the new Supreme Court rules on MSW, a landfill construction program is essential. The burden of implementing the MSW rules falls largely in the shoulders of the urban local bodies (ULBs). The shortest course toward compliance with the Rules is train ULB officials, and staff both administrative and technical.

As part of the project development process, it is highly recommended that the ULBs engage as soon as possible in a training program that helps "jumpstart" the process. While several formats are possible for implementing a training program, following is a possible outline for ULBs to follow, working in conjunction with regional infrastructure authorities such as iDECK and various federal agencies such as the Ministry of Urban Affairs.

What follows is a stylized outline for a five-day training course to train Indian engineers in the design and operations of Landfills. The training course curricula is summarized in Figure 4. This training course would have as an objective to allow officials from the ULB – and perhaps other professionals representing the local consulting engineering community, regulatory authorities and other regional agency officials to proceed to at least the site selection and preliminary designs for landfills. It would allow municipal and other government officials to review, evaluate, approve, inspect, and approve such landfill designs. It would allow regulatory officials to set the regulatory frameworks appropriate for specific local and general State and Indian conditions. It would allow municipalities to comply in appropriate time and certain budgets with the imminent requirements of the laws. And, most importantly, it would provide the raw material for a program of "demonstration" projects, which would be actual full-scale landfill design and operations projects.

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Such a training course would require a full week. A faculty of some four to five technical experts will be required to teach all the different components of landfill design, and will require roughly 25 -30 hours of lectures, plus exercises, practical work, reviews, discussions, etc. A student body of some 30-40 would be a good number to put through a first course. That would provide a sufficient pool of expertise to develop at least the initial stage of a landfill technology cadre, that would be able to handle the regulatory, administrative, planning, design, construction, operations, monitoring and management of such projects and enterprises. With this many instructors and participants, at least two concurrent sections would be recommended, with slightly different schedules to allow most effective use of instructors.

FIGURE 4: Stylized Landfill Training Course Curricula

Part I –Overview for Senior Municipal Managers

1. Regulatory issues, comparing India, U.S., European and developing countries and
   - MSW rules governing waste treatment and disposition
   - Benchmarking – review of case studies from abroad
2. Assessment process
   - Initial site selection
   - Technical and economic review
   - Tender development for management support contract

Part II – Technical Issues for Mid-Level Municipal Managers

3. Site selection process
   - Technical site assessments (geology, urban planning, etc.)
   - Data collection (e.g., types of data needed and methods of collection)
   - Benchmarking existing waste volumes and methane emissions
   - Legal and social issues
4. Landfill integration with waste collection and transfer stations, delivery methods etc.
   - Assessment of current waste practices
   - Integration with other related practices (such as composting)
5. Data collection/verification
   - Waste composition assessment
   - Detailed survey of current and anticipated waste volumes
   - Site conditions (e.g., geology and soil moisture)
6. Engineering of landfills
   - Vendor selection process
   - Site preparation process
   - Construction and commissioning
7. Emerging technologies in landfilling
   - Bioreactor landfills
   - Other technology options
8. Landfill operational practices
   - Developing Standard Operating Procedures (SOPs)
   - Daily procedures (daily cap, monitoring, rotation, etc.)
   - GHG Measurement, Monitoring and Verification systems
   - Power generation options
9. Long-term issues and monitoring
   - Landfill mining
   - Greenhouse gas mitigation
   - Demonstration projects

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Annex - A

Selected Recommended Background References

ANNEX A:
SELECTED RECOMMENDED LITERATURE CITATIONS ON LFG/GHGEMISSIONS FROM LANDFILLS

These following annotated literature references are illustrative, and are meant only as examples of publications that are recommended for development of a future annotated resource base for LFG abatement applications in Developing Countries. Copies of the cover pages and executive summaries are provided as part of Annex A.

1. Augenstein, D.C., and R. Yazdani, "Landfill Bioreactor Instrumentation and Monitoring" Proceedings EPA Workshop on Landfill Bioreactors, Wilmington Delaware, 1995. Review of methods for in situ sensors in landfills including measurements of gas recovery (gas flow and total flows), including pitot tubes, orifice systems, venturis, vortex shedding methods, thermal dispersions, turbines and positive displacement, along with turn-down ratios or ranges, and issues with in field applications. Problems in applying such methods for the large variation in gas flows commonly observed. This is a key paper.

2. Augenstein, D. and J. Pacey, 1992 "Landfill Gas Energy Utilization -Technology Options and Case Studies" U.S. EPA Report. About 200 pages. This gives case studies of landfill gas use at 6 U.S. and 5 U. K. sites, including modeling, the tuning of landfill gas extraction to fuel engines, and many other related practical topics.

3. Vogt, G. and D. Augenstein 1998, "Comparison of Models for Predicting Landfill Gas Recovery--a 19-landfill Study" Available from the Solid Water Association of North America (SWANA) Silver Spring, Md. A study of landfills to correlate methane emissions with models. See Text for discussion. This is a detailed technical report on landfill gas measurements.

4. Augenstein, D.C., D.L. Wise, N.X. Dat, and N.D. Khien, (1996). "Composting of Municipal Solid Waste and Sewage sludge: Potential for fuel gas production in a Developing Country". Resource Conservation and Recycling 16: 265 – 279. Discussion of technology for anaerobic composting (bioreactor landfills) as applied to a developing country (Vietnam). Provides liner designs, gas recovery estimates and cost estimates.

5. Gas Control Engineering, Inc. (1997) Landfill Gas Operation & Maintenance Manual. SWANA – (Solid Waste Association of North America). Appx. pp. 300. March 1997. Detailed technical manual in easy to use format of all things LFG. Much practical information, form LFG collection to flare operations and much, much more.

6. Edelmann, W. K. Schleiss, and A. Joss. (2000). Ecological, energetic and Economic comparisons of anaerobic digestion with different competing technologies to treat biogenic wastes. Water Sci. Techn. 41: 263-273 (2000). Looked at different compost/biogas plants and combinations for CO_2 and CH_4 emissions. "... even in

composts which are reversed very often, there also exist significant methane emissions, and ii) in digestion plants there is a considerable potential of methane emission even if just a small part of the organic breakdown takes place outside the (enclosed) digester. The measurements were taken on existing plants.". This is a most important finding for GHG emissions, as it demonstrates that composting plants are sources of methane. Indeed, composting may produce more CH_4 than bioreactor landfills depending on their exact operations.

7. Eam-o-pas, K., T. Wetherill, and B. Panpradist. (2000), Landfill Gas Generation and Recovery in Thailand. Proceedings 2nd Inter. Conf. Methane Mitigation. Novosibirsk, Russia, pp. 631 – 638. One of the few papers addressing methane emissions from landfills in LDCs. The differences in waste composition, moisture content and rainfall, temperature, and landfill practices makes most models and conclusions from U.S. and European practices inapplicable. Waterlogging was a major problem in the initial landfill, for example, making gas recovery impossible. A new landfill with better leachate control was operated with LFG recovery. The model used was based on the IPCC model based on an exponential decay with discount for gas emission prior to landfill closure. The main parameters were the methane generation potential (estimated at 50 m^3/t) and the decay constant, set at 0.15/y, compared to U.S. values of some 100 m^3/t and 0.04. They estimated some 300 m^3/hr of LFG to be recoverable from their 0.5 million ton landfill (18 m high, density 1 t/m^3) once it was closed in 2000. Gas production is expected to decline by half in ten years. They demonstrates the problems of making such estimates and need to consider local conditions, including weather and waste composition.

8. Diot, M., et al., (2001). Using a Landfill Mass Balance Model for examining Methane Pathway Field Measurement at Landfills. Proc. SWANA 6th Landfill Symposium, pp. 193. Compared methane measurements collected, emitted and oxidized with models. Reviews measurement methods and results as applied to landfills in France, including tracer methods, chamber methods, isotope methods (for bacterial methane oxidation) and compares results to models. A good example of the current state-of-the-art.

9. Dept. of Environment (UK). (1997). Landfill Design, Construction and Operational Practice, Waste Management Paper 26B. A detailed design manual with much practical information. Comprehensive, practical and useful.

10. Humer, M., and P. Lechner, (2001). Microorganisms against the Greenhouse Effect – Suitable Cover Layers for the Elimination of Methane Emission from Landfills. SWANA 6th Landfill Symposium. Excellent paper on using passive diffusion barriers of composted MSW for microbial oxidation. Demonstrates both the potential, limitations and pitfalls in this process. Clearly more R&D is required, but this is an excellent start.

11. Eden, R.D. and R. Smith, (1999). Guidance on Best Practice Flaring of Landfill Gas in the UK. Proc. Sardinia 99, 7th In. Waste Management and Landfill Symp., Review of the interim internal technical guidance fro best practice flaring of landfill gas" from the UK. Excellent guide to best practices as currently established.

12. Starka, F., et al. (1999). LFG Biofilter on Old Landfills. Proc. Sardinia 99, 7th In. Waste Management and Landfill Symp. A passive gas venting system combined with a filtering unit containing coal coke. A good example of the use of microbial oxidation for the destruction of methane in an actual landfill.

13. Dammann, B., J. Streese, and R. Stegmann (1999). Microbial Oxidation of Methane from Landfills. Sardinia 99, 7th In. Waste Managmt. Landfill Symp. Bench scale studies with MSW compost. Although experimental, the data is convincing, compost works.

Annex – B

Listing of Other References

ANNEX B:
OTHER PERTINENT LITERATURE CITATIONS ON LFG/GHG**EMISSIONS FROM LANDFILLS**

The following references are provided for background reference only. Many of these sources may not be as suitable for Indian conditions, but are nonetheless worthwhile for background purposes. The cover pages and executive summaries are not provided in this report.

1. Savage, G., L. Diaz, and C. G. Golueke. (1998). Guidance for Landfilling Waste in Economically Developing Countries. US. Environmental Protection Agency, EPA-600/R-98 040 April 1998. pp. 400. COMMENTS: This is a generic report that provides a very general, superficial and outdated guide to landfills. Landfill gas issues are treated cursorily, with the only reference to landfill gas modeling dating to 1979 (!) and most other references almost as dated. Technologies listed for LFG management (e.g. landfill gas drying using triethylene glycol) are inappropriate for even developed countries.

2. Bader, C. D. (2000). "Bioengineering. A Spurt in Technology in an Unexpected Area" MSW Management 12(4): 32 –41 (2002). A superficial and completely uncritical review of all new and novel technologies for MSW management, from the Yolo County bioreactor landfill project, to microturbines, anaerobic digestion and even ethanol from MSW.

3. SWANA (Solid Waste Association of North America). Annual International Solid Waste Exposition. Latest : 39th Annual Proceedings, "WASTECON 2001" (October 2001, Baltimore, MD). These Proceedings cover the whole MSW field, including some half dozen papers on LFG of specialist interest. One paper (see #7) reviewing bioreactor landfills.

4. Sullivan, P.S., R. B. Green. (2001). Air emissions, Methane Generation and Recovery and Energy Potential form Bioreactor Landfills: Comparing the Theoretical to the Actual." SWANA (Solid Waste Association of North America). Proceedings 39th Annual International Solid Waste Exposition, "WASTECON 2001" (October 2001, Baltimore, MD). pp. 243 - 250. A very general review of some half dozen bioreactor landfill projects, without specific data presented. Concludes that bioreactor landfills can increase LFG production without increasing fugitive emissions.

5. International Waste Management and Landfill Symposia. These Symposia are organized by the CISA Environmental Sanitary Engineering Center, Cagliari, Italy, and are held every two years in Sardinia (latest 8th, held in 2001). Latest Proceedings Available: 7th (1999). The proceedings are very extensive and expensive, but have few papers of specific interest.

6. Galle,B., J. Smuelsson, G. Borjesson and B.H. Svensson. (1999). Measurement of Methane Emissions from Landfills using FTIR Spectroscopy". Proc. Sardinia 99, 7th Int.

Waste Management and Landfill Symposium. CISA Environmental Sanitary Engineering Center, Cagliari, Italy, pp. IV-48 –54. This technique is very complex and requires "better meteorological supper... as well as model development, before reliable results can be obtained".

7. Scharff, H., and A. Hensen. (1999). "Methane Emissions Estimates for Two Landfills in the Netherlands using Mobile TDL Measurements". *Proc. Sardinia 99*, 7th Int. Waste Management and Landfill Symposium. CISA Environmental Sanitary Engineering Center, Cagliari, Italy, pp. IV-48 –54. The technique used, "Tunable Diode Laser" measures a methane plumes some 0.5 to 2 km from the source, at a "moderate cost" (about $8,000 per "campaign"), but this is a research tool not generally available. Data collected could be fitted to the LFG landfill emissions models by "with an assumed oxidation level in the top soil of 50%". The authors admit that maybe the model is too high and, thus also their assumed surface oxidation. They demonstrated at one landfill that a year after start of LFG extraction CH_4 emissions dropped by half, but the reliability of this is uncertain. An interesting approach, but not validated yet.

8. Block, D., (2000). "Reducing Greenhouse Gases at Landfills". Biocycle, April 2000. 41 – 49. A general overview, including of bioreactors, both aerobic and anaerobic, as well as of compost covers and C storage in soil from compost applications. Biocycle magazine has an editorial policy not to allow any critical commentary of any technology.

9. Garg, A., Bhattacharaya, S., P.R. Shukla, and V.K, Dadhwal, (2000). "Regional and Sectoral assessment of greenhouse gas emissions in India." Atmospheric Environment, 35: 2679 –2695. This paper provides a general overview of GHG in India, including an estimate of MSW (using IPCC default values). Recommended only for background information.

10. Baldasano, J.M., and C. Sorlano (2000), "Emission of greenhouse gases from anaerobic digestion processes: comparison with other municipal and solid waste treatments". Water Sci. Tech. 41: 275 – 282. This short paper compares total CH_4 plus CO_2 emissions for various treatment processes based on stoichiometric conversion factors (ignoring non-degradable waste fractions or kinetics). Contrary to IPCC guidelines treats CO_2 emissions from biological sources as a GHG. Composting is considered strictly aerobic. Results not interpretable.

11. Hellmann, B., et al. (1997). , Emission of Climate-Relevant Trace Gases and Succession of Microbial Communities during Open Windrow Composting" App. Env. Microbial., 63: 1011-1018 . This paper is one of the few that discusses, and measures, CH_4 and N_2O emissions from compost piles. Emphasizes measurements of microbial communities rather than quantitative trace gas emissions. Recommended only for background information

12. Jennings, A. and A. Cox. (2002). "Electronic Nose Technology Applied to Landfill Odors." SWANA 7th Landfill Symposium. Application of the "electronic nose", which

measures several organic contaminants creating odors. Difficulties in measurements detailed.

13. Cohen, S.H., (2002). International Project Development: Gathering Data to Support the Next Frontier for Landfill Gas Utilization. SWANA 25th Annual Landfill Gas Symposium.
A project to evaluate LFG utilization and mitigation opportunities in Developing Countries. "...data base still in its early stages" Could be a resource base for future projects.

14. Weitz, K. and S. Thorneloe, "EPA Applies MSW-DST to Assess its Own Composting Options". MSW Management 12 (4): 16 – 23 (2002).
A comparison of three options (landfill, on-site composting, and off-site composting) for treating the waste generated by the U.S. EPA' campus at Research Triangle Park in N. Carolina, using the MSW management "Decision Support Tool" developed by the US EPA. This is a very small waste generation, about 175 tons of organic refuse (57% food wastes, 35% yard trimmings, and less than 10% paper and animal bedding). Still the results were instructive: on –site composting was the preferred option overall, but landfills were superior to off-site composting because of differences in transportation impacts. Although interesting not a widely applicable result.

scenario". The experience of the KCDC in composting Bangalore MSW should be reviewed for an 'everyday' scenario.

"The performance of composting units in Bangalore has been a mixed bag" (Page 3-31). Although not amplified in the Report, we understand this to be due to problems with compost quality, inherent with MSW, due to lack of initial segregation or separation, which results in plastic, glass and metal in the compost. Marketing has also been difficult with MSW compost with prices (page 3-31 to 3-33) being about 1,000 Rupees/MT (see also Yazdani Report). However, the Reports (e.g. Chapter 9, elsewhere) states sales price of some 1,550 (US $31/MT), escalating some 12% every two years. However, these matters are not further addressed here. There is not discussed the type of waste that would be landfilled, in either option. The plant design and process economics (Chapter 9 "Estimated Cost of Operations") are based only on Option 2.

The compost process is assumed to be completed after 6 weeks (42 days), and there is little provision for curing and storage of compost on-site. More land is being acquired, which is needed to expand the compost operation to the full 680 TPD, as the present Kannahalli site only accommodates some 500 TPD. The plan is not to increase the flows to these sites over time. The calculations for the volume of windrows, in our opinion, appear to have been overestimated by almost two-fold in the Reports (the actual number is about 12 m3/linear meters, rather than the 23.5 m3/m stated on page 7-23, line 6). The exact value depends on the actual shape of the windrow (e.g. hemispherical or straight side with dome, as shown schematically on page 7-23). Thus the composting operation may require about twice the area anticipated. This calculation should be checked. (Yazdani reports that KCDC operates a 350 MT/day composting plant on 15 acres now). Also the windrows appear to be rather large in comparison to best practice windrow size.

The stated quantity of the "Digested Garbage" produced is given 364 TPD, at some 900 Kg/m^3, an almost 50% by weight and 70% by volume reduction. In our opinion, this result seems to be significantly overstated. The digested garbage is then processed by two stages of trommel screens to separate recyclables, producing 336 TPD of "Semifinished Goods" and finally 280 TDP "Finished Goods". The loss fractions are re-digestables (to be ground and returned to composting) and "remnants", which are landfilled. From this basis 80% of the MSW is "biodegradable" and composting will reduce the total weight of that fraction by 50% (Chapter 9). This calculates as a decrease in some 84 tons due to the processing of the "Digested Garbage". However, the Report (Table 8.4) states that the "remnants" from the composting plant that are to be landfilled amount to 105 TPD (year one, Option 1) or 70 TPD for Option 2. These mass balances appear inconsistent and should be rechecked.

From a GHG perspective, these are passive windrow composting operations, which apparently are only turned once a week. The large size of the windrows, their compaction, and infrequent turning, suggests that passive air diffusion will be the limiting factor (as it always is for passive systems), and there will be problems with odors and time to completion. The greatest impact, however, may be on compost quality, which is critical for its marketing. Sufficient experience exists in India, and Bangalore, to allow

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an in-depth discussion of these processes. From a GHG perspective, the major issue is the amount of methane gas that would be generated from the compost piles, as well as the fraction and methane potential of MSW that will be landfilled, both unknowns and further discussed in the next section of this report.

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Section 1.

Landfill Bioreactor Instrumentation and Monitoring

D Augenstein and R.Yazdani

Landfill Bioreactor Instrumentation and Monitoring

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Abstract

A number of landfill bioreactor measurements can be helpful in monitoring, controlling, and assessing progress of stabilization. Useful measurements include moisture content, moisture movement and temperature within waste, leachate flow and composition, and leachate pH. The anaerobic transformation of the organic fraction can be measured through gas flow rate, gas composition, and volume reduction.

Bioreactor landfill measurements may be demanding compared with measurements for "conventional" landfills. For example, gas generation is a good index of decomposition. Bioreactor gas recovery rates can vary over time scales from hours to years, however, and are often difficult to predict. Wide instrument range, and cumulative measurement, are necessary. In situ monitoring in the landfill environment requires robust instruments and careful installation techniques. In-waste sensors require leads, which can be subject to breakage; lead and sensor protection can be accomplished by various means including enclosure in rugged pipe. This document provides a general overview of reasons for various measurements, instrumentation types, and approaches for addressing some common problems.

Introduction

With "conventional" landfilling—defined here as the practice at most U.S. landfills—waste is placed in conformance to existing regulations. There is no particular attempt to manage conditions within the waste to facilitate biological reactions. Waste does decompose after landfilling (albeit slowly), however, and gas recovery may be practiced. Conventional landfilling usually has rather limited measurement needs associated with it. These may include monitoring of a recovered gas stream whose flow and composition remain relatively constant. Sometimes there is monitoring of ground water and soil methane to determine if there is undesirable migration of dissolved or gaseous species from waste to surroundings.

An alternative to "conventional" practice is to manage the landfill as a bioreactor in order to facilitate and speed biological reactions, methane generation, and waste stabilization. (This has been termed "controlled landfilling," with the landfill referred to as a "bioreactor landfill." Both terms are used below.) Controlled landfilling advantages can include waste volume reduction, increased energy recovery, and reduction of long-term landfill care costs, as addressed in other presentations of this symposium. Operation of the landfill as a bioreactor will benefit from monitoring and control of a variety of parameters, including (but not limited

are subject to breakage. High forces on leads and breakage can occur as waste is compacted or, later, as waste subsides with decomposition.

Even with such limitations, moisture measurements within the waste can be of high value. Readings from a sensor can verify arrival of moisture at a given point in waste. Moisture readings from sensors arrayed in a network throughout the waste mass are good indications of whether leachate recycle or other hydration means are effective. Hysteresis may be a factor (and shorten sensor lifetime), but these are not great problems; verification of initial moisture arrival is most critical, as it is likely that, once wetted, waste will remain sufficiently wet for biological activity. The lead breakage problem can be addressed as discussed below.

Gas Flow Measurement

Gas or methane generation (normalized in terms of volume per unit of dry waste) may be considered one of the best indicators of the progress of stabilization. The relative rate of generation—compared with typical landfill rates of 0.03 to 0.15 ft^3 methane per pound of waste per year (3 to 10 L/kg/yr)—indicates whether enhancement methods are successful in accelerating the normal rate of decomposition. The total cumulative generation—in turn a reflection of the mass of waste converted to gas—may be one of the best reflections of the degree to which stabilization is attained and, of course, of energy recovery.

Methods that may be applied to measure gas flow are shown in Table 2. It should be noted here that bioreactor landfill gas recovery measurements have been observed to be more demanding than such measurements with conventional landfills. The flow from bioreactor landfill sectors or cells may change rapidly, and variations of an order of magnitude or more (for various reasons) have been common (2-4). Figure 2 illustrates flow as measured from one test cell in the Mountain View, California, demonstration experiment. Similar fluctuations have been routine in other trials (4). "Conventional" landfill measurement approaches using infrequent, (say weekly) "point in time" measurements cannot accurately establish the rate of generation or the cumulative generation total of such a fluctuating gas flow. In addition, limited rangeabilities of common pressure-drop-based pitot tube and orifice methods (and venturi and turbine when used) cannot accommodate order-of-magnitude flow-rate variations. Ideally, bioreactor landfill gas recovery flow monitoring should combine cumulative volume measurement with wide range and contaminant resistance. This would also allow correction for temperature and pressure variation, although such corrections are usually minor. No method combining all desirable features has yet been reported in a bioreactor landfill operation; however, there are methods that should work (e.g., a corrosion-resistant positive displacement meter with temperature/pressure compensation). It is also possible to combine two or more meters that rely on differing measurement principles for redundance; agreement between two or more methods would strongly suggest accuracy.

Though the flow of recovered gas may be measured accurately, generation is often the measurement actually desired. Generation measurement can still be negated by gas leaks. These can comprise either leakage of gas out through containment (surface clay or membrane) or, in some cases, infiltration of air or gas from the surroundings into the waste. (In fact, it appears that full recovery of gas has not been validated in any bioreactor landfill test to date—which among other things has limited material balance closures.) With some types of containment design, it should be possible to detect and compensate for leaks. Leaks may be detected, and size of leak estimated, by following air intrusion (i. e., exit gas N_2/O_2) as

Temperature Determination in Pilled Waste

Temperature in waste importantly affects methanogenesis and other biological reactions (although it normally receives little attention as a bioreactor landfill variable). Methane fermentations appear to follow a classical Arrhenius reaction rate temperature dependence reasonably well; Figure 3 presents the Arrhenius plot of rate constant data from six different methane fermentation investigations (5) exhibiting an E_a of about 15 kcal/mol. (Temperature's importance is illustrated by the rate constant's 50-fold increase between 10°C and 55°C.) Landfill core samples have shown similar temperature dependence for methane generation (6). What could be termed "thermal effects" can occur as waste is warmed by methanogenesis, which is exothermic, while at the same time temperature is lost by conduction from the fill (2, 3, 7). The exotherm of methanogenesis can be sufficient to warm waste to 55°C to 60°C, at which point methanogenesis may be inhibited. Important consequences are that different portions of the waste may decompose at substantially different rates as temperature varies by locale; cooling may be necessary in situations where temperature can exceed 55°C to 60°C. Temperature monitoring can be useful in identifying these situations.

Sensing temperature is generally straightforward using thermocouples or thermistors. Temperature and moisture sensing are easily combined at locations within the waste. The principal problem with temperature sensing within the waste, common to all sensing within the waste, is lead protection, discussed below.

Leachate Composition and Flow Rate

Leachate composition and characteristics can reflect whether conditions are suitable for biological reactions or whether there are situations needing attention. Leachate should be at near-neutral pH. The principal concern would be high levels of organic acids and low pH (below about pH 6). These indicate "stuck" conditions that can inhibit methanogenesis. Such conditions, if more than transitory, require remedial action—by base addition, or withdrawal and recirculation/redistribution of acidic leachate through the waste. (Either approach should normally facilitate methanogenesis.) Other characteristics of leachate may be considered important in given situations. Alkalinity reflects the capability of leachate to buffer organic acids that may be formed in intermediate steps of decomposition. Nutrients, such as phosphate and free ammonia, may be of interest. Nutrients in waste appear normally to be at least minimal levels needed for decomposition. Supplementation may still be desired, however, and analyses of free nutrient levels in leachate indicate whether supplementation may be useful. (Leachate nutrient levels might also be correlated with rates of waste degradation in experimental situations.) Leachate biochemical oxygen demand (BOD) and organic acids are of environmental significance, as these reflect threats posed to ground water. Still other characteristics of leachate may also be of interest—assays for inhibitory activity of leachate may be important in cases where methane generation slows for unknown reasons.

pH measurements of leachate outflows (from waste sectors of interest) are easily made at the time and point of collection. (As noted, pH below about 6 indicates possible "stuck" [i.e., acid inhibited] conditions.) Other assays are typically more demanding. Organic acids are best assayed by gas chromatographic methods. Phosphate, ammonia nitrogen, BOD, and other assays that may be desired are standard wastewater tests. Biological methane potential assays

Hydrostatic head can be determined by differential pressure measurements, most commonly using transducers. Pressure at the base of the landfill must be compensated for gas pressure to get the true liquid head. Pressure can be measured at the base of the landfill and at elevations from one to several feet above the base. Pressure versus height measurements allow differentiation of the head, which is due to liquid (hydrostatic), and which is of regulatory concern, from the pressure component due to gas.

Waste Volume Reduction

By increasing waste-to-gas conversion, bioreactor landfill operation can substantially reduce landfilled waste volume. Lessened waste volume could be of major importance, insofar as it can translate into greater capacity of the landfill to accept waste for any given waste volume or height. Volume reduction can be straightforwardly followed by tracking subsidence of surface monuments, as practiced in past tests (3).

Placement of In-Waste Sensors and Lead Protection

In past field-scale demonstrations, moisture, temperature, and other sensors have typically been placed in waste by either of two routes: (a) insertion in pipes within vertical boreholes drilled after waste is filled, or (b) placement within waste as waste is filled. With the first route, leads within pipes are well protected and sensor replacement is possible. This process can be costly, however, and sealing of the well used to place the sensor may be a concern. Better contacting for moisture sensors can be afforded by the second route. With this route (i.e., placement within waste as filling occurs), horizontal lead wires to the sensors need to be protected during and after filling of the waste. Breakage may occur with compaction after sensors are placed or at later times as waste subsides with decomposition. The majority of landfill bioreactor tests appear to have experienced some loss of in situ sensors. In some cases, losses of some types of sensors with horizontal lead placement have been total.

Lead breakage can be reduced by enclosure of leads in rugged tubing or pipe. Preliminary tests (8) have shown that among candidate protective pipe (including flexible agricultural drainage and other types) flexible PVC fiber reinforced tubing best protects leads. Chances of breakage in leads can be further reduced by allowing 50 percent more tubing than the straight distance to accommodate for settlement. Further slack in the sensor lead—relative to the protective tube—can help ensure that any stresses are borne by the tube rather than the lead.

Computerized Data Collection and Processing

A complex system such as a landfill bioreactor can now benefit from real-time monitoring, data collection, and control. Recent advances in software and decreases in the cost of microprocessor instrumentation and controls now enable collection of various outputs and data from a variety of sensors simultaneously using a personal computer. The same software can control operations and further process archived data. The software has been developed for use in such applications as monitoring and control of heating, ventilating, and air conditioning (HVAC) systems and control of chemical processing trains. It appears quite adaptable to the needs associated with bioreactor landfill operation as well. A supervisory

Table 2. Methods for Assessing Gas Recovery (Flow Rate and Total Flow)

Method	Turndown Ratio	Contaminant Resistance	Accuracy of Reading (approx. limits, % of indicated reading)	Cumulation Possible	Comments
Pitot tube	Limited (4/1)	Excellent	+/-5 to 10%	Normally no	Simplest, most common field method
Orifice	Limited (ca. 4/1)	Excellent	+/-1 to 3%	Yes[a]	Common method—conventional landfills
Venturi	Limited (about 4/1)	Excellent	+/-1 to 2%	Yes[a]	–
Vortex shedding	Range (ca. 10/1)	Excellent	+/-1 to 5%	Yes[a]	–
Thermal dispersion	Range (ca. 10/1)	Excellent	+/-1 to 4%	Yes[a]	Gas composition may affect accuracy
Turbine	Range limited	May be poor	+/-1 to 5%	Yes[a]	Corrosion resistance needed; poor or absent in commercial versions
Positive displacement	Excellent zero to full scale	May be poor	+/-1%	Yes[b]	Corrosion resistance needed, poor or absent in commercial gas meters

[a]Cumulation normally electronic.

[b]Cumulation can be electronic or mechanical; cumulative gas volume normally registered mechanically.

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control and data acquisition (SCADA) system typically consists of a host computer linked to a remote telemetry unit (RTU) located at the landfill bioreactor site. It can collect and archive real-time data and perform control operations. Data collected at the landfill bioreactor and relayed by the RTU to the host computer can be displayed to observe trends and archived for future analysis.

Conclusion

This paper has provided a brief overview of some measurements that may be useful in monitoring and control of landfill bioreactors. Readers should recognize that other measurements are possible, and issues exist that were not covered above. (Further discussion and information on the various possible measurements is also contained in "Experimental System Instrumentation" by Dr. D.J.V. Campbell. An expert working group paper was prepared for the International Energy Agency in 1994 [9].) Bioreactor landfill technology is still developing. Where parameters were discussed, it should be recognized that optimum values for various parameters (e.g., nutrients, pH) in many respects remain to be established.

References

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2. Augenstein, D., J. Pacey, R. Moore, and S.A. Thorneloe. 1993. Landfill methane enhancement. Proceedings of the 1993 Annual International Landfill Gas Conference, Solid Waste Association of North America (SWANA), Silver Spring, MD.

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4. Campbell, D.J.V. 1991. Landfill gas enhancement: Brogborough test cell programme. Proceedings of the SWANA 14th Annual International Landfill Gas Symposium (March).

5. Ashare, E., D.L. Wise, and R.L. Wentworth. 1977. Fuel gas production from animal residue. Dynatech R/D Company Report 1551, final report under U.S. Department of Energy Contract EY-76-C-02-2991. Available from NTIS.

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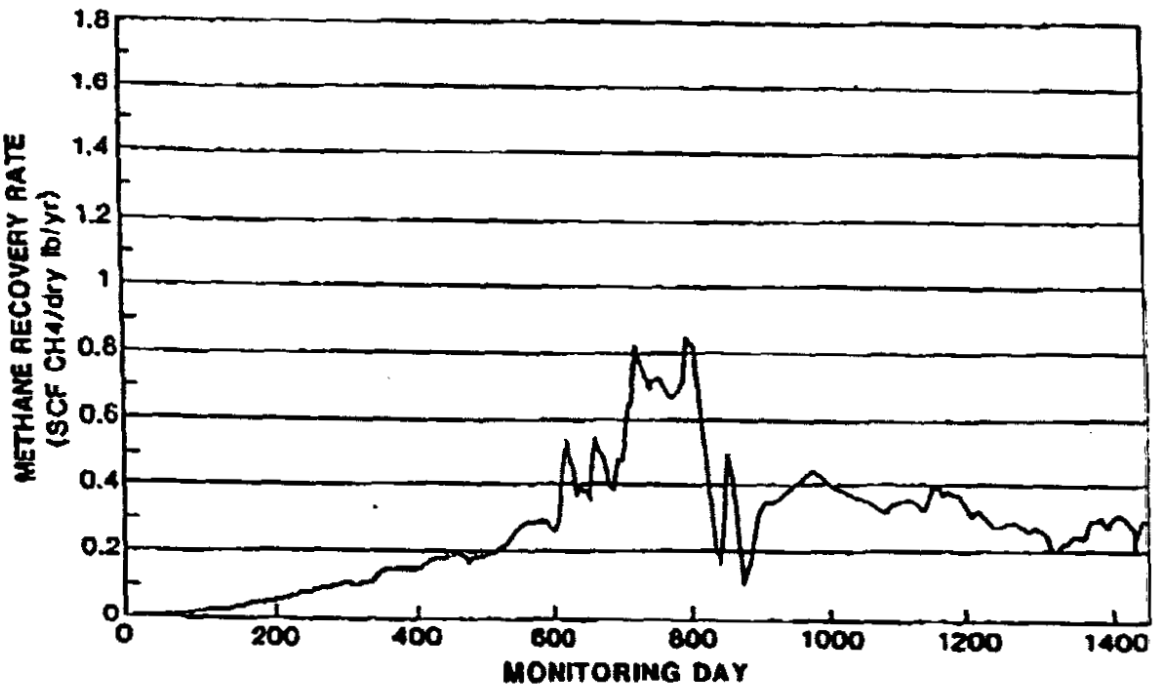

Figure 2. Gas recovery from Mountain View test landfill Cell F.

can show toxic or inhibitory conditions. Assays can be performed soon after collection (holding time minimized to limit associated composition changes). In some cases, however, it may be convenient to freeze samples on collection (which halts composition changes) until a number of samples can be assayed simultaneously.

Leachate flow rate can be measured in several ways. In many cases, flows can be estimated from level changes as holding tanks of one sort or another fill with outflowing leachate or empty as leachate from them is recirculated. A number of fouling-resistant flow measuring techniques are available including tipping bucket and magmeters, but there are few reports of actual long-term leachate flow rate measurements.

Waste Sampling and Measurements

Waste characteristics important in bioreactor landfill situations can include moisture content, cellulose and other decomposable content, lignin and other nondecomposable content, ash, nutrients, and bacterial populations. These parameters can in turn be important for purposes including development of material balances, estimating methane potential, and estimating needs for supplemental moisture or nutrients. One important sampling objective in past tests has been to determine the remaining methane potential of waste in landfills that are decomposing.

Probably the single greatest difficulty with waste sampling is posed by heterogeneity of waste. Significant batch-to-batch variations in waste arriving at the landfill may occur by season, area from which the waste was collected, etc. There will be variations in composition with location within the fill; reasons for in-fill variations include not only the mentioned variations in incoming waste but also hydraulic effects (liquid preferentially infiltrating or accumulating in certain areas). Waste characteristics in the fill may become even more variable with location and over time, as decomposition of either wetter or warmer waste is more rapid than slower and drier elements. (See above. In fact, it is an open question as to whether it is appropriate to refer to "the" waste composition in light of such variation.)

With all of the waste variability, however, the objective of sampling is often simply to determine an overall average of parameters within a given body or stream of waste. (The purposes, for example, include determining the degree of decomposition that has occurred and total methane potential that remains in the mass of waste.) Sampling can be carried out at multiple points to obtain the best possible "average" composition. Samples from corings should be taken at multiple levels. Samples from several locations may be ground and assayed for the average of the parameter desired.

Hydrostatic Head

Bioreactor landfills must operate in conformance to regulations affecting landfills. Perhaps the greatest regulatory concern with bioreactor landfills relates to increased moisture. Under current U.S. regulations, under elevated moisture conditions, hydrostatic head at the landfill base must nonetheless be kept below 30 cm to minimize the threat of ground-water contamination. Some state and local regulations may be more stringent (in the United States, California regulation requires "zero" head). Ground-water contamination concerns also exist in most other countries, although details of regulations may differ.

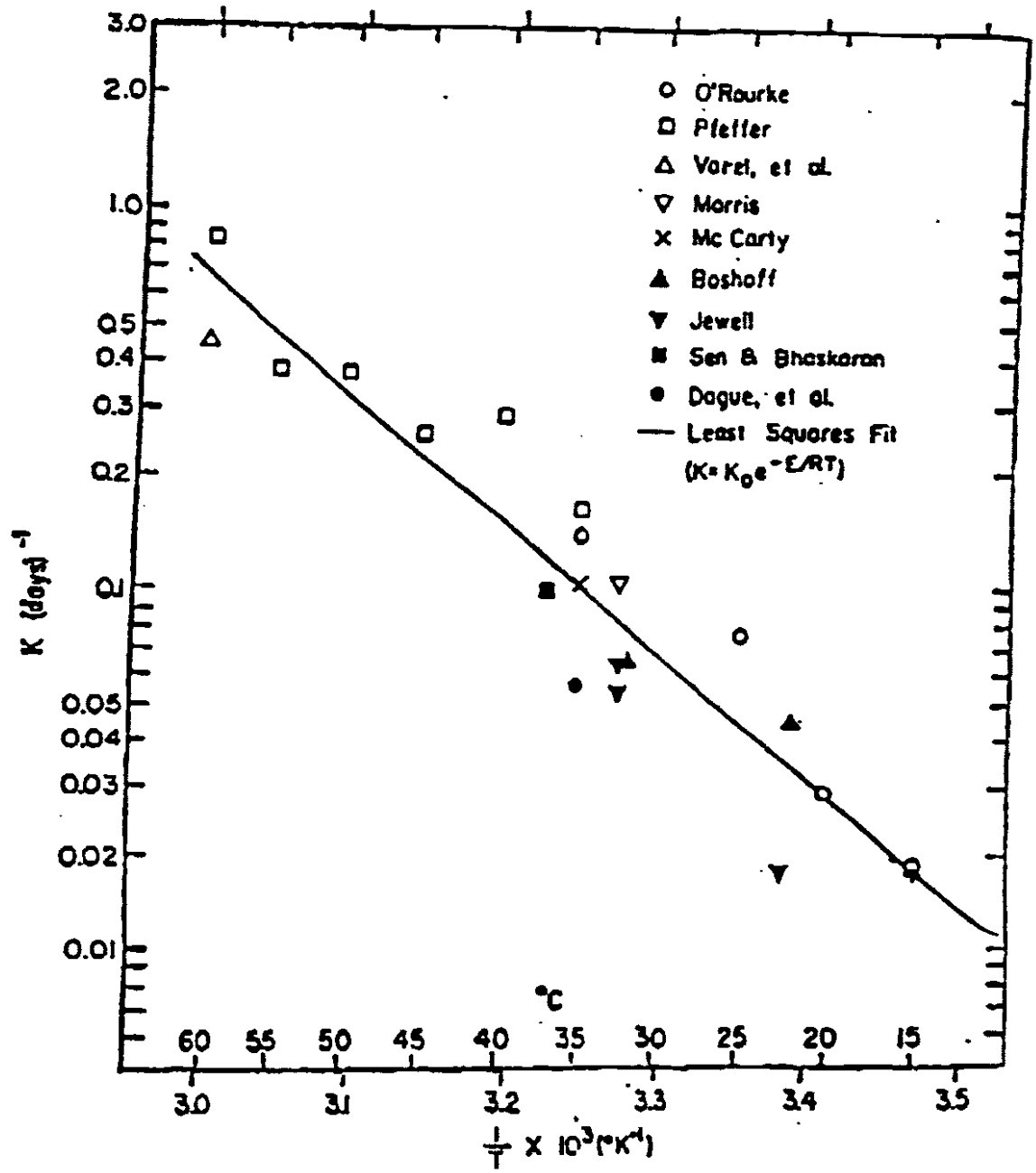

Figure 3. Arrhenius plot showing temperature dependence for methane fermentations of solid substrates (5).

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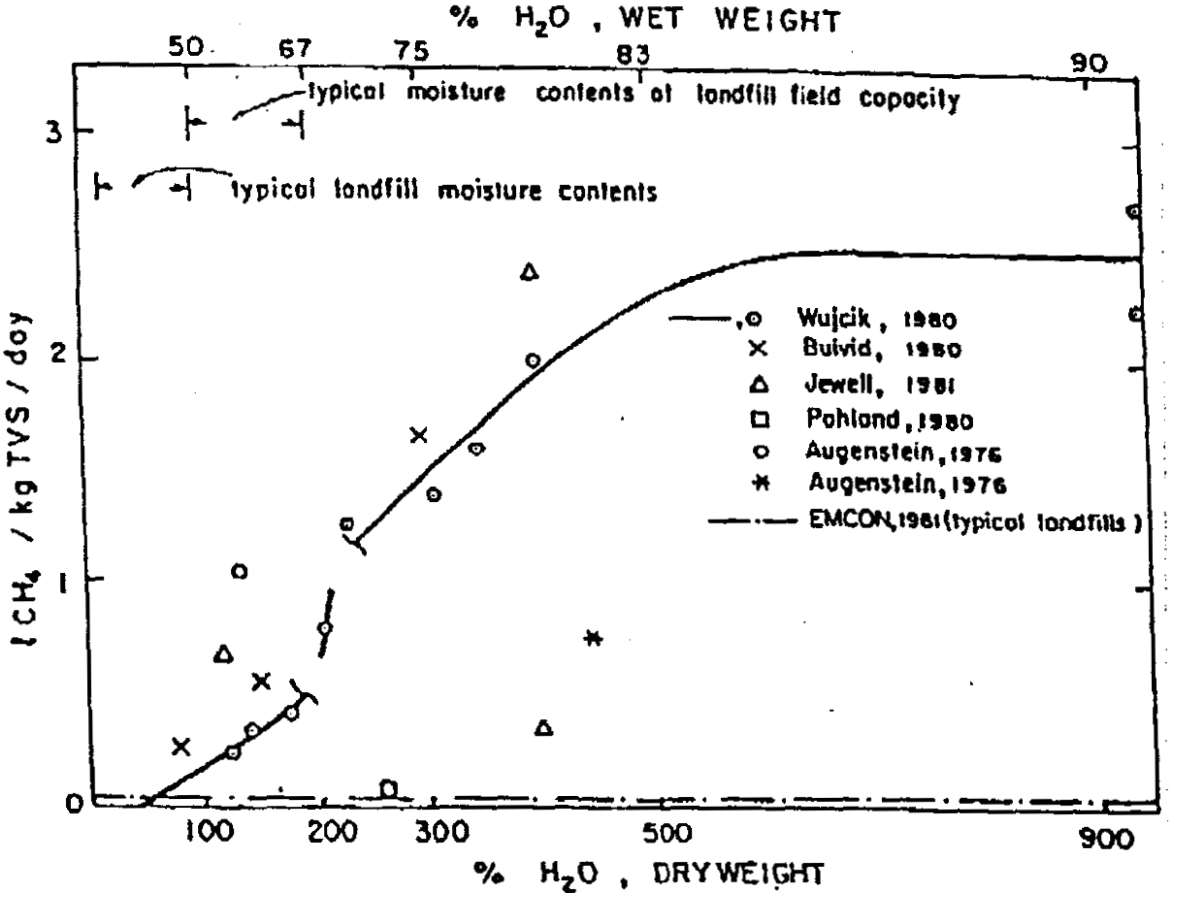

Figure 1. Methane production rate versus moisture content (1).

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to) moisture, pH, temperature, nutrients, and other factors discussed below. In addition, landfill bioreactors must be shown to operate within the constraints of all of the various regulations that affect landfills. Thus, numerous measurements can be quite useful in optimizing conditions and following performance. Some of the more important measurements are listed in Table 1.

The purpose here is to give readers, many of whom may be relatively unfamiliar with bioreactor landfills, a sense of why and how some measurements are made. The purpose of this paper is not to provide extensive detail on specific measurements or equipment (which in any case would be voluminous). Rather, the paper overviews measurements of Table 1 in general terms: importance of the measured parameter, instrument principles, issues and problems experienced in past test situations, and possible approaches that may be taken to overcome past difficulties.

Measurements

Moisture

Biological reactions leading to waste decomposition and methanogenesis can be promoted by numerous factors. While other factors can be important, moisture is paramount—essential for biological activities of methane generation. It is quite effective by itself (without other measures) in enhancing biological activity and methane generation with typical municipal wastes. Importance of moisture is illustrated by results of one survey showing effects of moisture on gas generation from solid waste as shown in Figure 1.

Moisture content at locations throughout the waste mass can be measured in situ by types of sensors (gypsum or other porous blocks) used in soil moisture determinations. Such sensors rely on electrical capacitance of the sensing element as it imbibes moisture from the surrounding waste. Issues in using such soil moisture sensors include:

- Installation: The sensors must be properly emplaced within waste to take up moisture and give a meaningful reading. Direct contact with even a slight amount of moist waste may give a high "false positive." The sensor can be surrounded by about a 1-ft layer of soil, which transmits moisture to the sensor so that its reading best represents the average level in the surrounding waste.

- Percentage of moisture measurements: The sensors' capacitance (current flow under applied AC voltage) is an indirect indicator of the parameter of interest, percentage of moisture by weight, the parameter most frequently correlated with biological activity and methane generation. (Calibration can be done to correlate sensor reading with percentage of moisture, however.)

- Hysteresis: Once wet, sensors tend to remain wet. Thus, sensors are most useful for measuring moisture arrival at the sensor locations in waste.

An additional, general problem exists with all measurements that are carried out in situ (in the waste itself): electrical (or sometimes other types such as gas conducting) leads are required to serve sensors within waste. Leads and, to a lesser extent, the sensors themselves

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8. Institute for Environmental Management. Yolo County, California, Landfill Methane Enhancement Project, Palo Alto, CA (in progress).

9. Campbell, D.J.V. 1994. Experimental system instrumentation. Expert working group paper prepared for International Energy Agency.

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Table 1. Important Landfill Bioreactor Measurements (Partial List)

(See text for discussion)

1. **Moisture content/activity/matric potential in waste mass**

2. **Total gas generation (normalized to waste)**

   Rate of generation
   Cumulative generation

3. **Gas stream composition (methane content)**

4. **Internal temperature in waste mass**

   Temperature by location

5. **Leachate flow rate**

6. **Leachate composition/characteristics**

   pH
   Nutrient content (NH_4^+, $PO_4^{=}$,)
   Alkalinity

7. **Waste characterization**

   Cellulose content
   Ash, lignin content
   Nutrient content

8. **Hydrostatic head, key locations (base)**

Section II.

Landfill Gas Energy Utilization – Technology options and Case Studies

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LANDFILL GAS ENERGY UTILIZATION: TECHNOLOGY OPTIONS AND CASE STUDIES

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FOREWORD

Landfill gas has been successfully used for energy at many locations in the U.S. and worldwide, providing economic, environmental, and other benefits. However, landfill gas energy uses are also relatively new, and technologies are far from "cut and dried." There are limitations and special considerations with landfill gas energy use; a number of landfill gas energy projects have experienced problems, or even failed entirely. There is current need for documentation of experience and consolidation of information in several areas regarding the use of landfill gas as a fuel.

This report reviews the various landfill gas energy uses, and their associated issues and constraints. It also presents case studies of six landfill gas energy projects in the U.S. The report's purposes include

- Presenting overviews of use and equipment options, and technical and other considerations with landfill gas energy applications.
- Providing information on projects that illustrate common landfill gas energy uses.
- Providing an awareness of limitations and potential pitfalls existing with landfill gas energy use.

In addition to providing background on energy uses, it is anticipated that the report will help identify areas needing attention, for entities such as researchers and equipment manufacturers. It is also hoped that the report can provide information useful in identifying ways to facilitate the beneficial uses of landfill gas by reducing nontechnical barriers.

The complexities of landfill gas energy uses are such that the discussions of many issues must be limited to overviews. Where detail is available elsewhere the report refers to available literature containing that information. This is also true for the case studies; these attempt to provide information so that a typical reader with some limited background will have a reasonable understanding of the operation, based on a representative description of a particular energy application. This document is not intended to provide the degree of detail needed to design and operate a landfill gas energy facility.

The case studies rely on information provided by many individual operators, equipment manufacturers, and others such as engineering firms. An effort has been made to verify statements and data as much as possible. In particular, all sections of the report have been reviewed by the providers of the original information and others with appropriate expertise. Background information is cited from literature and other sources considered reliable, and it has also been reviewed.

ABSTRACT

Combustible, methane-containing gas from refuse decomposing in landfills, or "landfill gas," can be fuel for a variety of energy applications. This report presents case studies of projects in the United States where it has been used for energy. It also presents overviews of some of the important issues regarding landfill gas energy uses, including appropriate equipment, costs and benefits, environmental concerns, and obstacles and problems of such energy uses.

With allowance for its properties, landfill gas can be used in much commercially available equipment that normally uses more conventional fuels such as pipeline natural gas. This includes equipment for space heating, boilers, process heat provision and electric power generation. Landfill gas energy uses, already significant, could increase based on estimates of the landfill gas that could be recovered, and providing that other factors, particularly economic ones, are favorable. Such energy uses have environmental and conservation benefits.

Factors to be considered in using landfill gas for energy include contaminants, which can corrode equipment and cause other problems, and its lower energy content, resulting in moderate equipment derating. Other issues that are of normal concern for landfill gas, such as forecasting its recoverable quantity over time, and its efficient collection, also bear importantly on its use for energy.

The case studies review landfill gas energy use at six sites in the U.S. The energy applications include electric power generation by reciprocating internal combustion engines, electric power generation by gas turbine, space heating, and steam generation in a large industrial boiler. Case study applications are considered to represent attractive candidate uses for implementation at additional U.S. landfill sites. The case studies present the relevant site features, background regarding the development of the case study project, equipment used, operating experience, economics, and future plans at the sites. Obstacles and problems at the sites are discussed. The case study sites exhibit wide variation in features such as cost and degree of operating difficulty experienced. Such variation is typical of landfill gas energy projects, which tend to be site specific. Literature containing information on other relevant case studies, in both the U.S. and other countries, is also referenced.

Important conclusions include

- Landfill gas can be a satisfactory fuel for a wide variety of applications. Such uses have environmental and conservation benefits. Many types of energy equipment designed for "conventional" fuels can operate on landfill gas with outputs reduced by about 5 to 20 percent.
- Allowances must be made for the unique properties of landfill gas and particularly its contaminants. Pitfalls possible in landfill gas energy applications include equipment damage due to such gas contaminants, and shortages resulting from over-estimation of its availability.
- The degree of gas cleanup and the methods used vary widely; the necessary amount of cleanup and the optimum tradeoffs between cleanup stringency and the frequency of maintenance steps (such as oil changes) are not well established.
- Cost-to-benefit ratios can vary widely; at some sites they are excellent, while at others they are a major limiting factor. Economics are probably the most important factor limiting landfill gas energy uses. Economics currently tend to preclude smaller scale uses, uses where electric power sale prices are low, and uses at remote sites lacking convenient energy applications or outlets. Much of the landfill gas generated today is not used for energy because of economics.

- Energy equipment emission limits in some U.S. locations may also restrict landfill gas energy use, despite an environmental balance sheet that generally appears to be positive.

This report identifies technical areas where energy uses are likely to benefit from improvements. Some of these are alluded to above. This report also comments briefly on incentive, barrier elimination, and other approaches that may facilitate landfill gas use. Finally, for present and future landfill gas users, further detailed documentation of the problems experienced, and the results of approaches to them (both successful and unsuccessful), would be very helpful.

This report was submitted by EMCON Associates, in fulfillment of subcontract 275-026-31-05 from Radian Corporation, as well as subcontract 93.3 from E.H. Pechan and Associates, and performed under the overall sponsorship and direction of the U.S. Environmental Protection Agency, Global Emissions and Control Division. This report covers a period from February 1991 to January 1992, and work was completed as of February 1992.

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CONVERSIONS

Readers more familiar with metric units may use the following to convert to that system.

Nonmetric	Times	Yields Metric
acre	0.4047	hectares
Btu	252	Calories
ft	0.3048	meters
ft^2	0.0929	square meters
ft^3	28.32	liters
gal.	3.785	liters
hp	0.748	kilowatt
in.	2.54	centimeters
in. H_2O (head)	248.9	Pascal
in. Hg	3386	Pascal
lb. mass	0.4536	kilogram
inch	2.54	centimeter
mile	1.609	kilometer
psi	6895	Pascal
U.S. ton	0.907	metric ton

Temperature

Degrees Celsius = 0.556 (Degrees Fahrenheit - 32)

Degrees Fahrenheit = 1.8 (Degrees Celsius) + 32

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1. INTRODUCTION AND BACKGROUND

This report's primary purpose is to provide information on landfill gas energy uses. The report is addressed to a range of readers, presumed to include not only those familiar with landfills, landfill gas energy, and related issues, but also some who may have relatively little familiarity with these areas.

A major report focus is case studies that document experience at representative U.S. sites where landfill gas has been used for energy. To accommodate needs of the expected range of readers, the report also presents background that should be useful to those developing knowledge of landfill gas energy uses, and helpful for understanding of the case studies. Thus, the first section of this report provides general background relating to landfills and landfill gas energy uses. This is followed in the second section by a discussion of technical issues associated with landfill gas as a fuel—including the specific characteristics of landfill gas as a fuel, and particular needs occurring with its use. The third and fourth sections of the report cover equipment issues and economics. These are followed by case studies and conclusions. It is hoped that this accommodates the needs of the anticipated range of readers.

The following section provides background primarily for the benefit of those who may have limited familiarity with solid waste landfills, landfill gas, and landfill gas energy topics. Some of the basics pertinent to the use of landfill gas as a fuel include

- what landfill gas is, and its origin
- its composition
- forecasting the quantity recoverable for fuel uses over time
- methodologies for its recovery
- environmental issues with landfill gas extraction and energy use
- regulatory demands and constraints regarding its use

These are covered below to provide a context for further discussion of energy applications in later sections. Summary discussions of certain topics are supported with more detailed information in appendices.

1.1 Landfills and Landfill Gas: General

Sanitary landfilling is the main method for disposal of municipal and household solid waste or refuse ("garbage") in the United States. With current practice at landfills (no longer called "dumps"), wastes received are spread, compacted, and covered daily with a soil cover to reduce blowing litter, manage bird and rodent activity, and control odors. The process continues over a given area until a planned waste depth is reached; wastes are then covered with a final cover that has a relatively impermeable component (often clay) to limit surface-water infiltration. Sanitary landfilling increased sharply in the U.S. in the early 1970s as open dumping and incineration were restricted. An estimated 145 million tons* of wastes are currently landfilled annually in the U.S. (Kaldjian, 1990).

Most early practitioners of sanitary landfilling apparently trusted that waste decomposition would be of minor consequence. However, even maintenance of an oxygen-free and relatively dry landfilled waste

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* For readers more familiar with metric units, conversion factors are provided at the end of the front matter

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environment still permits certain biological reactions; these produce "landfill gas," and its generation can be significant.

Landfill gas consists principally of a mix of two gases: methane (chemical formula CH_4) and carbon dioxide (chemical formula CO_2). It is generated through bacterial decomposition of organic refuse in the absence of oxygen (anaerobic fermentation) (Geyer, 1972; EMCON, 1982, Gas Research Institute, 1982). It is produced by nearly all landfills in which refuse is buried such that oxygen is effectively excluded. Although many reaction steps and intermediates can be involved, the basic biochemical reaction is exemplified by the decomposition of cellulose (the principal component of paper, and a constituent of much other refuse material):

$$\underset{\text{cellulose}}{n(C_6H_{10}O_5)} + \underset{\text{water}}{nH_2O} \xrightarrow[\text{(bacteria)}]{} \underset{\text{methane}}{3nCH_4} + \underset{\text{carbon dioxide}}{3nCO_2}$$

Though this reaction scheme is simplified, it represents the overall process fairly well; most landfill gas is produced from decomposing cellulose, and most cellulose that decomposes yields methane and carbon dioxide.

Because of its methane gas component (the same methane that makes up "natural" or pipeline gas), landfill gas is a fuel. With proper allowances for its properties, landfill gas can be used for fuel in many applications where other fuels, particularly natural gas, are used. These fuel uses of landfill gas are the major focus of this report.

Landfill gas can be a significant energy resource. It is currently used at more than 100 U.S. sites (Government Advisory Associates, 1991); its use is continuing to expand. Estimates of the ultimate energy potential of U.S. landfill gas vary, but information in various references (U.S. EPA, 1991; American Gas Association, 1980) suggest recoverable energy potentials ranging between 0.2 percent to over 1 percent of the total of U.S. energy use. Though the expressed percentage of U.S. energy use might appear modest, the quantities are significant, given the total amount of energy the U.S. uses.

1.2 Composition of Landfill Gas

Characteristic composition ranges for landfill gas are shown in table 1. These are typical for "as extracted" gas as it is recovered. Also shown for comparison are the properties of "natural" or pipeline gas. As seen in table 1, landfill gas consists primarily of methane and carbon dioxide, usually in close-to-equal amounts. In contrast to pipeline gas, landfill gas also contains significant amounts of water vapor and traces of various organic compounds. Almost all of the organic compounds found in the gas (usually referred to as non-methane organic compounds [NMOCs] or sometimes reactive organic gases [ROGs]) originate through evaporation into the gas of the man-made solvents, propellants, and similar materials discarded in the refuse stream; paint solvent vapors are one of many possible examples in this category. Further discussion of these landfill gas components is presented elsewhere (Gas Research Institute, 1982; Emerson and Baker, 1991). Landfill gas as extracted can contain nitrogen and, less frequently, oxygen from air entrained as a consequence of extraction; the concentrations of these gases depend on the extraction objective and approach (Augenstein and Pacey, 1991). Landfills also contain a large amount of soil and other particulate material, and the extracted gas can pick up and carry with it a significant amount of that particulate material.

The landfill gas components other than methane have effects that are often substantial on its energy uses. Carbon dioxide, nitrogen, and (to a slight extent) water vapor can result in dilution and other effects that moderately reduce energy equipment capacity. The trace organic components (particularly the halogenated hydrocarbons) and particulates can cause serious energy equipment problems, including corrosion and accelerated wear. These effects are discussed in more detail in the next section.

TABLE 1. COMPARISON OF COMPONENT CONCENTRATIONS AND OTHER PROPERTIES:

PIPELINE ("NATURAL") GAS AND LANDFILL GAS

Component	Pipeline Gas	Landfill Gas (as extracted)
Methane, CH_4, percent	90-99	40-55
Ethane + Propane, percent	1-5	-0-
Water vapor, percent	<0.01	1-10 (typical)
CO_2, percent	0-5	35-50
Nitrogen, other inerts, percent	0-2 (typical)	0-20
Trace condensible hydrocarbons (NMOC's; ppmv as hexane)	-0-	250-3,000 (typical)
Chlorine in organic compounds (micrograms per liter)	-0-	30-300
Hydrogen sulfide (parts per million)	up to 15	to 200
Higher Heating Value, Btu/ft^3	950-1050	400-550

Information from sources including references (Gas Engineers Handbook, 1965; EMCON, 1982). Units are those most commonly used for the stated component.

1.3 Estimating the Gas Recoverable for Energy Uses

Energy users have a critical need to know the gas quantity potentially recoverable over time from a landfill for energy use. The approaches that can be used to estimate this include modeling and field extraction tests. This topic is important because misestimates of gas availability are among the common causes of problems with energy applications. For readers interested in forecasting gas availability for end uses, further discussion is presented in appendix A.

1.4 Gas Extraction Systems

The landfill gas extraction system collects gas generated by the landfilled refuse, and delivers it to the energy application. The overall concern of the gas energy user is that the system will continue to provide a reliable supply of gas in the necessary quantity. Collection efficiency may also be a concern; it depends on design and operational factors and may range between 50 and 95 percent. Further discussion of gas collection is presented in appendix B.

The topics of gas recovery systems, and extraction practice are important because difficulties with collection systems are also among the common causes of problems with energy facilities.

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1.5 Environmental and Conservation Aspects of Landfill Gas Energy Use

The energy uses of landfill gas have significant environmental consequences that are considered to be predominantly beneficial. The gas extraction process helps abate both gas migration hazards and the emission of reactive organic gases that contribute to air pollution. A particular current concern is the contribution of landfill methane emissions to atmospheric methane buildup, "radiative forcing," and resulting climatic effects ("greenhouse effect"). Extraction and use mitigates these. The energy use of landfill methane also "offsets" fossil fuel use elsewhere, and reduces secondary pollution and the consequences of carbon dioxide emission that could otherwise be produced by use of that fossil fuel. Its energy use also comprises conservation. These issues are discussed elsewhere (U.S. EPA, 1991, Thomeloe and Peer, 1991; Augenstein, 1990); a further description of these issues with references to relevant literature is presented in appendix C.

1.6 Regulatory Issues

Those who become involved with using landfill gas for energy will generally be affected by many regulations that pertain to landfill gas energy use. Among the most important of these are

- Proposed federal regulations associated with the recently amended Clean Air Act. These propose limits above which NMOC/ROG emissions must be controlled, and specify the required degree of abatement. As one consequence of these regulations, most larger landfills now without energy systems, but which would be capable of supporting them, will probably be required to install gas extraction systems.
- Regulations applicable to landfill gas management, which vary locally across the U.S., and that define the performance of gas systems based on factors such as prevention of off-site migration and reduction of atmospheric NMOC/ROG emissions.
- Regulations associated with the Public Utility Regulatory Policy Act (PURPA). These facilitate the sale of electric power produced from landfill gas to utility grids.
- Federal tax credit incentives that significantly improve the economics of the gas recovery process and of energy uses.
- State regulations that provide incentives to energy production.
- Emission restrictions that apply to energy equipment.

An overview of regulations, regulatory issues, and their consequences is presented in more detail in appendix D.

2. USE OF LANDFILL GAS AS A FUEL—TECHNICAL ISSUES

This section describes the technical issues regarding use of landfill gas as a fuel. Noted as background is that a very large body of information on energy and equipment fundamentals is available from a variety of sources, such as standard texts, and equipment manufacturers. As such information is widely available elsewhere, discussion of such standard energy technology aspects will be limited below. This and later sections concentrate on the unique aspects of landfill gas, compared to conventional fuels, for which different approaches are needed and from which performance differences, surprises, and problems, may arise. These aspects would normally be of greatest concern to energy users. Discussion also concentrates more on applications (detailed further in section 3) that appear the greater near-term opportunities. Thus electrical and boiler use issues are emphasized over, for example, those with pipeline gas preparation.

Some major issues that must be recognized and dealt with in energy use are

- determining the composition and characteristics of the gas
- potential corrosion effects caused by gas components
- effects of particulates
- gas cleanup
- dilution and other performance reduction effects
- load factor

These are addressed briefly below. In addressing these issues it is assumed that readers have at least some understanding of energy technology.

2.1 Gas Composition Analysis

In contrast to the case with more "conventional" fuels, users of landfill gas for energy may need to check their fuel composition fairly regularly. Landfill gas composition and energy content can change because of extraction procedures, leaks, or other factors. Gas systems often need to be "tuned" to provide a gas stream of appropriate quality to keep energy equipment running, and this tuning can require frequent well-by-well analysis. The gas will also contain a range of contaminants, whose level varies by landfill and over time. Since gas composition can have important energy consequences, composition analysis is reviewed briefly in appendix E.

2.2 Corrosion Effects

Serious equipment corrosion can be associated with landfill gas energy use. Corrosion is generally due to hydrogen chloride and fluoride resulting from combustion of halocarbons (chlorine- and fluorine-containing or halogenated, organic compounds) that are present in the gas. These compounds include, for example, the chlorofluorocarbons (CFCs) that were widely used in the past as refrigerants and aerosol propellants. Though CFCs are now being phased out because of environmental effects, they are still found in landfill gas (as old aerosol containers in the landfills release their contents over time). Other chlorinated compounds (such as industrial degreasing and dry cleaning solvents) also find their way into landfills and then into the gas.

Though levels of hydrogen chloride in combustion product gases are low, the hydrogen chloride is readily reactive with, for example, the metal in reciprocating internal combustion (IC) engines. Damage can result when metal in IC engine cylinder walls and other engine parts (including exhaust valves) reacts and

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is removed. Hydrogen chloride and fluoride can also react with metal in other equipment such as the tubes of boilers. Secondary damage can result from the buildup of solid corrosion products on the surfaces of moving engine parts. For example, deposits can reduce piston/cylinder or other lubricated surface clearances to zero, at which point the engine seizes and will be severely damaged. Case studies presented later in this report document such damage.

One engine manufacturer reports, based on many tests, that the content of chlorine in landfill gas chemically bound in volatile compounds, is typically between 60 and 200 micrograms per liter of gas[1] Because of corrosion effects, all engine manufacturers recommend that landfill gas be analyzed for its content of chlorine in chlorinated compounds (Chadwick, 1989). Various operating modifications (to be discussed later) are also recommended to prevent engine wear. The measures taken are generally, but not uniformly or completely, successful in limiting corrosion effects.

The gas can also contain other potentially troublesome chemical contaminants; for example acetic and other organic acids in the landfill gas condensate can react with steel. Problems from this source are however, relatively minor.

2.3 Particulates and Their Effects

Experience has shown that particulate contaminants entering with the gas can build up in the oil used in many landfill gas engines, accumulating until they present problems. Particulate contaminants are of various types, including silica (a common soil component), iron salts (where steel is used in collection systems), and other normal soil components. (One interesting source of particulate contaminants in oil is a gaseous silicon compound, dimethyl siloxane, which will combust to products including silica. It is not removable by normal gas cleaning methods.)

Discussion of these compounds, and their effects on IC engines, are presented in references including Vaglia, 1989. Buildup of these components in oil above certain levels can contribute to wear. These materials can damage cylinder linings and rings; heavy deposits can also form on combustion chamber surfaces. The potential deleterious effects of particulate contaminants, as well as gaseous and liquid contaminants discussed earlier, make gas cleanup extremely important, as discussed next.

2.4 Gas Cleanup

Users of landfill gas for energy have often practiced what could be considered relatively limited cleanup (this excepts pipeline gas preparation, discussed later). Limited cleanup has provided satisfactory operating results at may sites including one case study site of this report. In other cases, however, the application of more apparently thorough cleanup, which for landfill gas can be considered "state-of-the-art," has not prevented "frozen" engines, or corroded equipment, and similar mishaps.

The primary "generic" cleanup approaches are filtration and condensate knockout. These are sometimes augmented by refrigeration, and less often by desiccation and other approaches.

Landfill gas filtration can employ the same type of equipment as used (for example) in large-volume cleaning for internal combustion engines and combustion gas turbines. Filters may include simple particle size cutoff or coalescing models. Some description of these is included in the case studies. Refrigeration, to remove gas steam contaminants by condensation, is now practiced at a number of sites. Typically the gas stream may exit a landfill wellhead at a temperature exceeding 100°F, saturated with water vapor; cool (with condensate removal) to near ambient temperature on its way to the energy facility and then be refrigerated further, for contaminant removal to a dew point (typically) of 1°C or about 34 This cooling will typically remove between 80 to 95 percent of the water and a fraction of ot

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1 Personal communication, Greg Sorge, Waukesha Engine Division of Dresser Industries, Waukesha, Wisconsin, June 1991

condensible contaminants (which is a function of the specific contaminant's vapor pressure, concentration, and other factors).

Where refrigeration is practiced, icing and high parasitic energy consumption normally limit gas cooling for cleanup purposes to a lower temperature slightly above the freezing point of water. The problem with this limit is that gas compounds that may cause corrosion problems, in particular the lower-boiling halogenated compounds that are a major part of the threat to equipment are not removed. Where prevention of condensate (ice or liquid) in the treated gas is a must—for example where compressed landfill gas is to be pipelined in cold climates—chemical desiccation may be applied to reduce dew points to well below the freezing point of water.

Approaches to more completely remove contaminants from landfill gas (but that still leave CO_2 in) have been applied; on a commercial scale, the Olinda site (Vaglia; 1989, GRCDA, 1986) uses the Selexol® process to remove contaminants. Other approaches, including absorption of gas components on activated carbon, have been demonstrated but only on a pilot scale (Watson, 1990).

As a summary observation, the cost-effective cleanup methods to date (except those for purification of gas to pipeline standards) all leave some fraction of contaminants, and particularly halocarbon components, in the gas. These contaminants are difficult to remove because of their low boiling points, concentrations, poor affinity for traditional solvents or a combination of these factors. The economic tradeoffs between more complete removal of various contaminants, and simply dealing with their effects when the gas is used for energy (by such means as more frequent engine oil changes) and other engine design and operational modifications, are not completely evaluated. The correlation between degrees of cleanup, observed levels of energy equipment corrosion, and performance needs further analysis.

These observations about cleanup pertain to most energy applications, except purification to pipeline quality gas, where far more thorough cleanup is applied to remove nearly all compounds except the methane component from the gas. Pipeline gas cleanup will be discussed further below.

2.5 Dilution and Other Performance Reduction Effects With Landfill Gas

Because landfill gas contains inert components—close to half carbon dioxide, and smaller amounts of nitrogen and water vapor—the performance of energy equipment is typically reduced compared to its performance with more "conventional" fuels such as pipeline gas. The equipment rating does not (as might first be thought) decrease proportionally to the gas energy-content reduction (i. e., the rating of equipment on 500 Btu per cubic foot [Btu/ft^3] landfill gas does not decrease to half the rating of equipment on 1,000 Btu/ft^3 pipeline gas). The fractional loss of rating (derating) instead depends in a complex way on fuel-air mix heating value and the combustion characteristics of the landfill gas used in the energy application. For naturally aspirated IC engines, the dilution effect of CO_2 at equal input flow rates of fuel-air mix can reduce the energy content of the gas in the cylinder's combustion chamber by about 8 to 10 percent, which will reduce the power output by this amount based on energy throughput considerations alone. The inert components can also have slight secondary effects in reducing flame-front velocity and combustion temperature, which reduce efficiency by a slight additional amount, so that the engine rating is reduced, overall, by 10 to 12 percent.

For energy equipment that burns pressurized nonstoichiometric fuel mixes, such as lean-burn IC engines and gas turbines, energy efficiency losses occur from another source: landfill gas at atmospheric pressure requires compression work that is a parasitic load. This is in comparison to pipeline gas, which is typically available at the required pressures. This tends to reduce efficiency (which can vary somewhat independently of output) by 5 to 15 percent for lean-burn engines on landfill gas.

In boilers and process and space heating applications where landfill gas is used in burners, heat output reduction at constant total fuel-air volumetric throughput is about 12 percent. About 10 percent of the reduction is because of inert gas dilution, with the remaining 2 percent because of increased stack heat losses. Refrigeration, if practiced for cleanup, can reduce efficiency by (very roughly) another 5 percent.

Overall, landfill gas energy users should be prepared for energy equipment rating losses that range between 5 and 20 percent, depending on the application.

2.6 Load Factor ("Use it or lose it")

One consideration regarding landfill gas is that there is currently no well-established way of storing it. It must be used essentially as it is generated, or it is lost. This means that it is most suitable for energy applications that are constant and continuous such as electric power generation, pipeline use (with purification), or continuous or near-continuous plant process use. Intermittent uses such as space heating can be practical, but are more efficient if combined with other energy applications, such as absorption cooling, that can assure higher year-round gas use. Some of the difficulty can also be overcome by using landfill gas to supply that part of the energy demand that is continuous, and other fuels to meet that part that may be variable.

3. ENERGY APPLICATIONS AND EQUIPMENT

Table 2 presents some of the more common and important current landfill gas energy applications and potential future applications. Considerations regarding their use are presented in the text. A brief discussion of applications, in order of increasing complexity, is presented next.

3.1 Current Applications and Equipment

3.1.1 Space heating (and cooling)

Normal gas-fired space heating equipment in widespread use can, with moderate burner and other modifications, use landfill gas. Such use has been limited to date because appropriately sized users of space heat are only infrequently located near landfills, and piping costs to more distant users can be prohibitive. Depending on climate and other factors, heat energy supplied by 500,000 cubic feet per day (cfd) landfill gas could correspond to heating needs of a 200,000- to 1,000,000-square-foot (or several acres of floor space) complex, large by normal standards. Space heating loads also vary undesirably over time, both during the day and by season; a higher overall load factor for the gas use can, however, be obtained by combining absorption chilling with space heating in temperate climate zones. Condensate

TABLE 2. LANDFILL GAS ENERGY APPLICATIONS

Current Applications[1]	Degree of Use[2]
Space Heating (and cooling)	Limited
Industrial Process Heat	Limited
Boiler fuel	Moderate
Electrical Generation: IC engines	Most common
Electrical Generation: Gas turbines	Common
Electrical Generation: Steam Turbine	Limited
Purification for pipeline use	Moderate
Potential Future Applications	
Electric generation using fuel cells	
Compressed methane vehicle fuel	
Synfuel or chemical feedstock	

1. Most significant actual or potential uses.
2. Statistics on use (such as in Government Advisory Associates, 1991) have included most, but not all, facilities. In defining degree of use in terms of the fraction of the total landfill gas recovered and used for energy in the U.S., "limited" is about 5 percent, "moderate" is 5 to 20 percent, "common" is 20 or more percent, and "most common" is about 50 percent. A recent, more comprehensive update on use has been presented (Thomeloe, 1992).

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in equipment can be troublesome in space heating applications and poses a corrosion potential; gas cleanup and construction materials are important. Despite these limitations space heating can work well; one of the case study sites uses it. The equipment is also economical and available even on a small scale.

3.1.2 Process heating and cofiring applications

Several industrial applications, such as lumber drying, kiln operations, and cement manufacturing, can be attractive applications for landfill gas. An advantage of many industrial processes, including drying processes, is that fuel is required continuously, 24 hours a day. Landfill gas can be also used as a supplemental fuel that meets a portion of the total demand. Many industrial processes such as cement manufacturing may be relatively insensitive to the contaminant components resulting from landfill gas combustion, and their gas cleanup costs may be quite low in such applications.

One application that can be attractive because of absence of gas cleanup needs, and frequently plant proximity, is co-firing of the gas as supplemental fuel in a waste-to-energy plant.

3.1.3 Boiler fuel

This is an attractive use, particularly for large industrial boilers with constant demand, or where landfill gas can be used as a supplemental fuel. Conventional equipment can use landfill gas with relatively little modification. One case study of this report, in section 5, describes a boiler application. To the extent that sensitivity to gas contaminants can be determined, boilers may be less sensitive and their gas cleanup needs less than, for example, IC engine applications. The capital costs of boilers, discussed later, are also attractive. Although steam users are not frequently located near landfills, the siting of boilers, or for that matter other uses of 3.1.2, near landfills can be an alternative worth consideration.

3.1.4 Reciprocating internal combustion engines with electric power generation

Reciprocating internal combustion engines, almost all driving electrical generators to produce electrical power, are the most widely used landfill gas fueled energy equipment. Electrical generation occurs because the output can be accepted (if not always at a high price) by the electric utility grid 24 hours a day, and the power sale may be facilitated by provisions of PURPA. Although available statistics are far from complete, data in the 1991 GAA yearbook (Government Advisory Associates, 1991) suggest that electrical generation using reciprocating internal combustion engines is practiced at about 50 percent of the landfill gas energy sites in the U.S., and electrical generation using gas turbines is practiced at an additional (approximately) 15 percent, so that electrical generation is practiced at about 65 percent of the total sites.

Almost all larger engines used in this application are made by three manufacturers—Caterpillar, Cooper-Superior, and Waukesha. Each has in place more than 20 engines at landfill sites in the U.S. Lists of the sites where the various models of the three manufacturers' engines are in place are presented in GRCDA/SWANA, 1989.

The engine-generator set (genset) equipment is well developed and is used not only with landfill gas but for numerous other applications; the landfill gas sets sold by the three manufacturers are largely identical to those of the complete "stand alone" package sets sold for use at remote sites such as offshore oil platforms and other remote sites requiring electric power. Currently increasing degrees of automated engine monitoring and control reduce the need for on-site operator attention. Genset electrical capacity with landfill gas is typically 100 kW and up, with capacities between 1 to 10 megawatts (MW) being most common because of economics. Multiple gensets are used to obtain the higher outputs.

The reciprocating engines are most commonly "lean burn" turbocharged designs that burn fuel with excess air. Less commonly, they may be "naturally aspirated" without turbocharging (which as the term is used also implies stoichiometrically carbureted, with air in the fuel-air mix just sufficient to burn the fuel). The naturally aspirated engines are easier to operate because they are less complex, but they have

reduced power output and unresolved emissions issues. When operated on landfill gas, reciprocating engine power ratings are commonly reduced by 5 to 15 percent compared to operation on natural gas. This derating is caused by different factors, depending on engine type: dilution effects in naturally aspirated engines and parasitic load in lean-burn engines. The overall heat rate for electrical generation with the more commonly used lean-burn engines (after all parasitic loads are deducted), is about 11,000 to 14,000 Btus of landfill gas higher heating value per kilowatt hour. For smaller scale electric generation, this efficiency is quite good; this is one reason these engines are popular.

Landfill-gas-fueled generation comprises a rather small portion of the total use of such engines. Despite this, the three manufacturers of these engines have modified both design and operating procedures so that they can be said to have "landfill-gas-adapted" engines. With turbocharged engines, the need to compress landfill gas initially at close-to-atmospheric pressure normally poses added capital and energy costs compared to pipeline gas fueling. Compression of the fuel-air mix post-carburetion avoids some of these costs and (along with other landfill-gas-specific adaptations) is now being applied by Caterpillar in their 3516 series engines (Chadwick, 1990). Various design modifications, by all manufacturers, include parts modifications for corrosion resistance, such as chrome valve stems and modified piston rings; proprietary modifications are frequently involved[2]. One of the important operating modifications relates to engine oil as recommended by the engine makers (Chadwick,1989). Oil is checked much more often than is usual in other applications, sometimes as often as every 50 hours. Oil is changed frequently, as often as every few hundred hours or when relatively low contaminant limits for chloride (chloride can indicate corrosion as discussed earlier) or metal content are observed, according to manufacturer's guidelines. Specialized lubricating oils with high total base numbers (TBN; for discussion see Gonzalez, 1987) are now recommended for landfill gas use. Chemically, the bases in these oils give the acidic combustion products something to react with before they react with the metal of the engine. These can be thought of as helping engines the same way that antacids help people (and by neutralizing the same acid).

With the design and operating modifications that have been made for landfill gas engines they can generally be operated successfully at landfills. Yet, for reasons that are still not completely understood, (but that may relate to presence or absence of various landfill gas operational and design adaptations) some engines at some landfills encounter serious operating problems. They are most frequent during initial operation.

3.1.5 Gas turbines

Combustion gas turbines are also widely used as landfill-gas-fueled prime movers (i.e., sources of mechanical power) at landfills to drive generators. The justifications for their use in electric power generation are the same as those for reciprocating internal combustion engines.

The gas turbines used at nearly all U.S. landfill sites are either Saturn or Centaur models made by the Solar turbine division of Caterpillar. As of 1989, more than 30 Saturn or Centaur turbines were in use at more than 20 landfills; lists of their applications are presented in Esbeck, 1989, and Maxwell, 1989.

The principal power-rating consequence of using landfill gas as opposed to pipeline natural gas in turbines is a decrease of 10 to 15 percent in the power rating, due to the parasitic load associated with compression of the landfill gas fuel to the turbine. When all factors are considered, a turbine has a somewhat lower net efficiency in typical landfill gas applications than a reciprocating internal combustion engine. The heat rate of smaller turbines is typically about 16,000 Btus landfill gas higher heating value per kilowatt hour generated when parasitics are accounted for.

A factor to be considered in turbine operation is that turndown performance is poor—that is, turbines do best at full load, and poorly if gas supplies are less than needed to supply full load operation. Gas contaminants have also apparently caused serious problems for some landfill-gas-fueled gas turbines. These have included combustion chamber erosion and deposits on blades, resulting in severe and

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2 Personal communication, Curtis Chadwick, Caterpillar Corporation, Mossville, Illinois. September 1991.

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unanticipated damage in a few cases. A well-documented instance of turbine damage and associate cost is presented in Schlotthauer, 1991. The use of improved coalescing type filters (in combination wit other modifications) has apparently solved or forestalled problems at sites described in Schlotthaue 1991. One danger of severe damage to turbines that does not exist with conventional fuels is that a larg "slug" of landfill gas condensate in the piping system could mobilize and reach the turbine (it is consideration with IC engines as well). Methods for intercepting such slugs are required when this dange exists at turbine sites.

Although problems are seen at some turbine sites, they appear to have solutions. Turbines have th advantages of low operator attention and maintenance needs.

3.1.6 Steam-electric

Steam-electric generation burns landfill gas in a boiler to produce high-pressure steam, which then drives a steam turbine to generate electricity. A large amount of gas is needed for economic and efficien operation; the result is that only a few U.S. sites use this approach, with few additional candidate sites apparent where a stand-alone plant might be attractive. The economic difficulties of scale are a lesser problem, however, if landfill gas can be delivered to supplement the conventional fuel at a conventiona steam-electric power plant; limitations here can be either piping costs or the on-stream time of the conventional electric plant.

3.1.7 Purification to pipeline quality methane

Very stringent cleanup technology is applied to remove all components except the desired methane at a small number (under 10) of the larger U.S. landfills to produce gas for pipeline use. The principal objective not required of other cleanup approaches is nearly complete CO_2 removal, but the criteria are also stringent for the removal of other contaminants. The technology for cleanup to pipeline standards (with needed gas compression to pipeline pressure) is expensive; most such projects were initiated in the U.S. at larger landfills, where the economics of scale are attainable, during the early 1980s when gas prices were high. Projects operating today all have favorable long-term contracts.

Several technologies are available for the necessary cleanup. Many of these originated as CO_2 removal approaches applied first in the natural gas industry, through further adaptations for landfill gas appear to have been major. Details of these can be found in several sources, including a rather comprehensive review by Koch, 1986. The largest operator of facilities producing pipeline methane from landfill gas is Air Products and Chemicals, Inc. (APCI) and the process in use by APCI is the Gemini® process; provisions for this process's contaminant removal and destruction are interesting and discussed in Koch, 1986. Because of recently falling natural gas prices, and because the largest landfills with best economics of scale already have energy projects, additions to pipeline quality gas production from landfill gas in the near future may be limited.

3.2 Potential Future Technologies

Landfill gas may be applicable to several technologies under development; these include fuel cells, compressed gas vehicle fuel, and possibly synfuels production. A brief review follows.

3.2.1 Fuel cells

Fuel cells are essentially electrochemical batteries. They can operate on various primary fuels (feedstocks) such as oil, natural gas, or coal. The potential primary fuels include landfill gas. As an intermediate step the primary fuel is converted at high temperature to "synthesis gas," which is a mix of hydrogen, carbon monoxide and dioxide, and other gases. This synthesis gas is what feeds the fuel cell.

Further discussion of fuel cell operation on landfill gas is presented in Leeper, 1986. Advantages include low emissions and quite high thermal efficiency (near 40 percent). It is a technology that has particular

promise for economical electric power generation on a smaller scale. The technology is considered sufficiently interesting that the U.S. EPA will be funding further trials (Sandelli, 1992)

3.2.2 Compressed gas vehicle fuels

Vehicle fueling with compressed methane is of high interest for environmental and other reasons, and technology for such fueling is advanced. It was reported that in 1990 at least 700,000 vehicles operating worldwide were fueled by natural gas (Rosen, 1990); such fueling is economically competitive in several situations, and expanding. Digester gas has also been used at sites including Modesto and Los Angeles, California (EMCON, et al., 1981). Using landfill gas would involve some purification, possibly to near pipeline quality, then compression of the purified gas for reduced-volume storage and use on board vehicles equipped with conversion kits. Although landfill gas applications have apparently been few, an early study (EMCON, et al., 1981) projected favorable economics. The most attractive use is for fleet vehicles, and in particular refuse trucks, which would need to return frequently to the landfill where the gas would be available. Gas availability and economics both dictate that the vehicle fleets should be large.

3.2.3 Synthetic liquid fuels and chemicals

Various technologies are available that could convert landfill gas to liquid fuels. These include hydrocarbon production by Fischer-Tropsch, methanol synthesis by various routes, including chemical catalysis at high pressures (Ham et al., 1979), or by partial biological oxidation. Most of these synfuels approaches have been examined for large-scale feasibility using feedstocks such as gas from coal. Synthesis gas-based chemical processes (for example, acetic acid manufacture) are also possible. These technologies are projected to produce expensive products, even at the larger scales. The principal difficulty with any of these, particularly fuels, would be that landfill gas generation can support a plant size that is generally only 1 to 10 percent of the plant size normally contemplated for these technologies. The small scale required with using landfill gas would appear to imply very high costs.

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4. COST AND REVENUE COMPONENTS

This section addresses cost and revenue components and particularly issues such as site specificity and cost variability that are considered to be important to energy users. It is not intended to provide extensive cost detail here, although some examples of costs and cost ranges are provided for illustration. Comment is also presented on issues including electric revenue requirements, initial cost estimating, and economics as barriers to landfill gas energy applications.

4.1 Components of Cost and Income

The cost and revenue factors to be considered consist of (1) capital costs, (2) operations and maintenance costs, (3) royalty payments, (4) tax and other credits, and (5) energy-related revenues.

- Capital costs include costs associated with energy conversion and sometimes other associated equipment such as that for gas extraction. They normally include the "up front" costs of implementing the project and plant, and may include other large lump sum costs incurred during the project, such as for equipment replacement. Some examples of capital costs include those for initial site improvements, energy equipment, buildings, and pollution abatement equipment. They can also include initial legal costs, commissions, rights to gas, permits, and the like. They can vary widely as discussed shortly.
- Operating and maintenance costs include costs associated with operating and maintaining the capital plant. Items such as labor, equipment maintenance, materials, debt service, and relevant taxes fall in this category. Operating and maintenance costs can vary substantially and depend on factors including the end use, landfill characteristics and configuration, gas composition, local rules and regulations, and many others.
- Royalty payments are continuing costs that are usually proportional to energy revenue. Royalties are negotiated and are occasionally changed as the marketplace, or other factors, change. Royalties may be paid to the landfill owner, owner of the gas extraction or delivery rights, or initial project developer. When they exist (a fair fraction of projects have none) they are usually in the range of 5 to 20 percent of gross energy sales.
- Federal tax credits are benefits proportional to gas energy delivery that were legislated by Congress (Section 29 of the IRS code). These credits are a direct dollar-for-dollar offset to federal tax that would otherwise be payable by the business entity providing the gas. The tax credits are allowable for extraction systems installed before the end of the year 1992 and will extend through the year 2002. They have had a significant effect on improving economics and viability of projects that might otherwise not have been implemented.
- Revenues for energy sales are most frequently based on prices of competing fuel or energy. They can be based on costs of the equivalent in heating value of a fuel grade petroleum product, on electricity sales (where cost is fixed by provisions of PURPA), or on other energy commodities. Energy market price fluctuations can materially and often adversely affect economics. Long-term contracts can often be executed, that fix prices per unit of output and provide a substantial degree of security to developers.

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Possibly the most important aspect of costs, revenues and other benefits is their specificity to site and situation; the site-to-site variation, even with the same application and scale, is far greater than is usual with other energy technologies. The reasons include

- Component capital cost variations: Key components such as gas cleanup, utility provisions (e.g., on-site water supply), and utility interconnects can vary in cost by at least an order of magnitude. Other capital costs, such as those for gas and power sale contract rights and pipelining, can be zero for many projects but may add substantial percentages (up to 25 percent or more of the costs) to others. Energy equipment costs can vary depending on details and whether the equipment is new or used. Fixed costs, which are proportional to capital costs, vary correspondingly.
- Operating cost variations: As an example, landfill-gas-specific maintenance costs relating to gas contaminants can vary by up to an order of magnitude. Other costs such as royalties (where they exist) and operator cost can vary several fold.
- Benefits accruing per unit of energy delivered can vary (by about a factor of five for the example of electric power), and also depend on whether the energy is sold to the utility transmission system or avoids utility retail cost. Nonenergy credits allocated for benefits such as for gas system maintenance and adjustment, and emission control vary widely.

Development of detailed economics regarding application, scale, and the host of site-specific factors that can exist is, as noted, beyond the scope of this report. (Also it should be noted that costs may be expressed in several different ways in literature sources, with many data appearing contradictory). Further discussion of various categories of costs—capital and capital-related, operating costs, and revenue and benefit components—is presented in appendix F. Examples of cost data, presented next, illustrate some typical costs and their levels of variation.

4.2 Cost Data: Examples

4.2.1 Hypothetical generating facility example: Cost component ranges

Table 3 presents example ranges for cost and benefit components that might be experienced for the hypothetical case of a 1 MW electrical generating facility. (As stated earlier about 65 percent of landfill gas energy facilities involve electrical generation). Note that capital costs are installed, that is, engineering, design, permitting, and other costs are factored into the costs; ranges given are "best estimates" generated by the authors for this report. The ranges suggest the potential for cost variability, even where (as in this example) the application (electrical generation) and scale (1,000 kW) are fixed. Note that electric sale price and other benefits per unit output may vary over an even greater ratio than cost factors. Economic factors may impede the energy use of much of the landfill gas that is generated, as discussed in more detail below.

4.2.2 Reported electric facility capital costs: GAA Yearbook

Some reported data on capital costs for electrical generation, are also illustrative. In the Government Advisory Associates' *1988-1989 Methane Recovery from Landfill Yearbook*, 38 electrical generating facilities report information (capital cost and nominal electrical generating capacity) from which costs per kilowatt of capacity may be calculated. The figures are for both current and projected facilities, including internal-combustion-engine-based facilities, gas turbine facilities, boiler/steam turbine electric facilities, and in some cases facilities using unspecified generating methods. The capital cost per kilowatt for each of these individual facilities, coded by facility type, is plotted against plant capacity in figure 1. All costs have been adjusted to 1991 dollars. The data probably have imprecisions for several reasons (additional plant costs experienced for postconstruction modifications may be omitted, experienced output may not

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TABLE 3. COST AND REVENUE RANGE FOR 1 MW ELECTRICAL ENERGY PROJECT

Capital Cost Ranges (Basis: 1 MW capacity)	Range of Capital Cost (thousands)
Administration, Development and other[1]	30 - 1,000
Extraction system	200 - 1,000
Pre-treatment system	10 - 500
Energy conversion equipment	500 - 2,000
Typical Range[2]	850 - 4,500

Typical Operating Cost Components	$/kWh		
Operations and Maintenance	0.01	-	0.03
Debt Service (interest and amortization)[3]	0	-	0.04
Return on Investment (ROI)[3]	0.01	-	0.04
Other (royalties, etc.)	0	-	0.02
Typical Range[2]	0.03	-	0.09
Typical Revenue Components			
Tax Credits (where applicable)	0	-	0.011
Other benefits (see text)	0	-	0.01
Electric Power Sales	0.02	-	0.10[4]
Typical Range[2]	0.03	-	0.11

Notes:

1. Costs could include payment for the rights to the gas, or for the power sales contract, or to obtain an equity position in the project: see section 4.1 for more detail.

2. All extremes are unlikely simultaneously within the same project, so typical ranges are less than possible span through adding components.

3. ROI may substitute for debt service - one will increase as the other decreases.

4. May include capacity payments as well as payments for kWh delivered.

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equal nominal, and so forth). However, the figure illustrates the variability (and, the lack of obvious pattern) of landfill gas electrical generating facility capital costs, even allowing for the databases' imperfections. The cost data and their scatter are undoubtedly explainable on the basis of site features and variables discussed above but detailed analysis is necessarily outside the scope of this report.

4.3 Other Economic Issues

In addition to cost ranges, of interest to many energy users will be the range of required revenues, the uncertainties of initial cost estimating, and constraints of economics on energy uses. Each of these issues are discussed as follows.

4.3.1 Revenue requirement for electric power generation

The average power revenue required to justify an electric generation facility at a scale of 1,000 kW (1 MW) or greater is regarded as being most typically about 5 to 8 or more cents per kWh[3]. Caveats are that the equipment must operate with an acceptably low down time and few problems due to factors such as energy equipment breakdowns or gas supply problems. There are obviously also sites where costs combined with return criteria can result in sale prices both above and below this range.

4.3.2 Initial cost estimating

Accurate initial cost projections are difficult to develop, and initial cost underestimates—leading to unwise projects—are frequently made (this problem is exacerbated when additional costs, such as for improved gas cleanup, or equipment modifications, are found to be necessary as the project proceeds). Those interested in developing economics for applications may wish to develop their initial data working with others experienced with landfill gas energy applications. The intricacies of costing and implementing an energy application are such that many—possibly most—of the smaller landfill owner/operators tend to form partnerships and participate with entities already experienced in landfill gas energy applications, who can provide help in stages throughout a project: examining use options, projecting economics, and continuing through selecting and implementing the (presumably) best option.

4.3.3 Economic Impediments to energy applications

Landfill gas energy projects, including some of those to be described later in this report, can do well economically. However, as can be inferred from table 3 and figure 1, low energy sale prices can combine with high capital and operating costs at many sites. Individual landfills with substantial methane generation often cannot find economic energy applications for the gas, and their energy potential is wasted. Well-developed options for energy applications for smaller landfills and generation rates are also lacking. Precise figures are not available but based on GAA (1988), a very small percentage (well under 10 percent) of landfills with outputs less than 200 cfm output (that could support 500 kW) appear to have energy systems. Those means suggested for barrier reduction and facilitation of energy uses under less than favorable circumstances are referred to in Section 6.

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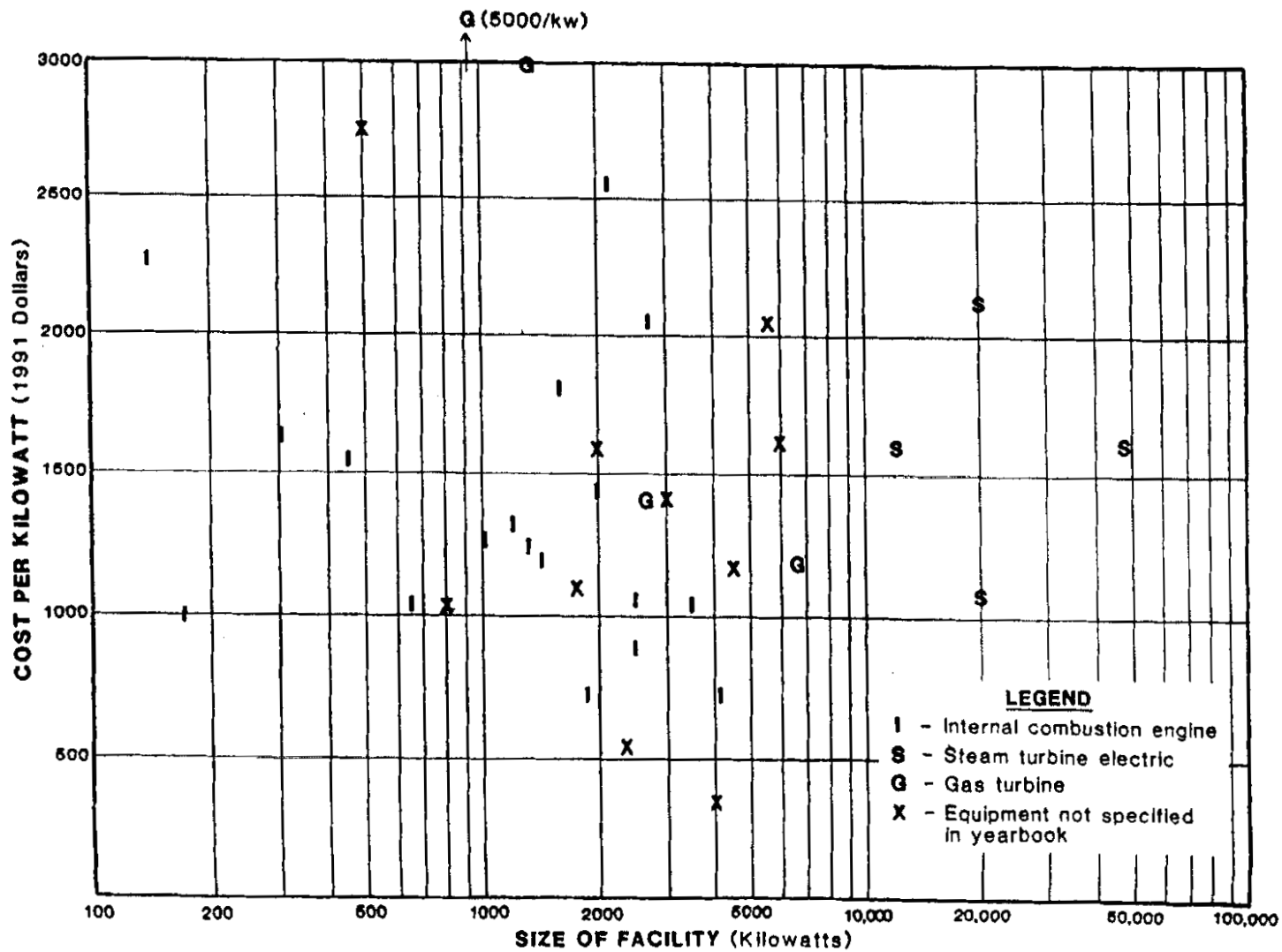
3 Authors' estimates; also discussed with Christine Nolin, Cogeneration and Independent Power Producers Coalition, Washington, D.C


G (5000/kw)
COST PER KILOWATT (1991 Dollars)
3000
2500
2000
1500
1000
500
100
200
500
1000
2000
5000
10,000
20,000
50,000
100,000
SIZE OF FACILITY (Kilowatts)
LEGEND
I - Internal combustion engine
S - Steam turbine electric
G - Gas turbine
X - Equipment not specified in yearbook

Section III.

Comparison of Models for Predicting Landfill Gas Recovery – a 19 – Landfill Study

G.Vogt and D.Augenstein

DRAFT

PROJECT FINAL REPORT

THE VERIFICATION AND VALIDATION OF SELECTED MODELS FOR PREDICTING LANDFILL GAS QUALITY AND QUANTITY

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ABSTRACT

Landfill methane models are widely used to project landfill methane (gas) generation and recovery, as well as landfill emissions to the atmosphere. While several models are used in the landfill gas industry and elsewhere, their "validation" is still, at best, limited. Validation is, simply, adjusting model parameters so that models best project methane recovery field data, or else, demonstrating that models project methane recovery actually experienced. Limited data have been used to develop most models. In addition, models have generally validated methane recovery against projections over relatively short intervals or at only single "points in time" whereas comparisons over longer terms would be desirable. Thus, confidence limits to be assigned to model projections are in large part unknown. In addition, failures of models have been (if anecdotally) reported. In some cases, energy equipment has been installed and left idle reportedly because landfill gas has been less than expected.

In light of this situation, this project's purpose has been to verify and validate models based on data from a greater number of landfills in the past, using gas recovery data over longer terms (several years when possible). Another objective is to use these data to develop a better estimate of key parameters, yield and kinetic coefficients, and associated confidence limits which may be assigned to model projections.

This project has assessed trial model forms against data from landfills meeting several criteria: gas extraction is maximized, waste placement tonnage is well known, and other site information characterized to the extent possible. To date, data have been obtained from 17 landfills which have met such criteria. The models tested are a zero-order, a simple first-order model, and two modifications of a first-order model. Parameters of all models were adjusted for "best fit" to field data through two statistical methods

Preliminary results show that the four models are similar in predictive ability. Based on available field data, some models may be better than others by a small margin, and a tight range for the model parameters (e.g., yield and kinetic coefficients) can be defined. Yield correlations (R^2 values) are acceptable, generally at least 0.85. Differing model outputs for U.S. East and West coast landfills give better correlations and lower variance of field results versus projections. Model refinements to reflect correlations with site conditions are being tested to further improve confidence limits and to ascertain model differences. Avenues to further refine the models will be discussed.

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Section IV.

Composting of Muncipal Solid Waste and Sewage Sludge : Potential for Fuel Gas Production in a Developing Country

D.Augenstein, D.L. Wise, N.X. Dat, and N.D. Khien

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Composting of municipal solid waste and sewage sludge: Potential for fuel gas production in a developing country

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Topics include technological management and change for reduced consumption or substitution, recovery of materials and energy from established and new sources such as from processing wastes from domestic, commercial or industrial sources, management of natural resources including implementation of public policies for conservation, and management of processes and product design, fabrication, and production for efficient utilization of materials and energy.

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Composting of municipal solid waste and sewage sludge: Potential for fuel gas production in a developing country

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Abstract

This paper reviews alternatives for composting of combined municipal solid waste (MSW) and sewage sludge in a developing country, Vietnam. Near-term Vietnamese plans are for aerobic composting. Anaerobic composting of the same waste stream using a landfill reactor, i.e., 'controlled landfilling', is also evaluated. Anaerobic composting should provide a major energy benefit in terms of fuel gas recovery to maximum potential from the waste.

1. Introduction

Landfill gas recovery and energy use has increased steadily in the United States and elsewhere in the world since about 1980. In the US, over 120 landfills now use their gas for fuel [1]. This increase in landfill gas energy use is occurring in a competitive energy market, despite price decreases in competing fuels (particularly pipeline natural gas). A recent report issued by the US Environmental Protection Agency (EPA) details landfill gas energy uses [2]. In this EPA reference, six examples (case studies) are presented of energy use in the United States and also four in the UK. As one example of gas use in the USA, Brown Station Road landfill in Maryland, near Washington DC, places about

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1200 tons/day of MSW. About 1.1 million cubic feet a day of gas (55% methane) are recovered for energy uses [2]. The gas fuels 2300 kilowatts of electric power generation, and provides space heating and hot water for a nearby county building complex. These represent typical energy uses, which in the US include electricity generation, boilers, space and industrial heat. Landfill gas uses in the UK and other OECD countries are similar. Energy use of landfill gas is perceived as highly desirable environmentally [2].

Landfill gas energy uses prove satisfactory now at a number of locations in the United States and other OECD countries, even though 'conventional' landfilling practice is generally much less than optimal for gas generation and gas energy recovery. Most 'conventional' landfills to date simply place waste in accordance with regulations. There is generally little attempt to manage biological reaction conditions [1]. It is possible, however, to optimize landfills for considerably increased energy recovery. Improving conditions for biological reactions within the anaerobic landfill environment may greatly accelerate generation of methane and increase its yield. Improved designs may allow capture of much higher fractions of the gas that is generated. These will be discussed further below.

Composting of residues is practiced in numerous locations around the world. It can be defined as controlled conversion of an organic waste substrate to simple metabolic end products, and a remaining residue of recalcitrant organics and microbial cells (compost), which can be used as a soil conditioner.

Composting's relatively low costs, as well as ability to treat mixes of both sewage sludge and MSW, suit it for waste management in developing nations. Aerobic composting, in which organics are oxidized to CO_2 and water, is the most common approach to date. However, composting may, alternatively, be anaerobic. One advantage of anaerobic, as opposed to aerobic, composting is that a methane-containing fuel gas is produced. The fuel gas can be of particular value to the developing nations, which tend to be energy short [6]. Anaerobic composting of municipal wastes to fuel gas as well as compost is under development using a variety of approaches [7–10]. Pertinent here is the fact that anaerobic reactors may include variants of waste landfills (see [4] for discussion of US EPA and International Energy Agency (IEA) working groups and publications on bioreactor landfills). In alternate terms landfilling may be adapted to accomplish composting objectives as well, to address limitations of conventional landfills noted above.

One organization with continuing interest in composting is the Urban Environmental Company of Hanoi, Vietnam (URENCO). Based upon URENCO's interests, review has been carried out of both aerobic and anaerobic approaches that might be applied in Vietnam. The technology for a possible anaerobic approach would be provided in part by technical experts in the USA. A cooperative technology transfer program between Northeastern University and the Technical University, Hanoi would be integral to an

[1] Leachate recycle, as discussed in Pohland [3] or Reinhart and Carson [4], helps improve biological conditions. However, its benefits may be only modest in most cases without other measures. Quantities of leachate may be very much limiting in newer deep landfill designs with less permeable covers [5].

anaerobic composting project. Below are discussed first, present plans for aerobic composting and then the potential for an anaerobic composting process applied to the same waste stream in Hanoi.

1.1. General background: Waste handling in Hanoi, Vietnam

In Hanoi, approx. 700 000 m^3 of solid waste are generated each year [11]. (Uncertainties are acknowledged in waste data; however, the organic, i.e., compostable, component of this waste stream is estimated to be at least 500 US tons/day.) Current methods and facilities for handling and disposing of largely organic urban solid wastes are inadequate to cope with the volume of wastes from Vietnam's urban areas. Some waste is deposited in two controlled sites but much refuse is dumped in uncontrolled sites throughout the city. A small treatment center exists at Cau Dien, 12 km from the city center. Refuse here is treated by natural fermentation (aerobic composting) in a manual operation. Cau Dien treats only 8000 m^3 wastes annually, a very low proportion (well under 5%) of the waste that is presently collected in Hanoi, and the quality of the resulting compost has been poor. The situation is similar in other urban areas of Vietnam (F. Nielsen, Senior Municipal Engineer, The World Bank, Infrastructure Operations Division, Country Department I, East Asia and Pacific Region, personal communication to D.L. Wise, January 1995).

The Hanoi Urban Environment Company (URENCO) has responsibility for the collection and processing of refuse and also the production of organic fertilizer. Its transportation teams have recently been strengthened to improve the removal of refuse from city blocks. URENCO has also undertaken research on alternative methods for improving the processing of urban solid wastes. (Personal communications of D.L. Wise with URENCO officials.) This research has identified one method, known as static forced air fermentation, as being best suited – on the basis of current knowledge – to the circumstances in Vietnam. Through this process, organic wastes are converted into quality compost by enhancing natural fermentation. Two bacteriological activators can be added, a protease and a nitrogen-fixing bacteria. Both of these additives are cultivated in Vietnam.

In response to a request from the Government of Vietnam for assistance with finding solutions to the serious problem with solid waste disposal in Vietnam, and the Hanoi City in particular, a project referred to as VIE/86/023 – Solid Waste Treatment in Hanoi – was conceived by the United Nations Development Programme (UNDP). The project management board consisted of: Nghiem Xuan Dat, Director of URENCO as National Project Director, Dinh Dang Minh, Deputy Director of URENCO as National Project Coordinator as well as UNDP staff and others. The Project's activities started in April 1990 and were completed in 1993. This project addressed the following goals: (1) The Government of Vietnam's wish to considerably reduce solid waste pollution in urban centers and improve the quality of environment by collecting and process urban waste and sewage sludge to produce organic fertilizer for agricultural use and (2) The government's intent to construct solid waste composting plants in and around urban centers to treat refuse and produce the fertilizer. The size, number and location of these composting plants will be based on the results obtained from forced air composting

experiments, in a pilot composting plant that the project would assist in establishing at Cau Dien Processing Enterprise (Tu Liem District). More details are presented below.

It should be noted that the waste stream in Hanoi city is typical of that of a low income Asian city which contains a high proportion of organic materials. Thus, composting options appear the most appropriate and economical solutions.

A detailed review was also performed of the existing waste collection, transportation, disposal and management. These appear far from satisfactory despite great effort of URENCO. Also reviewed was the status of international composting experience and technology to determine the optimum technology for the Cau Dien Pilot Composting Plant. The review settled on an aerated static pile bin system as being the most appropriate option for the Cau Dien pilot operation. Forced air composting presented the most effective present option for the Hanoi situation and viable to process up to 50% of Hanoi's solid waste. It is assumed that this will continue to be the case for 10–15 years, as changes to the waste stream are likely to be gradual.

The Cau Dien Pilot Composting Plant, constructed at what is called the Cau Dien Processing Enterprise is capable of processing 30 000 m^3 of solid waste by forced air composting to produce 7500 tons of composted fertilizer annually. It has the potential to produce high quality compost, in a manner acceptable from standpoints of occupational safety and public health. The Plant and support laboratory became fully operational in July 1993, delivering compost products to customers. Four laboratory technicians were trained in quality control. An intensive training programme was prepared and is conducted by national institutes. A report "Pilot Composting Plant Operation Report" was provided [11]. This report covered the objectives and principles of operation of the plant, together with a detailed description of plant management and operation aspects as well as the site laboratory operation and sets out maintenance requirements for the various plant items. The report also summarized the key plant and process operations.

All the necessary guidelines and instructions for Cau Dien Pilot Composting Plant operation and maintenance have been given to staff and workers. Review examinations for all the staff will be arranged after 6–12 months to determine the level of knowledge and skill of the staff. A report on the Strategy and Investment Programme for solid waste management and disposal for Hanoi elaborates on the use of compost for agricultural purposes. This report will present the results of the detailed study of Hanoi waste management and develop the Strategy and Investment Programme for solid waste management and disposal for Hanoi as the key element of the Hanoi City Development Plan. A large number of personnel have been trained; eight persons will be trained abroad specializing in micro-organism production, composting process and solid waste management. In-country training for 44 technicians and operators (including four laboratory staff) has been provided. Certificate and follow-up training programme was also given. Three study tours of 15 officers were taken to countries handling composting activities and operating composting plants. An international seminar was held on 25 March 1993, aimed to introduce the project results and dissemination of composting technology to other urban centers. A technology dissemination programme was prepared with the assistance of international and national consultants. The trainees under the project contributed their expertise gained to this programme.

2. Preliminary evaluation of anaerobic composting

Anaerobic composting is another alternative for Hanoi's wastes. One important justification for its consideration is Vietnam's energy situation, similar to that in most developing countries [6]. Energy and electrical power supplies are limited, of relatively high cost, and fuel purchases on international markets pose economic burdens. Anaerobic composting could not only address waste management needs but also realize much of the waste energy value in the form of a fuel gas.

As noted above, a variety of reactor types and approaches may be considered for composting [7–10]. The approach examined here is composting within a 'bioreactor' landfill adaptation. Specifically, a landfill may be managed in conformance to modern environmental standards to accelerate waste decomposition to a methane and carbon dioxide fuel gas, as well as to provide compost. A generalized equation describing the organics' conversion to fuel gas is:

$$\underset{\text{feedstock}}{C_aH_bO_b} + [n - a/4 - b/2]H_2O \xrightarrow[\text{bacteria}]{} \underset{\text{carbon dioxide}}{[n/2 - a/8 + b/4]CO_2} + \underset{\text{methane}}{[n/2 + a/8 - b/4]CH_4}$$

For cellulose, the dominant component of many wastes the reaction is:

$$\underset{\text{cellulose monomer}}{(C_6H_{10}O_5)_n} + nH_2O \xrightarrow[\text{bacteria}]{} \underset{\text{methane}}{3nCH_4} + \underset{\text{carbon dioxide}}{3nCO_2}$$

Equations are simplified for purposes of illustration (intermediate compounds, microbial biomass production and remnant compost, typically about half of feedstock, are not shown). What is important is that most energy of the decomposed organics is realized as a fuel gas consisting of methane and carbon dioxide. Gas composition is typically 50–60% methane. Much more information on gas composition and energy value may be found in numerous references elsewhere, including [2].

Before presenting further detail, it is appropriate to note numerous terms commonly applied to anaerobic processing, along lines under discussion. By regulatory definitions, the processing is 'composting', defined as biological decomposition of waste under controlled conditions (for example, this regulatory definition has been applied in California, USA); when under anaerobic conditions it is being called 'anaerobic composting' [7–10]. The process is also 'anaerobic digestion' or 'high-solids digestion' [12]. Beginning 20 years ago, in-landfill composting with surface membrane coverage for maximum gas capture has often been referred to as 'controlled landfilling' [12]. Another common term is 'leachate recycle' [3] which refers to the return of leachate generated by the landfill to the landfill. The approach has also been termed 'landfill methane enhancement' (referring to the increased methane generation) and most recently as 'bioreactor landfill' technology which refers to the improved biological reaction conditions within the landfill [4]. The terms 'controlled landfilling' and 'anaerobic composting' are used where possible below.

Controlled landfilling purposes may be summarized as: (1) accelerating gas (methane) generation to maximum potential; (2) maximizing recovery of gas and energy, and

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concurrently (3) accomplishing earlier waste stabilization to compost. An advantage of the landfill is that it can comprise a low-cost (or likely least-cost) reactor, for which much technology and experience are developed. Low cost is a key for applications in developing countries. Essentially all methane, generated to maximum potential, may be efficiently recovered by demonstrated surface membrane technology (discussed in more detail later). As discussed above, beneficial gas energy use is well established technology. Relative to more 'conventional' landfilling there is also major environmental benefit from maximizing gas capture. This includes minimizing landfill methane emissions that otherwise have significant adverse effects in terms of climate change and stratospheric ozone depletion [13,14]. Controlled landfillings' potential to ameliorate methane emissions that contribute significantly to climate change has also been recognized by its recent inclusion in the US Presidential Climate Change Action Plan (Action Item 37).

Bioreactor landfills are, also, subjects of ongoing effort in the US and other OECD countries (including the UK, Norway and Sweden). Objectives of that bioreactor landfill work are principally acceleration of waste stabilization and methane generation, and waste volume reduction [15].

Compost quality depends on preprocessing and removal or exclusion of undesirable waste components from organic fractions. However, processing constraints are similar whether composting is aerobic or anaerobic, and also regardless of what type of reactor – whether a landfill variant, or other type – is employed [2].

The following discusses the basic processing operations of controlled landfilling. Preliminary projections are then presented for an operation that might be conducted with wastes of Hanoi.

A process schematic that would apply to a full-scale controlled landfilling operation is shown in Fig. 1. Wastes arrive at the landfill (or anaerobic composting facility). Steps through controlled landfilling may then include: (1) removal of inorganics and inerts, i.e., rocks, metal, wood, etc.; (2) other pre-processing (such as breaking open plastic bags – if present) and any necessary size reduction; (3) addition of aqueous components and nutrients; and (4) controlled landfilling (discussed in detail below).

2.1. Anaerobic composting (controlled landfilling)

The controlled landfill is managed essentially as a high solids anaerobic composting reactor, to accelerate waste organic conversion to methane. This use of the landfill may involve in sequence:

1. Setup so waste is placed and contained to allow gas capture before any significant fraction of gas is generated.
2. Adding aqueous components with any desired nutrients, buffer and bacteria – or for example sewage sludge – and contacting with the waste. Methods could include

[2] Despite frequent assumptions (including in various waste management regulations) that landfilling and composting are separate, even mutually exclusive, processes, there appear no fundamental reasons why landfills cannot be adapted to serve composting functions.

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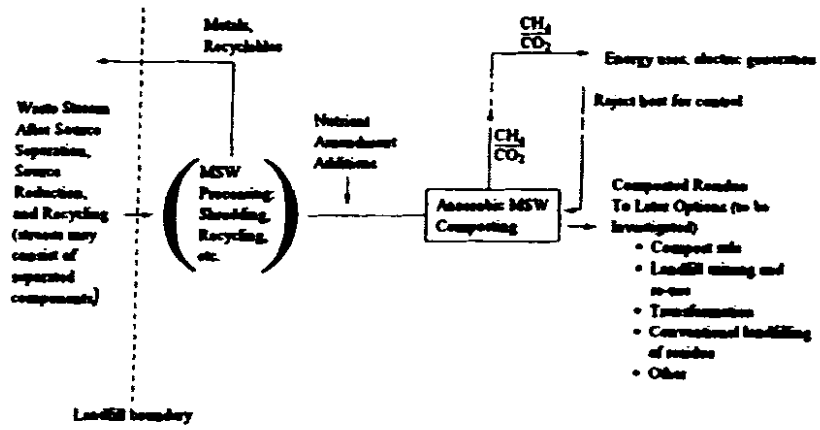

Fig. 1. Schematic of accelerated anaerobic composting process.*

prewetting before placement; alternatively, liquid components could be distributed over the waste after placement using a distribution pipe or other methods [16].

3. Completing the gas-tight containment.
4. Collection of methane until its generation, and waste stabilization, are complete.
5. At longer time once waste is stabilized (composted), use of resulting compost.

Note that this paper does not detail gas energy uses. Technologies for landfill gas/biogas energy uses that would be useful in Vietnam are readily available and reasonably straightforward [2,17]. For example, either direct fuel gas use for heat, or gas use for electric power generation [18] can be attractive. Energy uses may be further explored as the controlled landfill is established, and readily implemented once the available gas output is established.

Further design and processing details are covered next.

2.2. Details of design and operational aspects for controlled landfilling

Controlled landfilling will follow conventional landfill practice to the extent possible. However, it will also entail adaptations including:

- Amendments such as some mix of digested and primary wastewater sludges and perhaps water may be added to waste during filling. Finely divided limestone for buffer may also be included. Waste liquid content should approach 'field saturation', that is, maximum attainable content that incurs neither hydrostatic head nor liquid drainage from the waste. This level is expected to be between 35% and 45% moisture by weight.
- Temporary daily soil coverage is eliminated or modified based on liquid permeation considerations.
- Once waste reaches plan depth over a given area, membrane will be placed over the surface layers as soon as possible for gas capture.

- Gas offtake occurs via either permeable layers, or lateral or vertical gas extraction lines (conduits) in the waste.

With respect to timing it is expected that significant gas generation is obtained in 6 months to 1 year by management of inoculum and other conditions in the waste. Gas once generated would migrate to conduits or permeable layers and be recovered. However, light vacuum may be applied by auxiliary blower to facilitate gas recovery from any permeable layers used and limit any fugitive gas emissions from any open (working) faces of the fill.

Other landfill operational aspects, for example base lining, leachate collection, and waste placement procedures are expected to be identical or very similar to current practice.

A number of other operational, performance and cost factors merit discussion.

2.3. Methane recovery potential

Methane recovery with controlled landfilling in Vietnam is estimated at 1.5 cubic feet per pound (93 l/kg) of processed organic waste, after separation out of inorganics and inerts. Although solid wastes worldwide, and specifically Vietnamese solid waste, differ significantly from US solid waste, this yield and recovery should be attainable. (For US waste methane yield data see, for example, [12,19,20].) Lower paper content worldwide and in Vietnam is likely to be offset by higher levels of other decomposables, particularly food and plant wastes. Membrane containment technology proposed here for capture of essentially all generated gas is commercially demonstrated in United States practice (see for example [21–23]). At 500 tons per day, the methane recovery at ultimate steady state is thus 1.5 million cubic feet per day. This amount of methane is enough to fuel about 6 Megawatts (MW) of electric power, or even more, depending on efficiency of electrical generating approach. This amount of electric power would be very significant for Hanoi.

2.4. Methane generation: Kinetics

Laboratory experiments (for example, see [12,19]) have shown conversions in 1 to 2 years, to gas yields exceeding those assumed above. Rapid methane generation has been shown with solid organic residues other than municipal waste as exemplified in Wise et al. [24]. Field trials in Mountain View, CA (the most complete to date in the US) suggest decomposition times of approx. 10 years (vs. 25–60 for normal landfills) [16]. Such field results are expected to be bettered in further efforts. A first-order Scholl Canyon generation profile (see [20]) with a conservatively long time constant of 10 years, will be assumed for economic analysis purposes. In actuality, decomposition may be considerably accelerated compared to this assumption by such factors as the heat of methanogenesis [12,24]. A lag time of 1 year is also assumed from the time construction costs are incurred to the start of gas generation (by the Scholl Canyon model).

2.5. Fuel valuation

It can be assumed that the mixed CH_4/CO_2 product gas will displace alternate fuels, and perform in satisfactory fashion in commercial equipment such as gensets. This

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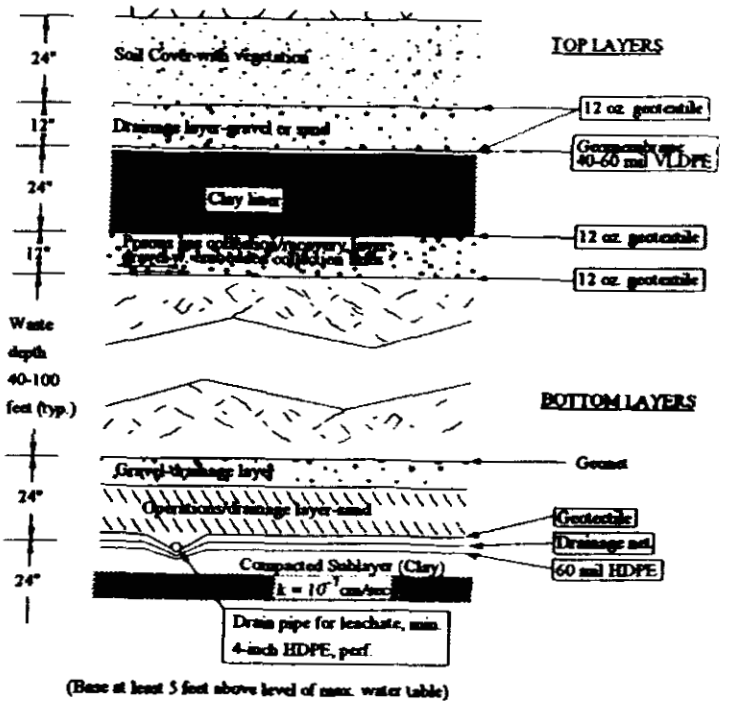

Fig. 2. Schematic of controlled landfill components layers (applying United States EPA Subtitle D Liner Containment Standards).

assumption is well-substantiated by US and other OECD experience cited above with landfill gas as fuel (for example, see references such as [2] and Thorneloe [25]). On the basis of savings in alternate fuel, the mixed CH_4/CO_2 fuel value is conservatively assumed to be \$2.00/mmBtu, equivalent to about \$12/barrel oil.

2.6. Design and costs

It is assumed that a controlled landfill for Hanoi will entail adaptations of lined and synthetic membrane-covered landfill design, as mandated for all new landfills in the US and already in use in US controlled landfill demonstrations. An arrangement of landfill layers is shown in Fig. 2. Total cost per unit area of such a landfill, if constructed to US specifications with US costs [3], would be in the neighborhood of \$300 000–500 000/acre (rounded), detailed in Table 1.

[3] Institute for Environmental Management (1995), these costs are adapted from experience with design and construction of new landfill sectors in California.

Table 1
Component costs of controlled landfill[a,b] (per acre from US experience, approximate; see Fig. 2)

	Costs per acre
Base layers	
Compacted clay liner (2 feet clay from nearby source)	$10000–40000
60 mil high density polyethylene (HDPE) base membrane	$26000–33000
Drainage layer: gravel and sand	$30000–40000
Leachate collection and removal system	$4000–70000
Geotextile/geonet	$13000–20000
Leachate recirculation pumps, piping control	$10000–30000
Subtotal base layers:	$93000–170000
Surface layers:	
Geotextile, porous layers, geotextile	$15000–30000
Gas recovery line plus blower	$5000–10000
Clay liner layer, 2 feet	$10000–40000
Geomembrane, very low density polyethylene (VLDPE) 40 mil	$25000
Geotextile/geonet composite	$30000–400000
Gravel, 12 inches	$30000–40000
Geotextile filter or 6 inches of gravel	$13000–20000
Excavation and backfill of onsite soil	$15000–20000
Subtotal for surface layers	$143000–225000
Other associated costs:	
Engineering and design (8%)	$20000–30000
Quality assurance/quality control for construction of base and surface layers	$20000–30000
Contingencies at 10%	$25000–40000
Total other costs:	$65000–100000
Total cost per acre	$301000–495000

[a] Does not include cost of waste handling.
[b] Costs are as-installed. Stated value for individual items would vary depending on how installation costs are factored in, and how other accounting is done. However, total US costs should be within bounds shown.

Above costs would be experienced for design now deemed necessary from a regulatory standpoint in the US. Such cost might amount to 5–9 dollars/US ton of waste placed at about 60000 tons waste/acre (see below). However, savings are also possible for situations of developing nations while still maintaining environmental protection. Examples of savings potentials include: (a) waste placement over pre-existing low permeability clay/soils should prevent groundwater contamination problems while avoiding much bottom lining cost; (b) other design modifications such as thinner layers are possible and receiving regulatory consideration in the US as technology evolves; (c) locally available materials and labor use to the maximum extent in Vietnam and other developing countries should also result in considerable savings; and (d) design

might be to standards and costs giving environmental impacts comparable to or less than those of aerobic surface composting now in limited use near Hanoi (see above).

In fact most solid waste, US and worldwide, has been landfilled to less stringent requirements until very recently, at costs well under those cited above. More detailed engineering, and other analysis, will be necessary before economies possible for a Vietnamese or other developing nation operation are determined. Until that analysis is done it is prudent to recognize that costs associated with environmental protection may be substantial. Hence, higher costs based on US experience will be used for reference in this paper. It is to be emphasized that, whatever the other design choices and environmental standards, the controlled landfill operation will be conducted to minimize solid waste methane emissions that are perhaps the greatest current international concerns with solid waste because of climate change [13,14].

For cost analysis purposes it is important to recognize that most of modern landfilling expenses will be incurred as part of basic environmental protection, i.e., hopefully, standards similar to US and OECD countries' will be applied worldwide. Most landfilling costs are independent of whether methane recovery or methane enhancement is practiced. For example: (a) leachate, the liquid that percolates from waste, will form in any event as ambient rainfall infiltrates down through waste. It must be addressed by an adequate leachate handling/recovery system which is needed in any case to prevent groundwater contamination; (b) waste surface coverage will be required in any event, to standards that prevent exposure with settlement over time, as well as bird, rodent problems, etc. This cover must not erode; and (c) all normal operation and maintenance work will be incurred in any case.

With normal design and environmental protection standards the capital and operating cost bases for controlled landfilling are only those incremental costs incurred when controlled landfilling with methane enhancement and complete recovery is practiced, compared to when it is not practiced. These are estimated at $75 000 to $100 000 (rounded), based on 1 acre of landfill 'footprint' as discussed below and shown in Table 2.

Table 2
Estimated incremental per-acre costs with controlled landfilling

Construction cost item:	Cost
Leachate recirculation (cost increment only)	$10 000
Geotextile/porous layer/geotextile	$15 000–30 000
Surface membrane	$25 000
Gas recovery lines and blower	$5000–10 000
Credit: surface cover saved with membrane	($10 000)
Subtotal added construction costs	$45 000–65 000
Engineering, QA/QC at 18%	$8100–11 700
Subtotal added construction	$53 100–76 700
Added operating cost at $200/day	$23 600/acre
Total	$76 700–100 300

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2.7. Additional assumptions and cost considerations

A number of other design details have been established (D.C. Augenstein (1994–95) Institute for Environmental Management, Palo Alto, CA). Among the further assumptions have been:

1. Waste is filled to a depth of 60 feet, to density of 45 lb./ft.^{3} (excluding any cover material). Thus, each acre filled will contain 60 000 tons of waste and will yield 1.8×10^8 cubic feet of gas (1.8×10^5 MCF) through completion of methane generation. At a 500 ton/day fill rate, 120 days are required to fill 1 acre; 3 acres will be filled per year.
2. Incremental labor and supplies will be \$200/day. This includes costs such as adding water/liquids to waste, extra labor, and the like.
3. Costs associated with controlled landfilling, both construction and incremental operating, will be incurred continuously at constant rate. This assumption introduces some error, which is modest, in economic calculations. In actuality, landfill construction will be in modules of 5–20 acres with construction costs intermittently peaking at about 2–5 year intervals.

A simplified economic analysis is possible using as the basis 1 acre of landfill with its associated incremental costs and incremental gas yield. Assumptions are: (1) the setup cost per acre are \$75 000–100 000 (see above); and (2) gas generation begins one year after costs are incurred, and is according to Scholl Canyon model kinetics [20] with a time constant of 10 years.

2.8. Calculation of discount rate or rate of return on a full-scale system

On the basis of any 1 acre's cost and subsequent revenue over time, a return on investment, or, alternatively, discount rate ($= d$), can be calculated for any time period t starting after costs are incurred and ending at time T, such that:

Sum from gas generation starting time t_0, to $t = T$ of $Iy\ (e^{-dt})$ equals present worth (1 acre's cost). (Where Iy equals gas energy revenue per acre in year y.)

The simplifying assumption is that incremental costs are incurred 'instantly' 1 year before gas recovery begins, which is an approximation.

For 1 acre, production and revenue beginning 1 year after waste placement, and a time constant of 10 years $Iy = \$39\,600\ (e^{-0.1t})$.

Given that the present worth of any future revenue Iy in year is $Iy\, e^{-dt}$, so:

$$\int_{t_0 = 1\text{ year}}^{T = 25\text{ years}} 39\,600\, e^{-(d+0.1)t} = \$75\,000 \text{ to } \$100\,000$$

For the assumed endpoint of 25 years it can be shown that the discount rate d, equivalent to return in this rather simplified analysis ranges from 22% to 33%. Note that this return holds whatever the number of acres.

Another way to estimate gas cost is to simply assign all continuing costs to all captured gas. As one simplification at long times after startup (over a decade) the captured gas cost might be considered to approach the annual incremental controlled landfilling cost of \$225 000 to \$300 000 divided by the annual gas yield of 540 000 mmBtu or 42 to 56 cents per million Btu.

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2.9. Commentary on preliminary cost analysis

It is to be noted that numerous variations are possible to analyses presented above. More favorable kinetics (shorter time constant and more rapid gas generation) are likely to be attainable and would yield higher returns. Also, the particular analysis above assumed that all incremental costs of controlled landfilling are assigned to all gas recovered. Implicit in this is the assumption that fuel gas is the only benefit. In fact, other benefits may accrue, among which are:

- Volume reduction of waste, which may allow significant extension of the life of the landfill.
- Savings in long-term costs, as gas generation is completed sooner and also as the waste stabilization and subsidence is completed sooner.
- From the standpoint of longer term and global environmental concerns, an extremely large 'greenhouse benefit'. This occurs as atmospheric methane emission that would otherwise occur is prevented [13,14].
- The potential re-use of stabilized/composted waste, and re-use of landfill space.
- Savings in liquids/sludges treatment or disposal costs.

Quantification of these benefits will not be attempted here, but their value compares with that of the energy itself.

The foregoing analysis compared controlled landfilling only to the situation of landfilling without gas recovery at all. Comparison could also be to 'conventional' landfilling where gas recovery by vertical wells is practiced. A full comparison between controlled and conventional landfilling would be complex and will not be attempted at this point. Qualitative comments can, however, be offered:

Conventional landfilling has major drawbacks in that gas generation is quite slow and that only in the order of 50% of the generated gas is recovered. Low gas recovery is in part due to the low gas capture efficiency of conventional wells of 40–90% [20] and also in part because economics and practicality of collection of the low-rate 'tail' of gas generation are extremely poor, as generated beyond, say, 30 years. Altogether, because of lower capture efficiency and incomplete waste decomposition, it is likely that conventional landfilling would at best yield less than half the gas that controlled landfilling would, and have substantially greater adverse 'greenhouse' environmental impact. Also to be considered in any comparison is that higher gas recovery with controlled landfilling may be associated with better economics of scale for downstream energy uses. The scale advantage should be substantial in some cases, although no quantification will be attempted here.

Preliminary estimates above show controlled landfilling to be financially attractive. In fact, expected favorable economics, among other forces, have prompted continuing worldwide interest in bioreactor landfills and controlled landfilling [15]. Effort was made above to use parameter values that are up-to-date and conservative. Cost factors may differ and uncertainties exist for various reasons, such as variations between US and elsewhere in the world, or that not all gas, so collected, finds continuous use. Still, there is a safety margin: a reduction in return by half, or a doubling of the gas cost stated above, still leaves an attractive situation. In addition the ancillary non-energy benefits, not quantified above, likely compare to or even exceed the energy in value.

2.10. Suggested steps for controlled landfill project in Vietnam

The following is a brief listing of further steps that would be needed as part of implementation of this process in Vietnam.

- Survey to update actual waste generation and disposal patterns now existing; better quantify waste.
- Detailed waste component characterization.
- Better quantify current sewage disposal practice and quantities.
- Site identification and characterization for controlled landfill.
- Preliminary planning and identification of needs for waste transfer to controlled landfill site.
- Preliminary planning and identification of needs for sewage provision to controlled landfill site.
- Preliminary design of controlled landfill.
- Detailed projections of cost, staffing and operation of controlled landfill.

These could culminate in construction and operation of a controlled landfill in Hanoi. To implement a controlled landfill, operator training and familiarization with anaerobic processing is also needed (as is the case with aerobic composting above). Thus, it is also anticipated that a training program would be developed jointly involving Northeastern University, Boston, USA, and the Technical University of Hanoi.

Based on the preliminary analysis above, controlled landfilling merits further investigation as an alternative to aerobic composting for Hanoi, and, for that matter, where fuel gas product and other benefits are desired elsewhere.

Acknowledgements

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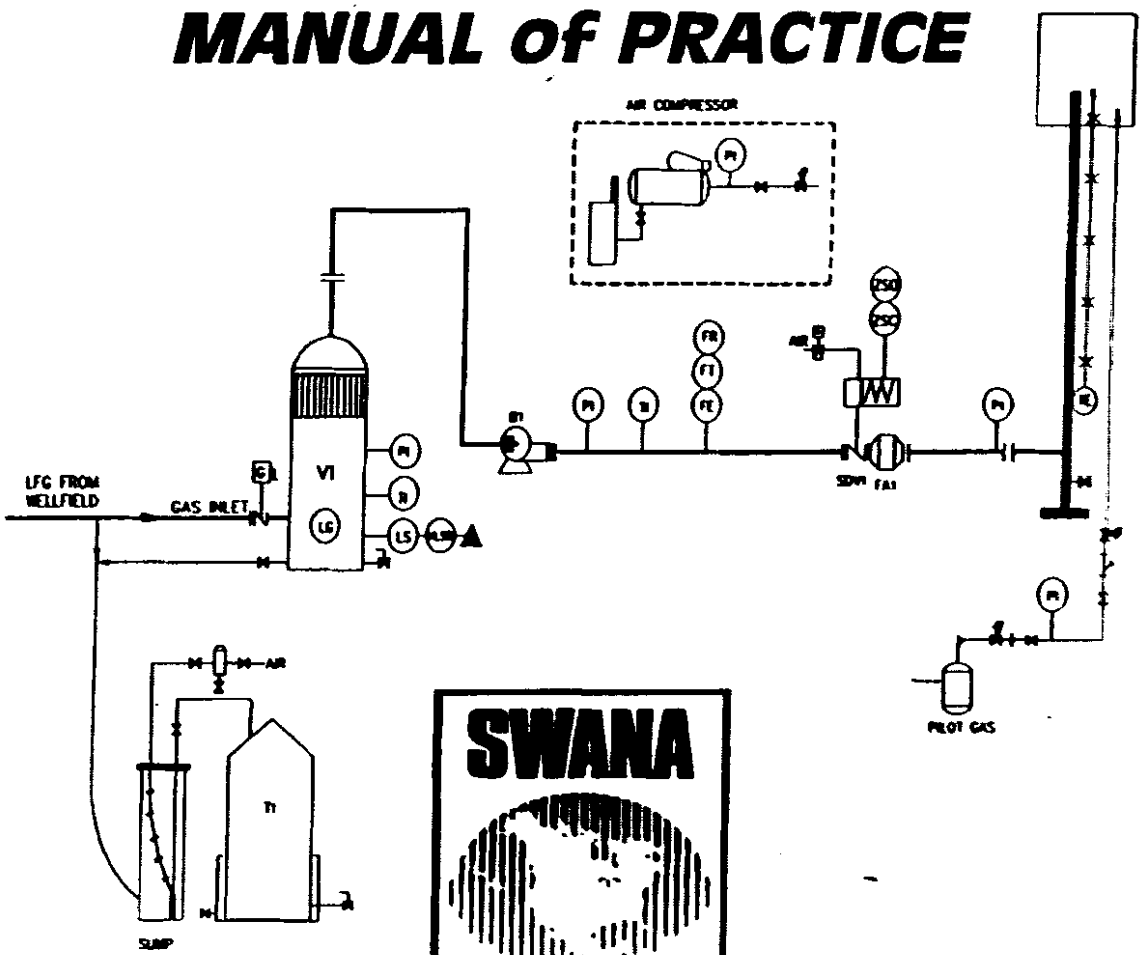
Section V.

Landfill Gas Operation & Maintenance Manual
Gas Control Engineering Inc.

JOHN TACEY

LANDFILL GAS OPERATION & MAINTENANCE *MANUAL of PRACTICE*



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The Peer Review Team included:

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- Mr. Tom Kerr
- Mr. Carlton Wiles

These advisors participated as individuals, not as official representatives of their organizations or institutions. We are grateful for their assistance and their insights; however, SWANA is solely responsible for the overall conduct of the study.

1. INTRODUCTION

1.1 PREFACE

1.1.1 Disclaimer

The naming of specific manufacturers or brand names is not meant to be a specific endorsement of that brand, or of one brand over another. Where, for a specific purpose, a brand has established itself as such an industry standard so that its name may commonly be used as a description of a generic type, that brand name is used here with the recognition that a comparable, competing item may be available and equally suitable. No specific endorsement of items or equipment is made or implied.

1.1.2 Purpose of Manual

This Manual of Practice (manual) is intended to be a source of information, practices and procedures for the operation of landfill gas (LFG) collection and control systems for both inexperienced and experienced operators..

1.1.3 Objectives of This Manual

This manual has the following objectives:

1) Compile and present key portions of the general body of knowledge about operating and maintaining LFG control systems.

2) Present information in an easy to understand format useful for hands-on practical use in the field.

3) Present accepted practices and procedures for LFG control practices.

4) Highlight key points, common mistakes and lessons learned from more than 20 years of industry experience. Point out areas of controversy and indicate alternative practices where applicable.

5) Compile key reference information.

6) Provide theory and discussion needed to develop a deeper understanding of LFG control and recovery.

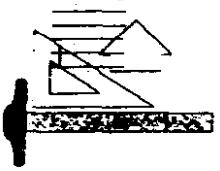
A brief summary of LFG health and safety issues is available in Chapter 19, Safety. For more detailed information on LFG health and safety issues refer to the Health and Safety Section of the SWANA "Landfill Gas Field and Laboratory Practices and Procedures" Manual.

1.4 PROJECT TEAM

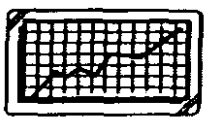
The development of this manual was a collaboration of a project team which included Mr. Jim Wheeler of James H. Wheeler Environmental Management (t) as principal author, Mr. Alan Janechek of Gas Control Engineering (GCE) as project manager and contributing author, Messers. Fredrick C. Rice of F.C. Rice and Co. Inc. and Mr. John Pacey of FHC as principal reviewers, and Mr. Richard Prosser of GCE as a principal reviewer. Additional staff who were instrumental in preparing this manual were Ms. Cheryl Wood (GCE) for word processing and layout, Ms. Denise Manchego (GCE) for Computer Aided Drafting, Ms. Monica Zuberbuehler (GCE) for graphic arts and layout, Mr. Kirk Hein (GCE) and the National Renewable Energy Laboratory (NREL) for technical editing/review.

1.5 MANUAL HELPS - INFORMATION IDENTIFYING ICONS

Throughout this manual key information is identified by icon symbols to aid the reader in identifying certain classes of information and key points. The identification is as follows:



Engineering Calculations



Tables and Charts

Point of Controversy or Controversial Topic

Key Point of Information

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2. LFG FUNDAMENTALS

2.1 REVIEW OF SCIENTIFIC FUNDAMENTALS FOR LFG SYSTEM OPERATION

There are a number of areas of science, engineering and management that apply to the multi-disciplinary understanding that is necessary for LFG practice. These areas may include:

- Biology
- Chemistry
- Physics
- Mechanical engineering
- Fluid mechanics
- Process operations and production management
- Maintenance management
- Civil engineering
- Geology and hydrogeology

Comprehensive knowledge in these areas is not essential to be a good LFG system operator. Nevertheless, it is helpful for operating staff to be observant and to have good general scientific and mechanical aptitude and problem solving skills.

2.2 COMPOSITION, CHARACTERISTICS, AND HAZARDS OF LFG

The most significant characteristics of LFG are as follows:

- Consists primarily of methane (about 55 %) and carbon dioxide (about 45%).
- LFG is wet; cooling almost always results in condensate water formation.
- LFG is flammable (i.e., potentially explosive).
- LFG may migrate through surrounding soils, within open conduits, permeable trench backfill.
- LFG may accumulate in confined spaces.
- The weight (specific density) of LFG is usually close to the weight of air.
- Typical temperature range is 16 to 52° C. (60 to 125° F.) within the landfill.
- Component gases (methane, carbon dioxide, water vapor and others) tend to stay together but may separate through soil and liquid contact.

Characteristics of Landfill Gas

Methane is a colorless, odorless, flammable and potentially explosive gas that as landfill gas together with other volatile trace gases may be emitted into the atmosphere; LFG that contains other gases may migrate through the soil into surrounding areas or contact groundwater. These other gases may adversely impact the environment. LFG may travel long distances under ground. It may accumulate underneath and in structures and confined or enclosed spaces creating a potential explosion hazard. Methane and carbon dioxide are simple asphyxiates. Carbon dioxide is colorless, odorless, and non-combustible.

The flammable range of methane is approximately 5 to 15 percent (by volume) in air. The lower limit of 5 percent is referred to as the Lower Explosive Limit (LEL); the upper limit of 15 percent is referred to as the Upper Explosive Limit (UEL). Walking across a carpet in leather shoes creates a static charge sufficient to ignite methane. The auto-ignition temperature of methane is 540° C (1004° F). The specific density of methane and carbon dioxide are 0.55 and 1.52 respectively, however, the specific density of LFG is close to that of air. For structure protection, it should not be assumed that methane gas will rise. The landfill gas mixture may be lighter or heavier than air and its behavior will be dictated by its overall composition.

LFG has its own characteristic odor due to trace compounds in the gas. Some of the most significant examples of the classes of odor causing trace constituents include esters, phenols, organic acids, solvents, and sulfur compounds (including mercaptans). However, LFG may not always exhibit an identifiable odor since the odor carrying trace components may be stripped off as a result of movement through cover or adjacent soil.

The methane in LFG is the same gas that is the main component found in commercial natural gas. Since methane by itself is odorless, commercial natural gas is odorized, usually with mercaptans (a class of sulfur compounds), to identify or "tag" the odorless methane for safety purposes.

The movement of LFG can also be affected by atmospheric pressure changes. These changes can occur as a result of:

1) Daily (or diurnal) cyclical fluctuation of atmospheric pressure and

2) Barometric changes brought on by weather changes (e.g., storm front movement).

The movement of LFG can also be affected by changes in soil pressure due to ground water fluctuations from recharge (e.g., after a heavy storm) or pumping and tidal fluctuations at sites near the ocean.

LFG May Migrate Offsite Developing Potentially Dangerous Accumulations

Under certain conditions, LFG can migrate laterally long distances from the landfill. An often used rule-of-thumb is LFG can migrate up to 1000 feet. Structures within this distance may require additional precautions to protect them from LFG accumulation. In some dramatic instances landfill gas containing methane above the LEL has been known to migrate for one-half mile or more into soils below surrounding communities. There are instances of lateral subsurface gas migration from landfills which fueled explosions with recorded fatalities and damage to structures. LFG will potentially migrate along all possible pathways, favoring those that present the least resistance.

2.4 BENEFITS OF LFG

LFG can provide an energy benefit when its significant methane content is put to beneficial use. For this reason it is considered a renewable resource. The viability of recovering LFG for its energy benefit has been well demonstrated as there are approximately 150 and 450 LFG energy recovery projects in the U. S. and Europe respectively. The general energy uses for LFG are shown in Figure 2.2.

Landfill methane may be used to fuel boilers, furnaces, engines and vehicles. LFG can also be used as a feedstock for chemical processes.

Recovering LFG for its energy benefit provides a side benefit of reducing liabilities associated with LFG.

- The placement history (refuse age and quantity),
- Conditions of the waste mass (nutrient substrate) present in the landfill that is available for the anaerobic bacteria,
- Moisture content of the refuse,
- pH of the refuse,
- Temperature of the refuse,
- Maintenance of the anaerobic environment (i.e., little oxygen present in the refuse).

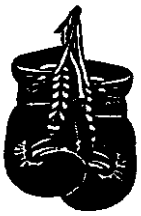
Most of the factors associated with LFG generation cannot be easily changed or improved. Of the above factors, other than composition, volume and age of refuse, moisture and temperature are the most important factors in controlling the rate of LFG generation and the volume of LFG generated. Usually, most of these factors are naturally limited and less than that required for optimum LFG generation, but may often be sufficient for generation of significant volumes of LFG.

2.5.1 Conditions for LFG Generation

When municipal solid waste (MSW) is placed in a landfill, the void volume (the volume not occupied by solids or liquids) within the MSW is filled with air from the surrounding atmosphere. Through natural aerobic processes, the oxygen from the air is quickly consumed and an anaerobic environment is soon established within the landfill. This anaerobic environment is one of several conditions necessary for the formation of methane.

Introducing Oxygen into the Landfill

If oxygen is reintroduced into the landfill, those portions into which the oxygen are introduced are returned to an aerobic state and the methane producing bacteria are inhibited. If the introduction of oxygen is stopped, some time must pass before the oxygen is depleted. The affected refuse mass then gradually returns to an anaerobic condition and LFG is again produced. This process impacts the rate of LFG generation. For an energy recovery project this may have dire consequences. For a migration control project the introduction of small quantities of air is typically not significant. However, introduction of large amounts of air can result in erratic production of LFG and a site that is difficult to control.



Effectiveness of Testing

The usefulness and validity of LFG testing is controversial and most experienced LFG practitioners tend to discount its value. It has been used in the past primarily to support development of energy recovery facilities. Regardless of the value of testing programs, understanding testing theories, techniques, and procedures can provide a better understanding of how to better operate a LFG collection and control system. A detailed discussion of LFG testing is beyond the basic scope of this manual. Appendix A of the NSPS for MSW Landfills (See Chapter 5, LFG Regulatory Requirements) includes a procedure for performing field testing.

2.6.3 Basis of Design of the LFG Control System

A LFG collection system is sized based upon current and future municipal solid waste intake, corresponding LFG generation and yield potential, rules-of-thumb, designer experience and observations, and any field testing performed. LFG generation will normally peak shortly after site closure and will continue for decades. For some sites, a formal basis-of-design document is prepared as part of the design process. Operating staff should become familiar with the Basis-of-Design which should be integrated into the operating documentation.

The basis-of-design document should state the assumptions and conclusions that provided the basis for the design of the system including:

- Sizing of system components
- Materials of construction
- System layout
- Method of operation

Section VI.

Ecological, Energetic and Economic Comparisons of Anaerobic Digestion

Edelmann, W.K.Schleiss, and A .Joss

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Ecological, energetic and economic comparison of anaerobic digestion with different competing technologies to treat biogenic wastes

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Abstract In order to get more detailed information for better decision making in future biogenic waste treatment, different processes to treat biogenic wastes in plants with a treating capacity of 10,000 tons of organic household wastes per year were compared. The comparison included life cycle assessments as well as economic considerations for different treating methods. Measurements on compost plants showed that methane emissions are higher than estimated so far. With the tools ECOINDICATOR and UBP anaerobic digestion shows to be advantageous as compared to composting, incineration or combination of digestion and composting, mainly because of a better energy balance. In fully enclosed, professional treatment plants, the specific biotechnological treatment costs are in the range of about 150.-sFr/ton for aerobic, anaerobic and combined technologies. It can be concluded, that anaerobic processes will become considerably more important in the future mainly for ecological reasons.

Keywords anaerobic digestion; composting; incineration; MSW;biogenic wastes; environmental impact study; economy; methane emission; life cycle assessment

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Introduction

Some years ago, humid biogenic wastes had been dumped or burnt in incineration plants. Today in Switzerland, the biotechnological treating methods became more important because of legal restrictions such as TVA [1], a law which favours separate collection of wastes and their appropriate treatment and recycling.

For the biological breakdown of biogenic wastes both aerobic and anaerobic technologies exist. The aim of this study is to compare the different treating methods from ecological, energetic and ecological points of view. So far, some comparisons have already been made (Membrez *et al.*, 1997, Aebersold *et al.*, 1993, IEA 1997). However, most of them focus on single aspects such as economy or only on the environmental impacts of a few parameters. The work presented in this paper tries to approach the problem in a more holistic way comparing as many parameters as possible for standardized plants with treating capacities of 10,000 tons/a. Five different biotechnologies plus treatment in a modern incineration plant were examined.

Assumptions, definition of the compared objects

Data were sampled on existing Swiss plants. However, these installations differ in several ways: For example, the treating capacities of the plants, which were observed in this study, vary from 5,000 to 18,000 t/year. In order to get comparable data, all data were standardized: data, such as construction materials, investment costs or salaries, were calculated for plant sizes of 10,000 t/year. It was assumed that all plants were constructed in the same suburban area. This allows us to assume identical transporting distances while collecting the source separated biogenic waste for all biotechnological treatment methods. It was assumed that there is no possibility to externally use the waste heat of the cogeneration of electricity and heat from biogas, at this theoretical site.

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The compared plants mainly differ in (i) process technology, (ii) construction costs (financial, energy and environmental factors) and (iii) running costs including energy and emissions. The following process technologies have been compared:

- EC: fully Enclosed and automated Composting plant with waste air treatment in a biofilter: The data were derived from a fully enclosed channel composting plant (IPS) with a compost biofilter,
- OC: Open Composting in boxes covered by a roof and in open windrows: COMPAQ-Boxes protected against rainfall followed by composting in open, low windrows reversed frequently and covered by gas permeable textile sheets,
- DP: fully enclosed, thermophilic, one step plug flow dry Digestion (horizontal KOMPOGAS-digester) with aerobic Post-treatment in an enclosed building equipped with compost biofilters,
- DE: combination of thermophilic dry Digestion combined with fully Enclosed, automated composting in boxes (BRV-technology), where 40% of the raw material was digested before the addition to the compost line. The air is cleaned by bio-washers,
- DO: combination of multiple stage, thermophilic dry batch Digestion (ROMOPUR-technology) combined with Open windrow composting: digestion of 60% of the raw material before addition to the compost line,
- IS: Incineration in a modern incineration plant including Scrubbing of the exhaust gas streams.

For the waste incineration, a plant with a treating capacity of 100,000 t/a of mixed wastes was chosen. The effect of burning 10,000 tons of biogenic wastes in addition to mixed wastes was determined after Zimmermann, (1996). The larger incineration plant causes longer transporting distances as compared to biotechnological methods. On the other hand, there is not an additional green waste collection necessary. Identical impacts by waste transporting were assumed for all processes (for a detailed discussion see Edelmann, Schleiss, 1999). For all plants, exactly the same waste composition was assumed (60% material relatively rich in kitchen wastes from public collection and 40% material rich in lignin derived from private suppliers). Table 1 shows the elementary composition of the waste. The waste composition corresponds to mean values of separately collected biogenic wastes (median values of large own data base as well as data taken from literature).

As shown in Figure 1, it was assumed that all the biotechnological treatment technologies are capable to cause a 50% loss of the organic matter (OS) by biological activities. The gaseous emissions, which were measured or taken from data bases, were distributed according to the assumptions of Figure 1 and to the percentage of material treated in aerobic and anaerobic ways (see above).

Table 1 Elementary composition of the biogenic waste compound in this paper

Substance	Content	Substance	Content	Substance	Content
Water	50.00000%	Arsenic	0.00000%	Tin	0.00000%
Oxygen (without O of water)	13.74000%	Cadmium	0.00001%	Vanadium	0.00000%
Hydrogen (without H of water)	2.00000%	Cobalt	0.00000%	Zinc	0.00000%
Carbon (organic plus inorganic)	16.24000%	Chrome	0.00004%	Silicon	0.00004%
Sulfur	0.14000%	Copper	0.00178%	Iron	0.00000%
Nitrogen	0.40000%	Mercury	0.00001%	Calcium	2.10000%
Phosphorus	0.11000%	Manganese	0.00043%	Aluminium	0.00001%
Boron	0.00102%	Molybdenum	0.00004%	Potassium	0.30000%
Chlorine	0.40000%	Nickel	0.00004'	Magnesium	0.30000%
Fluorine	0.01000%	Lead	0.00156%	Sodium	0.10000%

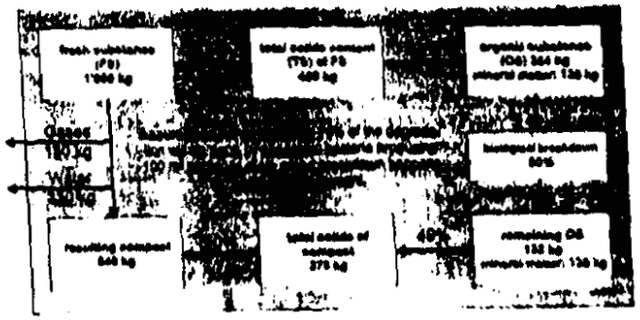

Figure 1 Assumptions for mass fluxes while degrading biogenic wastes with biotechnology

The functional unit consists in the treatment of 1 kg of waste such as defined in Table 1. All data refer to the yearly treating capacity of 10,000 tons of fresh substance of biogenic waste. It was assumed that 1% of the waste was undesired (e.g. glass, metal, plastic) and had to be burnt in an incineration plant. The whole life cycle of the biogenic wastes was compared including all environmental impacts caused by the different treating methods as well as those while producing goods necessary for the specific treatment. The assessment starts at the moment when the waste leaves the household, and includes all steps to the final application on the field (compost) or to the storing in a landfill (ashes of incineration). Energy plays a very important role while treating biogenic wastes. As far as electricity had to be bought externally, it was calculated with the European electricity mixture (UCPTE) for the electricity needs of the processes (Frischknecht, 1996). It seemed to be reasonable to use the European electricity mixture, because in Europe all countries are connected with each other; additional electricity need in Switzerland will cause additional (mostly) thermal production in EC or will reduce the export of renewable water power, respectively - which shows the same effect in EC.

Figure 2 shows the system borders: There are external additions to the system, such as material and energy necessary for the construction of the plant (infrastructure). The conversion of the renewable energy freed while degrading biogenic matter still is within the system borders (e.g. emissions of the motor burning the biogas). The emissions by compost application on the field and those caused by storing the ashes of incineration in a landfill are integrated into the consideration. Credits were taken into account for the benefits of the renewable energy and of some of the fertilizing substances within the compost.

It was assumed that the fully enclosed biotechnological plants can be run without an excess of process water with (this kind of waste (40% dry matter). The biologically generated compost heat is significantly higher than the heat need to evaporate the water in Figure 1. In Switzerland, the anaerobic plants generally have no problems with surplus water, today (for a detailed discussion see Edelmann, Schleiss, 1999). However, while composting in open windrows, which were exposed to the rain, the production of leachate had to be taken into account.

Materials and methods

Eco-inventory

All data refer to 10 [illegible] of biogenic waste. [illegible] equipment of each process included the [illegible] buildings, asphalt surfaces [illegible]

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infrastructure for pre- and posttreatment etc.. The materials used to provide the treating infrastructure were divided by the span of their life time in order to obtain the yearly amounts of cement, metals, asphalt etc. necessary to treat the 10,000 tons (assumptions: life span for mobile machines: 5a, stationary engines: 10a, buildings: 25a). The ecological pre-investments to produce the building and the construction materials were included by taking the data from ECOINVENT, a data base tool developed by the Swiss Federal Institute of Technology, ETH (Zimmermann, 1996).

The ecological running costs of the plant included energetic and material parameters such as energy fluxes, parts replaced because of attrition, commodities etc. as well as the emissions into air and into water caused by the process.

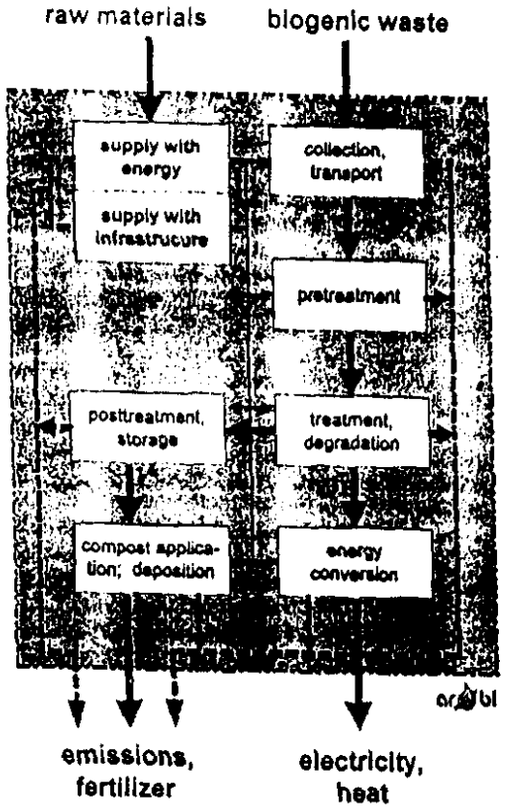

Figure 2 Definition of the borders of the observed systems: gray, thick arrows: mass and energy fluxes entering and leaving the system; dotted black arrows: emissions; black arrows: internal connections

Gas emissions

For the methane emissions of composting sites there exist only few data. In order to get appropriate values, the gaseous emissions were measured three times over the year by the closed chamber method (viz. Figure 3). Because the amount of [illegible]ded organic matter is

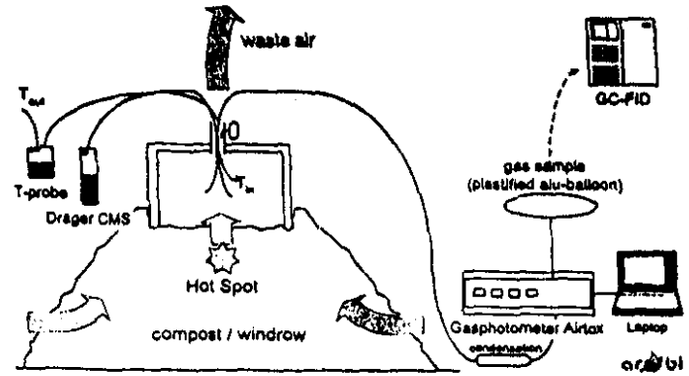

Figure 3 The closed chamber method to measure the gaseous emissions of compost: a box is placed over the hot spot, where it will be filled by the (warm) ascending gases. The ratio of CO_2 to CH_4 to O_2 is monitored on line. For each process, measurements of one half up to two hours were made at different places on several composts of different ages or on the biofilters. The box was insulated and with heating facilities in order to prevent condensation

defined (viz. Figure 1) and its carbon content (defined elementary composition) is known, the moles of emitted carbon containing gas molecules could be calculated. Because CO_2 and CH_4 both contain just one carbon atom and have a similar volume requirement, it is possible to calculate their total emissions, as soon as their relative ratio is known.

Environmental impact assessments and sensitivities

After the determination of the mass fluxes, the emissions of these fluxes were determined and weighted. All processes, such as raw material extraction, distribution and manufacturing were included up to the moment of building the plants. Two tools were used for the weighing of the impacts: an improved version of ECO-INDICATOR 95 (Goedkoop,1995) and UBP, a tool developed by BUWAL (1998). Calculations as well as the work on waste incineration were done by S. Hellweg at the Laboratorium für technische Chemie, ETH Zürich, with data from Zimmermann (1996): The effect of incinerating 10,000 t of biogenic waste (as defined above) together with "gray" waste was determined (ratio of "green" to "gray" corresponding to the composition of not separately collected Swiss household waste).

In ECOINDICATOR 95+, ten impact categories (such as greenhouse effect, ozone layer depletion, acidification etc.) were defined. All the impacts caused by the different activities of a waste treating process are first sorted and attributed to the relevant categories. For each damage category, a reference substance has been defined. The impacts are brought to a comparable size by multiplying with a factor corresponding to their relative damage potential (e.g. in the greenhouse effect methane is weighted – depending on the observation period – 21 times stronger than carbon dioxide, which is the reference). Like this the effect scores can be normalized for each category. The damages caused by the reference substances are weighted for causing mortality, damage to health and ecosystem impairment. For the damage weighting factors, subjective weighing would be possible. In this study, the default values of the software as proposed by the authors have been applied.

The method UBP of BUW[illegible] was used to compare the results of ECOINDICATOR to a tool, where the target set values are the Swiss national policy objectives. In UBP normalized

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Ecopoints are distributed not to the effects, but to individual emissions, energy consumption and environmental scarcity.

Because ECOINDICATOR only takes account of heavy metals leached from soil to water, sensitivities were calculated for different heavy metal washouts from the grounds, where compost was applied. Additional sensitivities were established for the emissions of NH_3, N_2O and H_2S (data from literature), for an optimal reduction of methane emission while digesting and for not giving benefits to the fertilizer values while applying compost.

Results

Gas emissions

Figure 4 shows that (i) there also exist significant methane emissions even in composts, which are reversed very often (OC), and that (ii) in digestion plants there is a considerable potential of methane emission, even if just a small part of the organic breakdown takes place outside the (enclosed) digester. The measurements were taken on existing plants. Because the situation on the real plants differed somewhat from the assumed situations, it seems probable that – taking mass streams such as defined in the assumptions – the emissions of DO will be rather higher and those of DP rather lower than shown in Figure 4. For detailed gas analyses and discussion of the emissions see Edelmann Schleiss, 1999.

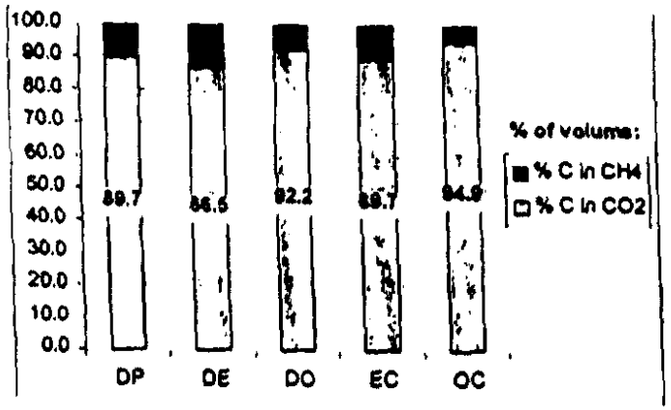

Figure 4 Rate of CO_2 to CH_4 of the different biotechnological processes (% of volume, weighted mean values of 3 campaigns). The graph shows the ratio of the total of the emissions, i.e. it was taken into account the fact that different percentages of the substrate were composted and/or digested depending on the technology applied. The methane generated by anaerobic digestion is counted as CO_2, because it will be outdated while being burnt in the engine/generator.

The gaseous emissions of NH_3, N_2O and H_2S were very low as compared to the emissions of CO_2 and CH_4 and difficult to measure accurately in the wet and warm gas emissions. Additional measurements have to be made in order to obtain data, which are statistically significant. For this reason sensitivities were calculated with data taken from literature (Grosseuer et al., 1997, Schattner et al., 1995)

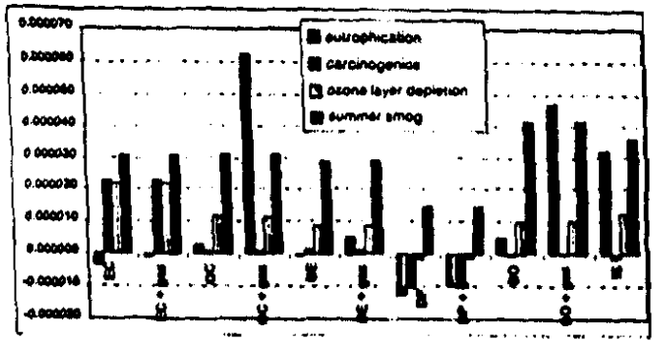

Figure 5 ECOINDICATOR 95+ -points for the impact categories radioactivity, energetic resources, greenhouse effect, acidification and winter smog. The data "+gases" of the biotechnological processes were calculated including emission data (taken from literature) for NH_3, N_2O and H_2S into the air. NH_3 -emissions are reduced to a large extent by the biofilters of the fully enclosed plants (EC, DP and DE). The radioactivity as well as much of the acidification is caused by the European electricity mixture (including nuclear plants as well as thermal plants running on fossil fuels)

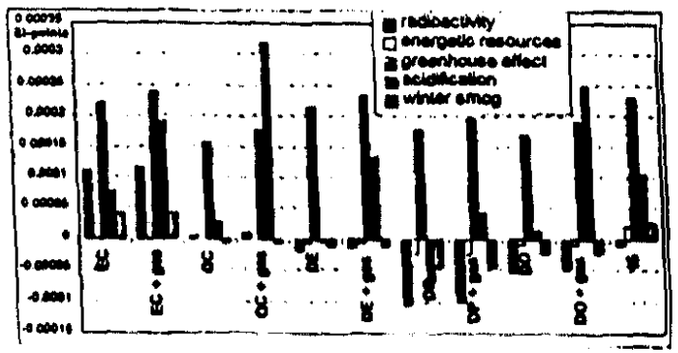

Figure 6 ECOINDICATOR 95+ -points for the impact categories eutrophication, carcinogens, ozone layer depletion and summer smog. The data "+gas" of the biotechnological processes were calculated including emission data (taken from literature) for NH_3, N_2O and H_2S into the air. For the sensitivity with gas emission, the eutrophication becomes especially large in OC and DO, where ammonia is able to escape into the open air. Similar to Figure 5, DP shows some negative values which are caused by the high net production of electricity that substitutes UCPTE-electricity

Impact assessments

Figures 5 and 6 show the sums of the ECOINDICATOR 95+ points for 9 impact categories. For the nitrogen and phosphorus present in the compost, benefits corresponding to the savings because of less artificial fertilizer production were taken into account. In the incineration plant (IS) the nutrients are lost. In Figure 7, which shows the total ECOINDICATOR-points (EI-p[illegible]), a sensitivity is calculated without fertilizer benefit. One heavy metal sensitivity is integrated in Figure 7. ECOINDICATOR only takes heavy metals into account, if they are exported from the [illegible]

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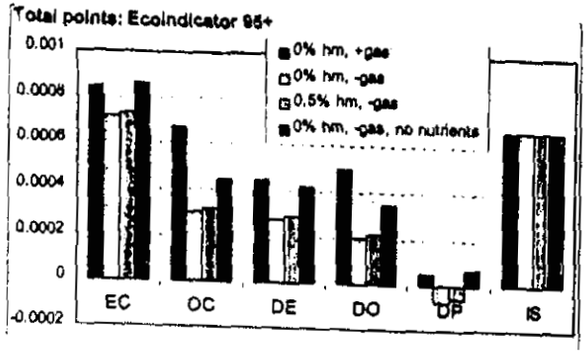

Figure 7 Total sums of ECOINDICATOR 95+ points for 4 sensitivities: +/– gas: with/without emission of NH_3, N_2O and H_2S into the air; no nutrients: no benefit for fertilizer substitution; 0/0.5% hm: amount of heavy metal export from soil by water

were calculated for the heavy metal leaching. In Figure 7 data are shown for no leaching and for 0.5% heavy metal export into water. With 5% export into water – which is a very high value – only DP has a slightly lower sum of total EI-points than IS (not shown in Figure 7). UBP showed a similar ranking as compared to ECOINDICATOR. However, because UBP gives very much weight to the heavy metal import into the soil, IS performs better than OC and EC due to the fact, that heavy metals are withdrawn from ecological cycles while dumping the ashes. Also in UBP, DP showed the best results. For details see Edelmann, Schleiss, 1999.

Figure 7 shows the overall performances of the processes. High scores correspond to high environmental impacts. Energy plays a predominant role: Taking all the necessary activities into account, the anaerobic digestion (DP) causes +/- no environmental impacts, i.e. the impacts are compensated by the generation of a surplus of renewable energy, which substitutes for fossil and nuclear energy. In addition to the energetic and environmental construction costs, the energy running costs of EC are more than 100 kWh electricity per ton of waste, which causes considerable negative impacts. Composting in a highly automated plant seems to be even more polluting than incineration in a modern incineration plant with advanced energy recovery. A comparison of EC with DP on the level of primary energy (energy necessary for the production of electricity, substitution of non-renewable energy by biogas, etc.) showed a difference as large as 700 kWh per ton of waste treated (Edelmann, Schleiss, 1999). The substitution of the nutrients present in compost with mineral fertilizers causes a primary energy need of nearly 90 kWh/t of compost, in addition to considerable environmental impacts in different impact categories (*ibidem*).

For incineration, no sensitivities were calculated, because not the same sensitivities are relevant as for biotechnological processes. For more details on incineration, see Hellweg (1999).

The gases, such as NH_3, N_2O and H_2S could not be measured on site (see above). The sensitivities calculated with data from literature show, that the environmental impacts of these emissions play a very important role. Mainly because of acidification and greenhouse effect (Figure5) as well as eutrophication (Figure 6), outdoor steps of the waste treatment increase the total impacts considerably (Figure7; +/– gas). The benefit of re-using the fertilizing value of the green waste is shown by the sensitivity "no nutrients" in Figure 7: for example, if it is not necessary to produce ammonia by the Haber-Bosch synthesis, fossil

energy use including a lot of negative impacts may be prevented. The only considerable negative impact of DP is observed in the category of greenhouse effect (see Figure 5; attention: the scaling of Figure5 differs from that of Figure 6!). This is mainly caused by the relatively large methane emissions of the material, which is (post-)composted after digestion. Here, there is a considerable improvement potential by creating as quickly as possible aerobic conditions immediately after digestion. The measurements cited above suggest that biofilters reduce only a relatively small part of the methane emissions by methane oxidizing biocenoses. For detailed discussions see Edelmann, Schleiss, 1999.

Economy

The investment and running costs of the different processes were investigated at existing plants (Schleiss, 1998) and afterwards corrected for plant sizes with treating capacities of

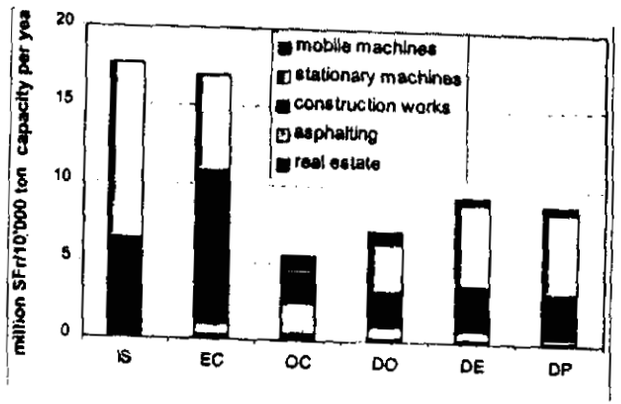

Figure 8 Investment costs of the different processes: The investment costs for the incineration plant are derived from a project, which is under construction in Switzerland (incineration plant with advanced gas scrubbing and selective catalytic reduction of NO_x)

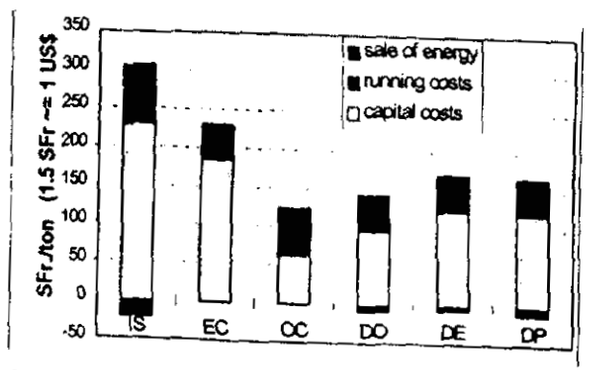

Figure 9 Specific treatment costs of the different processes. In contrary to anaerobic digestion, it was assumed that with IS waste heat could be sold for house and water heating purposes (therefore considerably higher sale of energy than AD). Effective costs: sale of energy has to be deducted

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10,000 t/a. In Figure 8, the investment costs of the fully automated EC are very high; it may be suggested however, that it could be possible to construct a new plant of similar design with some financial savings. The data of IS refer to the treatment of 10,000t/a in a plant with a capacity of 100,000 t/a (no separate collection of the organic fraction). Detailed information is given in Edelmann, Schleiss, 1999.

In Figure 9, the costs for waste collection are not included. For the biotechnological treatments they can be assumed to be identical. With incineration it is not necessary to collect twice ("gray" and "green"), but the transporting distances are longer due to the larger radius of the collection area caused by the higher treating capacity. OC shows the lowest treatment costs due to the relatively low investment. On the other hand, the running costs of OC are higher than those of the other biotechnological treatments because of lower automation. DO is cheaper than the other digestion technologies because of lower investment (open composting without biofilter etc.), but it is not suited for all applications (high content of kitchen wastes, etc.) due to gaseous emissions. EC shows the lowest running costs, but very high investment costs which cause high capital costs.

Discussion

The ecological and the economic comparisons (Figures 7 and 9) show that the biotechnological treatments for biogenic waste treatment are generally favorable with respect to incineration. The pure composting technologies (EC and OC) appear to be less ecological than digestion: the higher the percentage of digestion, the better the score. The three categories greenhouse effect, acidification and heavy metals play an important role in the impact assessment. The greenhouse effect is caused mainly by CO_2 and CH_4. CO_2 emission cannot be prevented if biogenic matter is degraded. For theoretical reasons (Edelmann, 1995) it is not surprising that a considerable amount of methane is emitted while composting; here, there seems to exist a potential for improvement.

Heavy metals have a very strong effect in UBP and also in ECOINDICATOR 95, provided that there exists an export into the water. Heavy metals are deposited by rain and air on the biomass which afterwards is treated in a processing plant. The treatment itself does not attribute significantly to the heavy metal load of the biomass (metal deriving from chipping and from transporting engines etc.). Because the heavy metals are supposed to be in a more or less inert form bound in the ashes of the dump, IS shows an advantage: in this case the heavy metals are withdrawn from ecological cycles. Considering the fact that the heavy metal load of the compost usually is far below the legal limits (Schleiss, 1999), it does not seem logical at all to burn the (very precious) organic substance in order to "reduce heavy metals present in air and rain", however.

When comparing the different technologies, energy plays a predominant role. Digestion plants are better from an ecological point of view, because they don't need external fossil and electrical energy. If only one quarter of the biogenic waste is digested, a plant can be self sufficient in energy (Edelmann *et al.*, 1998). The production of renewable energy has positive consequences on nearly all impact categories, because of saving of or compensation for non-renewable energy. This reduces the impacts of parameters such as radioactivity, dust, SO_2, CO, NO_x, greenhouse gases, ozone depletion, acidification or carcinogenic substances. Digestion plants could show an even better performance, if they were constructed near an industry which can use the waste heat of electricity production all year round.

It is nearly impossible to take advantage of waste heat while composting (Edelmann *et al.*, 1993). Looking at the results of the impact assessment and the economic situation, it is very difficult to understand that today composting plants are constructed, where high value fossil and nuclear energy is invested to *destroy* the renewable solar energy, which is fixed in the chemical compounds of biomass and thus in the biogenic waste.

Acknowledgement

Our thanks go to Steffi Hellweg, ETH, as well as to BFE and BUWAL for supporting this study.

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Section VII.

Landfill Gas Generation and Recovery in Thailand

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LANDFILL GAS GENERATION AND RECOVERY IN THAILAND

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A relatively limited amount of information is currently available regarding appropriate input parameters for methane generation models for Asian countries. This paper provides an overview of the preliminary findings of the Energy and Environmental Engineering Centre at the Kasetsart University based on their work at the Kamphangsaen Landfill in Thailand. Work on this project has also been supported by the Chai Pattana Foundation, Group 79 Co. Ltd., National Energy Policy Office, United States Environmental Protection Agency – Methane Branch, US-Thailand Development Partnership/Kenan Institute Asia, and the World Bank. The methane generation rate was estimated using parameters developed from a review of waste stream composition analyses and landfill gas recovery testing. The paper also addresses the implications for estimating greenhouse gas emissions and for planning energy utilization projects.

1. Introduction

The Kasetsart University, Thailand has been developing a landfill gas-to-energy (LFGTE) project at Kamphangsaen Landfill, which is located in Nakhonprathom Province, Thailand approximately 80 kilometers northwest of Bangkok. The landfill is owned and operated by a private company, Group 79 Limited. It was opened in 1988 and currently receives approximately 4,000 tonnes per day of municipal solid waste from the Bangkok Metropolitan area. The total amount of waste in place is estimated to be approximately 11 million tonnes, which has been landfilled in an area that occupies approximately 61 hectares.

In 1996, the Energy and Environmental Engineering Center, Faculty of Engineering, Kasetsart University successfully tested a gas engine modified from a gasoline engine using landfill gas (LFG) from a portion of landfill. A pilot project was established in 1997 and a LFG collection system consisted of 39 vertical extraction wells was constructed in a relatively shallow portion of the landfill. The project also incorporated a LFG pipeline and a power plant that includes two of 435 kW Waukesha engine-generator sets. It is planned that the electricity will be used to supply the University campus grid.

After the construction of the vertical extraction wells, it was found that the leachate level was approximately 1-2 meters below the ground surface during the rainy season, therefore the slotted portions of the vertical extraction wells were below leachate level. Leachate pumps were installed, but they did not function properly due to clogging in the pump casing. This resulted in low LFG quantity and quality. It was further observed that the LFG quantity and quality dropped sharply as time progressed.

The original collection system was subsequently abandoned and a new area of the landfill, which was about 18 meters in height, was selected for recovery of LFG. However, during

construction of the first new vertical extraction well it was found that this portion of the landfill also had a very high leachate level, which would constrain the ability to recover LFG. Based on this finding, an alternate collection system design was developed and two horizontal LFG collectors were installed in January 1999. The new horizontal collectors included provision for drainage of leachate from within the landfill. Based on the successful performance of these new collectors, five additional collectors were installed in January 2000.

For project planning purposes, it was necessary to reassess the approach that had been used to estimate the methane generation and recovery potential for this landfill. The United States Environmental Protection Agency's (USEPA) Landfill Air Emissions Model (version 2.01)[1] has been used in the analysis. Input values for the model were developed from a review of available information for the landfill and the methane generation potential (Lo) and the methane generation rate (k) were reviewed and selected based on consideration of the local waste stream and climatic conditions.

In addition, a comparison was performed to obtain a co-relation between the estimated and actual methane recovery rates. Therefore, methane generation rate under conditions in Thailand, which may be representative of other Asian countries, can be more accurately estimated. This paper presents the initial findings and the implications for estimating greenhouse gas emissions and for planning energy utilization projects.

2. Methane Generation Estimate

Methodology

There are a variety of methods that can be used to estimate the methane generation rate at landfills, however, the USEPA's Landfill Air Emissions Estimation Model (version 2.01) is generally recognised as being the most widely used approach. The USEPA model is a first-order decay model, and this approach is also consistent with the more complex methodology (rather than the default methodology) recommended by the Intergovernmental Panel on Climate Change (IPCC)[2] for calculating methane emissions from landfills. The equation is as follows:

$$Q = L_o R (e^{-kc} - e^{-kt})$$

Where:

Q	=	Methane generated in current year (m^3/yr)
L_o	=	Methane generation potential (m^3/Mg of refuse)
R	=	Average annual waste acceptance rate (Mg/yr)
k	=	Methane generation rate constant (1/yr)
c	=	Time since/to landfill closure (yr)
t	=	Time since landfill opened (yr)

Input data for the model was developed from a review of available information for the landfill. A further calculation was performed to convert the methane generation rate into a LFG generation rate. The projected LFG generation rate for the landfill was calculated by multiplying the methane generation result by two, which is based on LFG comprising 50 percent methane and 50 percent carbon dioxide.

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An additional calculation was performed to estimate the quantity of LFG that could potentially be recovered from the landfill during the first phase of the project development. A discussion of the key input information, assumptions, and model outputs is provided below.

Methane Generation Potential

The methane generation potential (Lo) depends upon the composition of refuse present in the landfill. The USEPA[3] reports that the values for (Lo) can range from 6.2 to 270. In addition, the USEPA has established the following default parameters for Lo

- Clean Air Act (CAA) default value of 170 m^3/Mg
- AP-42 default value of 100 m^3/Mg

However, utilization of the USEPA default parameters for Lo was not considered to be appropriate for the landfill and other similar sites in Thailand. The basis for this conclusion is that there is a considerable difference between the composition of solid waste that is disposed to landfills in the United States and that which is generated in Bangkok and disposed at the landfill.

In order to estimate an appropriate value for Lo for the landfill, representative data regarding the composition of the waste was obtained for the Bangkok Metropolitan area. The waste composition for Bangkok was obtained from data collected by the Bangkok Metropolitan Authority (BMA)[4] at the On-Nuch transfer station on an annual basis for the period from 1986 to 1996. The data from the period from 1993 to 1996 was selected as being representative of current conditions. Information was also obtained from USEPA[5] that shows typical waste characteristics in the United States.

The waste composition data for Bangkok and the United States was then reviewed and allocated into four major waste categories as shown below. The readily degradable items included food waste and a portion of green waste (grass). The moderately decomposable items included a portion of the paper waste and the remaining green waste, and the slowly degradable portion included the remaining portion of the paper waste, wood, textiles, and other materials. The non-degradable items included plastic, glass, metal, concrete, rubble, and other inert materials.

Waste Type	Waste Composition Bangkok (1993 to 1996)	Waste Composition USA (1996)
Readily Degradable	20.0	13.8
Moderately Degradable	6.9	27.8
Slowly Degradable	17.2	25.8
Non-Degradable	55.9	32.6
Totals	100.0	100.0

As indicated above, the Bangkok waste stream contains a higher percentage of readily degradable waste (which comprises entirely of food waste), but a significantly lower percentage of moderately degradable wastes. Notably, the Bangkok waste stream did not include any green waste material. In addition, the Bangkok waste stream contains a lower percentage of slowly degradable waste and a significantly higher percentage of non-degradable waste. It was also noted that the Bangkok waste stream contains approximately 50 percent moisture, whereas the moisture content of waste in the United States is typically about 25 percent.

Based on the assumption that the Bangkok waste stream may have an average methane generation potential of approximately 225 m3/Mg (on a dry basis), and the waste composition and moisture content are as outlined above, an Lo value of 50 m3/Mg was estimated for the Bangkok waste.

Methane Generation Rate Constant

The methane generation rate constant (k) determines the rate of generation of methane for refuse in the landfill. The value of k is a function of a number of factors including refuse moisture content, availability of nutrients for methanogens, pH, and temperature. The USEPA[3] reports that the values of k can range from 0.003 per year to 0.21 per year. In addition, the USEPA has established the following default parameters for k:

- Clean Air Act (CAA) default value of 0.05 1/yr
- AP-42 default value of 0.04 1/yr for moderate climates and 0.02 1/yr for dry climates

However, utilization of the USEPA default parameters for k were not considered to be appropriate for the landfill or other similar sites in Thailand. The basis for this conclusion is that there is a considerable difference between the moisture content of solid waste that is disposed to landfills in the United States and that which is generated in Bangkok and disposed at the landfill.

In order to select an appropriate value for k for the landfill, representative data regarding the composition of the waste was obtained for both the United States and the Bangkok Metropolitan area, as discussed above. A review was also performed of published data on values that may be applicable to the landfill. Based on information that was developed by Hoeks, as compiled by Hans-Jurgen Ehrig[6], k values for the different waste categories were as follows:

Waste Type	Reported k Value
Readily Degradable	0.693
Moderately Degradable	0.139
Slowly Degradable	0.046
Non-Degradable	0.000

A calculation was then performed to develop a weighted value for k that would be representative of the potential methane generation rate for the landfill. Climatic conditions are also different in Thailand than the United States. Information regarding climatic conditions in the vicinity of the landfill showed that the total annual rainfall in 1998 was 1,225 mm, with monthly rainfall ranging from 0.0 mm in February and March to 302.9 mm in September[7]. In addition, the waste mass in the landfill was observed to be saturated with leachate. Based on the findings of this assessment, a k value of 0.15 1/yr was selected for the Bangkok waste.

Projected Methane Generation Rate

Based on the information developed above, a model run was performed to estimate the potential methane generation rate at the landfill. It is estimated that the total quantity of methane that is generated at the landfill will peak at approximately 9,000 m3/hr (18,000 m3/hr of LFG) at the estimated time of site closure in approximately 2020. The modelling also indicates that total quantity of methane that is generated at the landfill will decline rapidly in the future. It is estimated that the total quantity of methane that is generated in the year 2030 may decline to approximately 2,350 m3/hr (4,700 m3/hr of LFG).

Projected Methane Recovery Rate – Phase 1 Area

The Phase 1 area covered an area of approximately 2.4 hectares. The landfill was constructed by excavating approximately 4 meters below the ground. The deposited waste mass extends approximately 18 meters above the ground. Using a current in-place density of 1.0 tonne/m3, it was estimated that approximately 0.5 million tonnes of waste had been placed in the Phase 1 area.

It has been assumed that the LFG collection system that has been installed in the Phase 1 area at the landfill covers approximately 4 percent of the waste in place and has a collection efficiency of approximately 75 percent. As a result, an overall methane recovery rate for the Phase 1 area of 3 percent has been used in this assessment.

Based on the results of the recovery projection, it is estimated that approximately 150 m3/hr of methane (300 m3/hr of LFG) could be recovered from this portion of the landfill in 2000. After closure of the Phase 1 area in 2000, the methane recovery rate is projected to decline and is estimated to be approximately 45 m3/hr (90 m3/hr of LFG) in 2010.

3. Field Test Results and Comparison to Estimated Values

Installation of Horizontal Collectors

Two horizontal LFG collectors were installed at the landfill in January 1999, and five additional horizontal collectors were installed in early 2000. The first two collectors were 90 meters long and the additional five collectors were 100 meters long. Each horizontal collector extended from the outside edge of the landfill into the centre of the site. Each collector was constructed in a manner that included provision for gravity drainage of leachate from within the landfill (rather than by pumping). The horizontal collectors were installed at 30 and 40 meter spacings.

For the first two collectors, LFG was only recovered from headers that were installed at the outside edge of landfill. For the additional five collectors, LFG was recovered from both ends of the collectors. Four of the additional collectors were tested for LFG quality and quantity. One collector was not tested because construction activities had not been completed.

The projected LFG recovery rates for each collector were estimated to be approximately 50 m3/hr per collector. This estimate was based on the assumption that the horizontal collectors would provide an average recovery rate of approximately 0.55 m3/hr of LFG per meter of LFG collector length.

LFG Quantity and Quality

LFG flow rates from the first two collectors were tested during the period from August 1999 to December 29, 1999. Average flow rates were approximately 60 m3/hr and 62 m3/hr. The average methane concentration was approximately 55 percent and 57 percent, respectively.

Test results conducted during February and March 2000 showed that average flow rates approximately 70 m3/hr could be recovered from the collectors with LFG recovery at both ends. The LFG quality was approximately 50 percent methane. For the collectors with one header at one end, the flow rate of 50 m3/hr could be collected at approximately 50 percent methane. A slight decrease in the LFG quality in the original two collectors was observed.

The recovered LFG was burned in three separate flares, and the total quantity of LFG recovered from the Phase 1 area averaged approximately 310 m3/hr. The LFG quality averaged approximately 59 percent methane and less than 1 percent oxygen during the testing period.

Comparison of Estimated and Actual Methane Recovery Rates

The preliminary results indicate that the actual methane recovery rates at the landfill are higher than projected for the Phase 1 area. However, experience with field testing at other landfills has shown that the sustainable LFG yield is usually lower than the rates obtained during an initial testing program. As a result, the LFG collection system is being operated on a continuous basis and monitoring and testing of recovered LFG is being performed to provide further data for ongoing comparison.

Confidence Levels

There are four sources of uncertainty associated in the estimation of methane and LFG emissions from solid waste landfills. These include the uncertainty attributable to the method, data uncertainty, uncertainty associated with the estimate of the collection efficiency of the LFG collection system, and other factors.

The USEPA first order model is widely used for estimating methane emissions from landfills and is considered to be applicable to the landfill. The model accounts for changing LFG generation rates over the life of a landfill and takes into account the various factors that influence the rate and extent of LFG generation.

The sources of data uncertainty are directly attributable to each of the data inputs. Information regarding waste quantities and composition was developed from a review of site specific data. Input parameters for Lo and k were chosen to reflect conditions at the landfill.

Another source of uncertainty influencing the quantity of methane that is emitted from the landfill is the degree of oxidation that occurs as the LFG diffuses through the soil fill material and the cover soils. As the landfill contains large areas with little or no cover material, an oxidation factor was not used to reduce the estimated quantity of methane that is being generated. As a result, the accuracy of methane generation and recovery models is generally estimated to be approximately plus or minus 25 percent for the current year, with potentially greater variances over the long-term.

Conclusions and Implications

Disposal of municipal solid waste in landfills produces methane, which is a potent reenhouse gas. In recent years, scientists and policy makers have become concerned that the uild-up of greenhouse gases may increase the share of the sun's heat retained in the atmosphere, hich may in-turn affect the Earth's climate in uncertain but potentially disruptive ways. In ddressing these concerns, each nation has commitments under the Framework Convention for limate Change to address sources and sinks of all greenhouse gases.

Under the FCCC, Parties in Annex I (developed countries, and those countries with conomies in transition) are required to report inventory data for all greenhouse gases on an nnual basis. The IPCC has identified methods for calculating greenhouse gas emissions, owever, there has been limited information available that can be used for estimating greenhouse as missions for landfill disposal of solid waste in Thailand and other Asian countries.

In addition, development of LFGTE projects is recognized internationally as being a viable nd cost-effective method of controlling emissions from landfills. While there are many hundred f these facilities throughout the world, there are only a limited number in Asia. Planning for FGTE projects also requires a good understanding of local conditions to ensure that LFG eneration and recovery estimates are appropriate for each particular landfill.

Based on the work that has been accomplished by Kasetsart University to-date, preliminary alues have been selected for Lo and k that are considered to be applicable to the landfill, and ther sites in Thailand. While this work is ongoing, the preliminary value for Lo of 50 is ignificantly lower than default values that are often used in gas generation and recovery stimates in other countries. The value for k of 0.15 is significantly higher than the default alues that are often used in gas generation and recovery estimates in other countries. Use of hese preliminary values may significantly change estimates of greenhouse gas emissions in Thailand. This finding could be assessed by comparing emission inventory estimates that are developed using both the IPCC default and first order decay methodologies.

It is also anticipated that use of these preliminary values will impact the criteria that are used for identifying and screening feasible LFGTE projects in Thailand. Due to the composition of the waste stream and rapid degradation of the waste, LFGTE projects may only be economically feasible at larger operating landfills that have long-term disposal capacity. Alternatively, LFGTE facilities may have to be reduced in capacity to ensure the availability of LFG in the long-term.

In addition, LFG collection systems should also be designed to allow for management of leachate so that elevated leachate levels do not restrict recovery of LFG. Collectors that allow for drainage of leachate are preferred over extraction wells that require pumping systems. LFG collection systems should also be designed for ongoing expansion into active disposal areas to ensure that sufficient quantities of gas are available. Excess LFG should be flared to control greenhouse gas emissions.

5. References

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Section VIII.

Using a Landfill Mass Balance Model for Examining Methane Pathway Field Measurement at Landfills

Diot, M.

USING A LANDFILL MASS BALANCE MODEL FOR EXAMINING METHANE PATHWAY FIELD MEASUREMENTS AT LANDFILLS

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ABSTRACT

One tonne of municipal solid waste stored in a landfill produces from 120 to 150 m^3 landfill gas within several years. Without any recovery system, the landfill gas can migrate toward the atmosphere and contribute to the greenhouse effect. Alternatively, due to its methane content, it can be recovered and used as an attractive source of energy from waste. The research program METAN has been developed in the Waste and Energy Research Centre (CREED, VIVENDI Environnement Group) to identify and quantify the various methane flows in landfills. This work has sought to improve estimates of the net contribution of landfill emissions to global warming, particularly for different landfill configurations and various on-site management practices. Specifically, field work was conducted at two landfills in France, Montreuil sur Barse MSW Landfill and Lapouyade MSW landfill (ONYX) during winter conditions. Methane mass balances were established at each site based on measurements of methane collected, methane emitted toward the atmosphere, and methane oxidized as it moves through the cover. Several landfill configurations were tested, including: covered, temporary covered, and non-covered cells, with and without active landfill gas extraction. Complementary measurement methods were used to improve the precision. An infrared thermography technique was applied on one site to obtain a map of the thermal anomalies of the site so as to locate significant point sources of methane emissions. In addition, two chamber methods and a tracer method were used to quantify landfill gas emissions to the atmosphere. Lastly, an isotopic analysis method was used to quantify the fraction of methane oxidized through the cover. The quality and the quantity of LFG recovered had also been measured. The methane mass balance equation was utilised as a technique to validate the field data from a landfill site. The results of the field campaigns present good correlation of the methane balance at the two sites and, as a consequence, provide good correlation of the assessment of the emission of methane to the atmosphere. These results indicate that a landfill with ordinary soil cover, but accurate design and expertise in LFG recovery, reduces methane emissions to the atmosphere by achieving a high rate of methane recovery. For the two case studies with recovery systems, at least 94% of the biogas produced was recovered and flared.

INTRODUCTION

Methane, which is a more potent greenhouse gas than CO_2, has increased in atmospheric concentration by a factor of 2 in the past century. About 70% of the current emissions are from human related activities (US EPA, 1990). Methane generated in landfills is a direct result of the natural decomposition of solid waste. The organic component of landfilled waste is broken down by bacteria in a complex

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biological process with gaseous products consisting mainly of methane and carbon dioxide.

Estimates of global landfill methane emissions to the atmosphere have ranged from 9 to 70 $Tg.y^{-1}$, differing mainly in assumed methane yields from estimated quantities of landfilled refuse and assumed methane oxidation. The most recent estimates indicate an annual atmospheric contribution of about 20-30 $Tg.y^{-1}$. For France, national estimates prepared for the United Nations Framework Convention on Climate Change indicate that about 25% of the annual methane emissions are from waste disposal, constituting the second largest source after agriculture (United Nations, 1995).

None of the existing national and global estimates are based on field measurements of emissions; rather they rely on estimated rates of methane production applied to national statistics for landfilled refuse. That is why this study was undertaken to quantify the various biogas flows on a landfill. At individual site, a methane mass balance provides a useful framework to describe landfill methane processes and net emissions. Landfills are often well-inventoried, and the implementation of active methane recovery systems can achieve significant and readily quantifiable reductions within a relatively short time frame since the atmospheric lifetime of methane is quite short (about 10 years).

Such a mass balance approach should be applied to the partitioning of methane production into emissions, oxidation, recovery, lateral migration and the change in internal storage (Bogner and Spokas, 1993) :

Methane production = Σ(emission + lateral migration + recovery + oxidation + Δ storage)

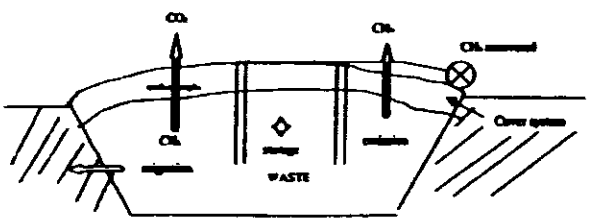

Figure 1: Schematic representation of the landfill methane mass balance (from Bogner and Spokas, 1993).

The research program METAN began in February 2000 with field measurement campaigns of (i) recovered fluxes (ii) surface fluxes of methane on the landfill and (iii) of methane oxidation through the landfill cover.

The investigated landfills present several types of cell configurations. The adopted strategy to quantify the emitted biogas was to use complementary approaches: (i) Infrared thermography to locate thermal anomalies of the site, potentially due to emission zones, (ii) Direct measurement of methane emissions using both a tracer method and chamber methods, (iii) A stable carbon isotopic study to determine the portion of methane oxidised during transit from the landfill surface.

STUDY AREAS

Lapouyade Landfill

The ONYX landfill Lapouyade (VIVENDI Environnement) located near Bordeaux in France has been operating since October 1996. This site receives 150000 tonnes of waste per year.

This site consists of two different configurations (Figure 2): (i) a final covered zone since 1998 (cell 1) and (ii) an operating zone including temporary covered cells with or without active biogas recovery and an operating cell (cell 2).

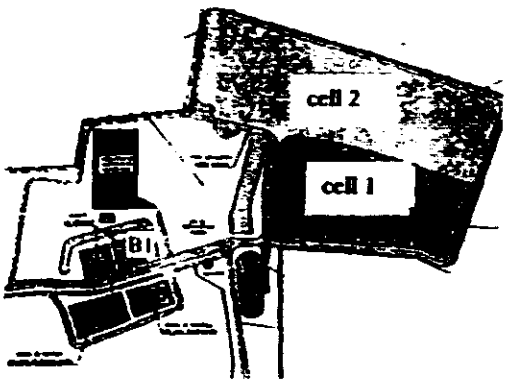

Figure 2: Schematic map of Lapouyade Site.

The LFG mass balance has been developed for the final covered zone cell 1 and a temporary covered cell (A10) without LFG recovery, from cell 2. The amount of waste landfilled in these areas is presented in table 1.

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Table 1: Amount of waste landfilled in the different zones

Year	Cells (amount of waste in tonnes)	
	Phase I	A 10
1996	32 777	
1997	127 472	
1998	149 681	
1999		37 800
TOTAL	309 930	37 800

Montreuil sur Barse Landfill

The Onyx landfill "Montreuil sur Barse" (VIVENDI Environnement) located near Troyes in France has been operating since 1986, and has received ISO 14001 certification in 1999.

This municipal solid waste landfill (MSW) consists of three different parts (Figure 2): (i) a former area where MSW was disposed of from 1986 to 1993, (ii) an experimental area where MSW was disposed of from 1994 to 1999 (iii) and a new operating zone.

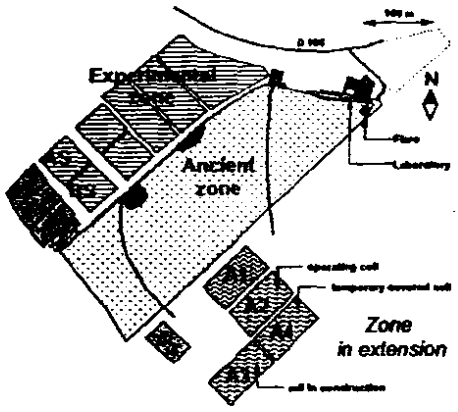

Figure 3: Schematic map of the investigated areas

It has the advantage of a broad range of cell configurations: (i) an active cell (A2), (ii) a temporary covered cell (A4), (iii) two experimental cells made of different top cover configurations (AS with a clay cover and BS with a synthetic bentonitic geocomposite), and (iv) areas with and without gas recovery (AS and BS). The amount of waste landfilled in these several areas is presented in table 2.

Table 2: Amount of waste landfilled in the different cells

Year	Cells (amount of waste in tonnes)			
	As	Bs	A2	A4
1993	180,00	0	0	0
1994	8 556,96	0	0	0
1995	0	8 114,46	0	0
1996	801,42	1 054,64	684,08	0
1997	0	0	35 246,21	0
1998	0	0	0	0
1999	0	0	2 816,60	36 603,58
2000	0	0	25 926,24	26 017,00
TOTAL	9 538,38	9 169,10	64 673,13	62 620,58

All of the measurements took place in the same two weeks so that it occurred approximately in the same conditions. The Infra Red Thermography (to establish the map of the thermal anomalies of the site and to locate the areas to be investigated) and the local flux measurements were the first campaigns to occur. Then the special fluxes measurements (according to the IR thermal anomalies map) and oxidation measurements campaign begun. The measures were first realised on the two cells As and Bs with the recovery of the biogas (pressure at the well of –2.5hPa for As and –1.4hPa for Bs). To evaluate the influence of the recovery of the biogas on the emission of methane through the cover, the recovery was stopped for two days (the pressure at the biogas well increased until 1.8hPa for As and 7hPa for Bs) before the fluxes were measured again.

METHODS

For each field campaign, all of the measurements took place over a period of two weeks with approximately the same conditions repetition (in February 2000 for Montreuil sur Barse campaign and in December 2000 for Lapouyade campaign).

Infra Red Thermography measurements

The IR thermography consists in visualising the spatial distribution of discernible surface temperatures, in the form of a thermograph. This visualisation is achieved by measuring the energy in a given spectral bandwidth radiating from an object. The sensor used is a thermal line scanner. The entire system is installed on an aeroplane, which, for this project, made transects once during the day and once at night. The use of the IR Thermography allowed the establishment of a map of the thermal anomalies of the landfill. On a landfill, these anomalies may have several origins, among them: wet areas, zone of LFG emissions, areas where the microbial activity is important under the cover. The map of the thermal anomalies has been used to determine local chamber

measurements location and to identify a possible correlation between the IR and the emissions of biogas.

Large area measurements of the fluxes of biogas by the tracer method

This method is based on tracer measurements and has already been described in Trégourès *et al*, 1999. It relies on concurrent concentration measurements for the methane and an inert tracer gas (here SF_6) released at a known rate upwind the landfill. Two methods were tested (Figure 4 and Figure 5). The methane flow is derived from the atmospheric transfer coefficient K measured by the tracer gas. From a methane source to a given point, K is the relationship between the concentration of methane integrated at that point and the mass released. When the methane flow rate Q is constant, K equals to C/Q where C is the concentration of methane at the point of measurement. While K is a function of the position of the point of measurement in relation to the source and weather conditions, it is independent of the type of effluent released. The flow rate Q is derived from K, which is determined (i) by the emission of a known mass flow of SF_6, and (ii) by measurements of tracer gas and methane concentrations at the same point.

The downwind method consists in injecting the SF_6 above the landfill and measuring the integrated concentrations of SF_6 and methane on a line situated downwind, based on the average wind direction. The readings were made using two gas phase chromatography devices equipped with a flame ionisation detector for methane and an electron capture detector for SF_6. (Trégoures et al., 1999). The error rate is inversely proportional to the X/L ratio. For the Montreuil measurement campaign, the uncertainty is on the order of 50%.

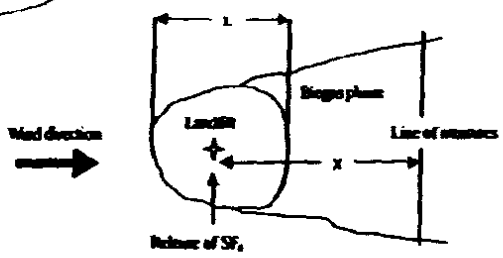

Figure 4: Schematic principle of the downwind method

This method has been used at Montreuil sur Barse and at Lapouyade A10 cell.

For the *in situ* method, the landfill is divided into N parallel strips and the integrated concentrations of methane and tracer gas are measured at the downwind edge of each strip. Using this procedure, the methane flux emitted by each strip can be measured and then summed to evaluate the total flux of the zone (Trégourès et al, 1999).

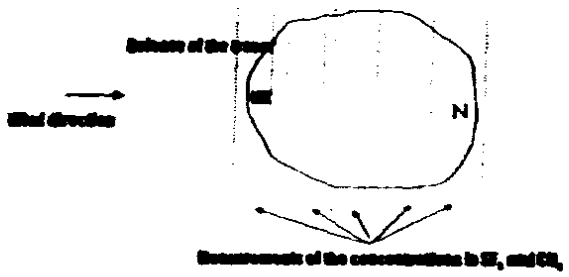

Figure 5: Schematic principle of the *in situ* method

This method has been applied on phase I at Lapouyade.

Local measurements of the fluxes of biogas by the chamber methods

Two kinds of chambers have been used: a static chamber method was applied at Montreuil sur Barse and an external recirculation chamber was deployed at Lapouyade.

The static chamber method has been used to measure methane fluxes from small areas of the landfill surface (0.25 m²). This portable method is static, without outside circulation of the gas. Its design revolves around a sensor, which operates within the chamber itself, downstream of a desiccant. This device is equipped with a sensor voltage regulator, a pump, a fan and two autonomous loggers, one for the temperature and the other for relative humidity.

The measure involves the placement of the static accumulation chamber on top of the ground surface for short measuring periods. The flux is calculated from the change in chamber methane concentration with time and the chamber volume/area ratio: the concentration of CH_4 is measured continuously (and analysed on site) which allows to calculate the flow of methane in the chamber and then the flux of methane emitted by the area covered.

The external recirculation chamber used at Lapouyade site uses a pump with a flow rate of approximately 10l per min to circulate the chamber atmosphere to an outside loop. The rate of methane enrichment in the loop is measured using a laboratory chromatograph transported in a utility vehicle (Trégourès et al, 1999). A grid of 20m*20m was followed for the investigation of phase I.

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Quantification of the methane oxidised through the cover

Microbial methane oxidation is carried out by methanotrophs. Methanotrophs are a class of methylotrophs which have the specific enzyme (methane monooxygenase) that allows them to oxidise methane to methanol (Anthony, 1982). Methylotrophs are microorganisms capable of gaining energy from the oxidation of reduced carbon compounds.

Many factors can seasonally affect the mass of methane oxidised through landfill cover soil. These include all the controlling variables for soil microbial processes: temperature, moisture, nutrients, substrate form and availability, and presence/absence of toxins. A major uncertainty in estimating CH_4 flux from landfills is determining the attenuation of CH_4 emissions by methanotrophic bacteria in the aerobic outer portions of the cover soil. These bacteria intercept the gas as it migrates toward the atmosphere. To estimate cover soil oxidation, the difference in the $\delta^{13}C$ (carbon isotopic composition) of CH_4 within the anoxic zone and CH_4 released from landfills and captured downwind on the landfill is measured.

Diagram (Figure 6) shows CH_4 escape from landfills through (i) fissures and vents, which is measured through downwind plume sampling and (ii) transport through the soil cap, which is measured utilising the chamber technique and the downwind plume sampling method (Chanton *et al.*, 1999).

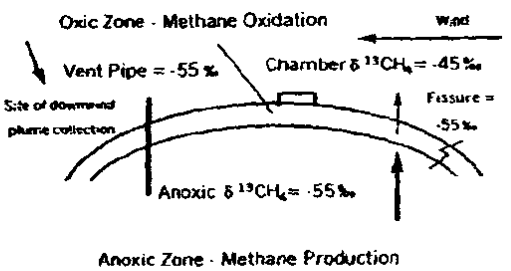

Figure 6: Plot to illustrate carbon isotopic variations for landfill methane (Chanton et al., 1999).

Stable isotopes are useful for determining CH_4 oxidation because, as it occurs, the remaining CH_4 becomes ^{13}C enriched due to preferential utilization of the lighter ^{12}C isotope by bacteria. The difference in the isotopic signature of these two pools of methane is directly attributable to the fraction of methane oxidised [f_0]. Oxidation percentage is determined by equation 1 (Chanton *et al.*, 1999), which describes isotopic fractionation in an open system.

$$f_0 = [(\delta E - \delta A)/(\alpha_{ox} - \alpha_{trans}) * 1000] * 100$$

where

f_0 is the % of CH_4 oxidised in transit trough the cover soil cap

$\delta E = \delta^{13}C$ value of emitted CH_4

$\delta A = \delta^{13}C$ value of anoxic zone CH_4

α_{ox} is the isotopic fractionation factor for bacterial oxidation

α_{trans} is the isotopic fractionation factor associated with gas transport.

Equation 1: Expression of the isotopic carbon fractionation.

Liptay *et al.* (1998) and Bergamashi *et al.* (1998) have argued that gas transport across the soil cap is dominated by advection. Therefore, it could be assumed that $\alpha_{trans}=1$. The bacterial fractionation factor associated with methanotrophy was determined by incubating cover soil samples at *in situ* temperatures. The fractionation factor α can be determined with equation 2 (Chanton *et al.*, 2000):

$$\delta^{13}C_t = 1000 * (1/\alpha - 1)\ln(n/n_0) + \delta^{13}C_{t=0}$$

where

n/n_0 is the fraction of methane remaining at time t

$\delta^{13}C_{t=0}$ is the $\delta^{13}C$ value of the methane at the initial time

Equation 2: Equation for determining the fractionation factor α

A time-series of analysis was performed to determine the fractionation factor α : cover soil samples were placed in closed flasks and a known concentration of methane was added. These flasks were incubated at outside temperatures, and two gas samples were taken every day during seven days. The determination of the isotopic composition of these samples permits calculation of, as in equation (1), the fractionation factor inherent to the soil and to its specific microbial flora.

This stable isotopic study was conducted at the two sites to determine the major pathways of methane emission from the landfill and the portion of methane oxidised during transit from the landfill surface. Samples of methane were collected from the plume of air downwind of the landfill. Methane within these samples integrates the total emission for methane from the landfill. Specific samples were also collected from all major sites of potential emission including from ventilation pipes, from pipes harvesting methane from the subsurface and from bubbles of landfill gas effusing from cracks and borders of landfill cells.

Quantification of the Methane Recovered through Gas Recovery Systems

For the experimental areas where methane is being recovered by an active system of vertical wells or horizontal collectors, the mass of recovered landfill gas is directly calculated from measured flow rates and concentration data. If these measurements are taken at a site, the recovery pathway is the best-quantified input for the methane balance calculations.

Mathematical Modelling for the achievement of the methane mass balance

The Landfill Methane Generation Model developed for these test sites is based on a first-order degradation model with multiple waste-types as inputs. This type of model has been used successfully in the Netherlands and Germany where it has been applied to actual landfill sites with excellent agreement (Coops, et al., 1995, and Scheepers and Van Zanten, 1994).

The amount of methane was calculated from the following relationship (Coops et al, 1995):

$$\vartheta = G\beta \sum_{n=1}^{I} A_n C_{org,n} k_n e^{-k_n t}$$

ϑ =Predicted amount of generated methane

G =0.94 m^3 methane per 1 kg of organic carbon [1.87 m^3 LFG per 1 kg] (assuming 50% methane production)

β = Formation constant (value set to 0.65)

A_n = Amount of waste stream n present in the refuse (kg)

$C_{org,n}$ = Percentage of organic carbon in waste stream n

k_n = 1/halflife rate of decomposition of waste stream n (yr^{-1})

t = current time in elapsed years from start of filling

The default values used were taken from the Dutch work on modeling gas production from European landfills.

For achieving the mass balance, the lateral migration of methane must be calculated. The sites had a geomembrane (HDPE) coupled with other engineered controls to prevent lateral migration of gas through its sides and base. Some of these other controls were 0.6 m of compacted clay, geosynthetic bentonite mats, and other drainage materials. However, the geomembrane would be the rate-limiting barrier. Once a system reaches steady state the flow through a combination of barriers is controlled by the slowest diffusion rate. Therefore the transmission of gas molecules through the polymer structure of the membrane would be the rate controlling the step. The HDPE liner will allow 0.58 cm^3 of CH_4/m^2/day at 1 atm pressure and 1.5 mm membrane thickness to pass through it (50% methane test gas) (Lim, 1995 and Pauly 1989). By accounting for the total surface area of the lined cells, the estimated amount of lateral migration was calculated.

The change in storage of methane within the landfill is a function of several variables: the creation of additional void space by the decomposition of the contained waste, settlement that occurs due to the increased void space created by decomposition, fluctuating leachate levels within the landfill which directly impact the volume of available gas-filled void space, the concentration changes within the trapped gas in the landfill and the variation of the atmospheric pressure. All of these factors can retain or release methane from the landfill reservoir. The void space that is available for gas storage is considered to be relatively constant over a short time period (measured from day to day). This void space will however change significantly over time based on the factors cited above, primarily as consolidation occurs. The volume of gas will not change but the concentration and density of this compressible gas represents the change in storage that occurs.

The change in storage value was not measured in the field. The change in storage is found by taking the maximum change observed in the gas concentration from the landfill, and then calculating the amount of methane that would need to be added or subtracted from the estimated gas-filled porosity to achieve the observed concentration changes. This value was used as the maximum allowed change in storage to achieve the methane balance.

RESULTS AND DISCUSSION

Localisation of the points of methane emission

Figure 7 presents the IR thermography performed in Montreuil sur Barse Landfill in February 2000. Thermal anomalies (in white) clearly show the site configuration. The saturated zone, like leachate lagoons or surface water collection network define the landfill contour. Heat emitted from composting platforms, operating zones, surface landfill gas collection systems and flare are also clearly detectable on the IR picture.

Unexplained thermal anomalies localised on different areas on the landfill have been investigated in order to determine if they correspond to LFG emissions zones. The measured flux in those areas present the same order of magnitude than the flux of cell As and Bs. The thermal anomaly is not directly linked to a higher LFG emission. The possible explanation to that thermal difference would be either the

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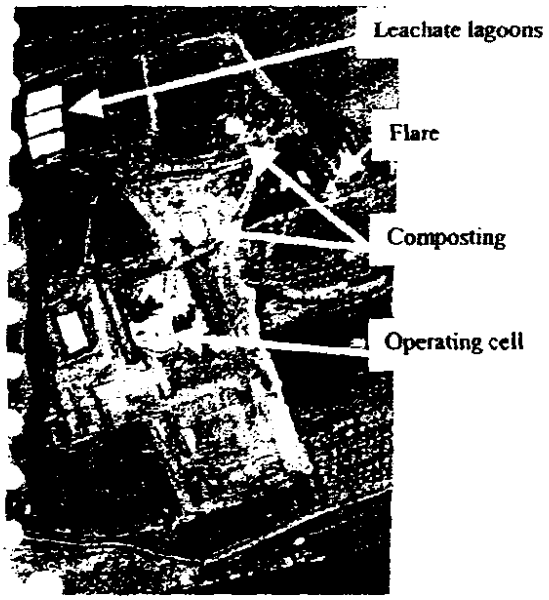


Figure 7: Black and white map of the thermal anomalies of Montreuil sur Barse site (anomalies are in white)

presence of saturated zone in the cover, or a weaker thickness of the cover layers in these areas or temperature variabilites within the waste mass that radiate to the surface. The thermodynamic properties of the waste, the cover system, and the biological process occurring within the landfill will effect the temperature profile of the landfill surface. External meteorological conditions will also effect the thermal readings at the surface. Among the 26 measurements performed in areas with thermal anomalies, 7 measurements have presented higher flux and were mainly linked to a zone with a different nature of the cover.

Chamber measurements have been used to locate the points of methane emissions. At Montreuil sur Barse, static chambers were deployed, whereas at Lapouyade dynamic chambers were used with external recirculation of gas. The static chamber method used at Montreuil sur Barse presented high uncertainties in determining fluxes.

Data obtained by the chamber method differ depending on the techniques. As an example, on cell Bs, fluxes given by the static chamber method described above (with a fan and on site analysis of the CH_4 concentration) range from 198.64 to 214 830 $mg.m^{-2}.d^{-1}$, whereas fluxes measured by another type of static chamber (constructed of a stainless steel hemisphere, which covered a surface area of 0.11 m^2, placed on top of a semi-permanent iron collar which was pushed into the cover materials, without fan and further analysis in a lab) give values ranging from –2.47 to 33.8 $mg.m^{-2}.d^{-1}$. On top of that, the n°1 chamber method seems not to be precise for little fluxes. Due to the high uncertainties, the chamber measurements have been used only to locate the points of methane emissions.

Fluxes measurements' distribution is presented in Figure 8 at Montreuil sur Barse tests cell As (clay covered cell) and Bs (geosynthetic bentonitic covered cell). Each cell presents a broad range of values for the emission of methane. It appears clearly that only few limited areas are emitting methane (in black). Those areas are mainly localised near discontinuities such as the leachate or biogas wells or the cell's borders which represent preferential pathways for gas transfer. Apart these local zones, emissions through the cover are insignificant.

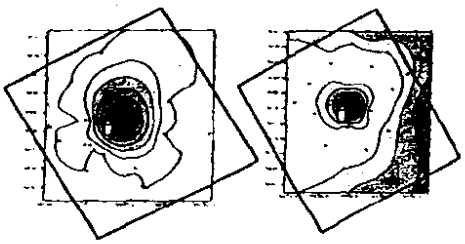
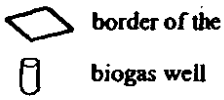


Figure 8: Schematic localisation of the emission of methane on the geocomposite covered cell (Bs, left) and on the clay covered cell (As, right) at Montreuil sur Barse



Often in the experimental zone, where strong suction was being applied in the process of methane recovery, negative fluxes were measured, indicating that atmospheric methane was being taken up. Apparently, no methane was supplied to the chamber from below, probably as a result of the negative pressure at depth.

Figure 9 presents the spatial repartition of the local biogas emissions (in $ml.min^{-1}.m^{-2}$) at Lapouyade on phase I, which is covered and recovered since 1998. The main emissions are situated on the slope of the embankment, which is consistent with the previous results at Montreuil sur Barse. This condition is often observed in landfill applications due to the preferential horizontal gas flow pathways which occur in the waste mass.

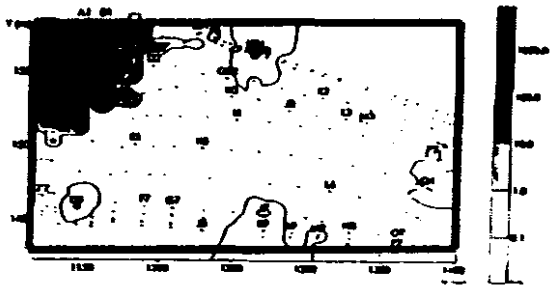


Figure 9: Schematic localisation of the emission of methane on the covered and recovered phase I at Lapouyade.

The oxidation of the methane throughout the cover

To calculate the fraction of methane oxidised in the soil cover, three factors were determined: (i) α the fractionation factor, which expresses the more rapid consumption of the lighter isotope of methane, $^{12}CH_4$ relative to $^{13}CH_4$, (ii) the isotopic composition of methane in the anoxic zone where it is produced and exists prior to exposure to oxidation (δA, equation 1) and (iii) the emitted methane (δE, equation 1) which has been exposed to oxidation.

Emitted methane was sampled in two ways, by collecting it in chambers and by collecting air samples, particularly during a calm period at night at the site, and downwind of the site. The fractionation factor (α) was determined from the results of Figure 10.

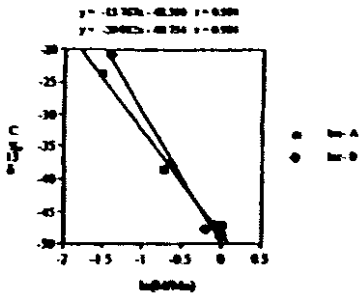


Figure 10: Exemple of the evolution of the CH_4 concentration in the chamber (Lapouyade) as a function of the isotopic composition.

The data on Figure 10 represent two incubations of landfill soil and methane at ambient temperature. Graphed are the methane isotopic composition (y axis, $\delta^{13}C$‰) versus the ln of the fraction of methane remaining (M = concentration at time t, Mo = concentration at initial time 0). From the slope of the line, the fractionation factor is determined as 1.0160 (A) and 1.0205 (B) for a mean value of 1.0182 ± 0.0022 for Montreuil sur Barse.

The fractionation factor measured at Montreuil sur Barse and Lapouyade can be compared to other observed in the literature (Table 3).

Table 3: Comparison of the fractionation factors measured at the two sites with literature values.

Sites	Fractionation factor
Lapouyade	1,0182 ± 0.0022
Montreuil	1,01615 +/- 0,00005
Florida landfills	1,025 - 1,049
New Hampshire landfill	1,022+/- 0,008
Swedish landfills	1,023 - 1,037
Litterature values	1,005-1,103

The fractionation factors are in the range of the literature values. Table 4 presents the results of the isotopic study expressed as the rates of methane oxidised by the methanotrophs at the two sites.

Table 4: Rate of methane oxidised through the top cover

	Rate of methane oxidised (average value in %)	
	Winter	Summer (preliminary study)
Lapouyade	0 - 35	in 2001
Montreuil	0 - 4	20
Northeastern of the US	close to nil	30
Florida		25-35
Germany		39-53

It appears that in winter, at Montreuil sur Barse, oxidation is confined to the temporary soil cover and is absent in the other zones. At Lapouyade, a limited measurements of oxidised methane indicated a value of 35% of methane oxidised throught the cover (winter was quite mild) but globally, oxidation is close to zero.

In comparison with other landfills, it has generally been observed that the occurrence of CH_4 oxidation varies seasonally, being lower or absent in winter and greater in summer (Chanton et al., 1999, Chanton and Liptay, 2000, Börjesson et al., submitted, Börjesson and Svensson, 1997, Boeckx et al., 1996). Summer values suggest ratios between oxidized and produced CH_4 in landfills at around 25-30 % in the northeastern USA (Liptay et al., 1998), 25 to 35% in Florida, USA (Chanton and Liptay, 2000), and 39-53 % in Germany (Bergamaschi et al., 1998). This has been interpreted to indicate that oxidation takes place only

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in the surface soils which are temperature sensitive and not deep down in the profile. The lack of CH_4 oxidation at low temperatures has implications for budgets of CH_4 turnover in landfills, which on a global scale should include a latitudinal factor.

Achievement of the methane mass balance at the two sites

Each of the individual factors for the methane balance equation is evaluated. By applying the methane balance equation, the well-quantified methane pathways can be used to bracket or verify the ranges on the modelled values. The methane balance can be expressed as:

Methane Generated = Methane emitted + Methane oxidized + Methane recovered or flared + Methane migrated + Δ Methane storage (Bogner and Spokas, 1993).

For the analysis, all values will be expressed in kg CH_4/day. Table 5 presents the results of the methane balance for the Montreuil sur Barse site. This includes the chamber and tracer emission measurements that were done on the Test Cell As.

Table 5: Montreuil sur Barse Landfill (Test Cell As)

	Chambers		Tracer	
	Input	Output	Input	Output
	kg/day (%)	kg/day (%)	kg/day (%)	kg/day (%)
Methane Production (modelled)	109.2 (100)		109.2 (100)	
Methane Recovery (measured)		102.4 (94)		102.4 (94)
Methane Emissions (measured)		0.81 (0.7)		19.97 (18.3)
Methane Oxidation (measured)		0.03 (0.02)		0.83 (0.8)
Methane Migration (modelled)		1.1 (1)		1.1 (1)
Change in Methane Storage (difference)		4.88 (4.5)	15.1 (13.9)	
Total	109.2	109.2	124.3	124.3

The value for the methane storage is set to achieve balance and then analysed to determine if the change in storage would be realistic. This is assumed to be the maximum daily observed change, which is calculated by determining the amount of methane that would need to be added or removed from the gas-filled pore space of the landfill in order to achieve the observed concentration change.

At the Montreuil site, this was 2% that corresponds to a maximum of 32 kg CH_4 per day, and the Lapouyade site was 318 kg CH_4/day for the Phase I cells and 55 kg CH_4/day for the A10 cell. Tables 6 and 7 presents the methane balance for phase I and A10 cells of the Lapouyade site.

Table 6. Lapouyade Site (phase I cell, covered and recovered since 1998)

	Chambers		Tracer	
	Input	Output	Input	Output
	kg/day (%)	kg/day (%)	kg/day (%)	kg/day (%)
Methane Production (modelled)	3970 (100)		3970 (100)	
Methane Recovery (measured)		3883 (98)		3891 (98)
Methane Emissions (measured)		58 (1.4)		26 (0.7)
Methane Oxidation (measured)		9.8 (0.3)		7,6 (0,2)
Methane Migration (modelled)		20 (0.5)		20 (0,5)
Change in Methane Storage (difference)	8.8 (0.2)			26,4 (0,6)
Total	3978.8	3978.8	3970	3970

Table 7: Lapouyade Site (cell A10, temporary covered without recovery system)

	A10 Cell	Chambers	A10 Cell	Tracer
	Input	Output	Input	Output
	kg/day (%)	kg/day (%)	kg/day (%)	kg/day (%)
Methane Production (modelled)	460 (100)		460	
Methane Recovery (measured)		0 (0)		0 (0)
Methane Emissions (measured)		425 (92)		253 (55)
Methane Oxidation (measured)		75 (16,7)		44,6 (9,7)
Methane Migration (modelled)		3 (0.7)		3 (0.65)
Change in Methane Storage (difference)	43.1 (9.4)			159.4 (34.65)
Total	503.1	503.1	460	460

At Montreuil sur Barse site, the developed Landfill Methane Generation Model (LMGM) provided an accurate estimate of the produced methane. This model has compared favourably to other general landfill gas production models. Therefore the LMGM model should provide an accurate estimation of the methane generation potential of the Lapouyade cells. In addition, the model will thus provide an accurate estimate of the generation term for balancing the methane balance equation.

There is good agreement in the methane balance for the scenario described in Table 5, Table 6 and Table 7 (chamber). The tracer technique and the chamber provide a realistic estimate regarding the achievement of the methane mass balance except for the A10 cell. We can observe that the "change in storage" term for the mass balance achieved with the tracer method exceeds the limit. In this case, the tracer technique did not take all the emissions into account thereby underestimating the true emissions.

However, the tracer studies used to measure methane emissions seemed to generally provide more accurate measurements for the Montreuil sur Barse As test cell. As seen for test cell As with the chamber measurements, localised "hot spots" existed on the landfill cover, but these were missed with the low density of chamber measurements on the surface. These hot spots could also be accounted for in the determination of the flux footprint with alternative micrometeorological models. The grid of the chamber measurements was not systematic and could have lead to underestimation of the total emissions of the cells. Even if 94% of the methane produced is recovered, about 18% of the production were emitted to the

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atmosphere (assuming a change in storage reflecting release of methane from the pore space in the waste). Thus it was decided to test another kind of accumulation chamber with a more systematic grid in order to consider the entire cell at the Lapouyade site.

Static chambers have been shown to underestimate the true value of the surface flux in laboratory simulations. Recent work conducted at a Swedish landfill (Borjesson, et al., 2000) also showed the order of magnitude differences in fluxes that we had seen in the data from the test cells. In their work the highest emission estimate for the entire landfill surface from static chambers was 9.7 kg CH_4/hr, however, the tracer gas technique resulted in 41 kg CH_4/hr. Borjesson et al. recommended chamber measurements only for small-scale estimation of methane fluxes.

The chamber measurements at Lapouyade were more reliable indicators of surface emissions than the measurements taken at the Montreuil sur Barse site. The achievement of the mass balance seems to be better with the chamber results than with the tracer results. For phase I, this could be explained by the fact that the tracer measurements did not take the embankment into account. Indeed, the chamber measurements taken on the embankment showed increased emissions compared to the rest of the cell. So, in this case, the mass balance was improved with the chamber measurements. On phase I, only 1 to 2 % of the methane produced is emitted towards the atmosphere and about 97% of the methane produced is recovered.

For the two scenarios with recovery systems, at least 94% of the biogas produced was recovered and flared. The net emissions for a country are generally estimated by the equation provided by the IPCC (IPCC, 1995), and national estimates are summed to provide a global estimate. In that equation, the methane recovered during active extraction is assumed to be a maximum of 80% of the methane produced. The field results at Montreuil sur Barse and Lapouyade show that this value of 80% is conservative and that on well-managed landfills, a value of 90% for the methane-recovered term can be used. However, a cell without a recovery system allows the emissions of 92% of the methane produced towards the atmosphere (chamber results).

At Lapouyade site, the downwind samples say that the methane escaping to the atmosphere sees little exposure to oxidation. But methane escaping through the soil cover sees more oxidation. Therefore, the primary mechanism of methane loss to the air from this landfill must not be through the topcover but via large cracks (not covered by the chambers) or via vent pipes.

CONCLUSION

Utilising the methane mass balance equation is a technique to validate the field data from a landfill site. The results of the field campaigns present good evaluation of the methane balance at the two sites and, as a consequence, more confidence in our assessment of the emission of methane to the atmosphere. These results permitted us to obtain a set of original data, which show that ONYX landfill management with ordinary cover but accurate design and expertise in LFG recovery reduces methane emissions to the atmosphere by achieving a high rate of methane recovery: for the two scenarios with recovery systems (at least 94% of the biogas produced was recovered and flared).

The net emissions for a country are generally estimated by the equation provided by the IPCC (IPCC, 1995), and national estimates are summed to provide a global estimate. In that equation, the methane recovered during active extraction is assumed to be a maximum of 80% of the methane produced. The field results at Montreuil sur Barse and Lapouyade show that this value of 80% is conservative and that on well-managed landfills, a minimum value of 90% for the methane-recovered term can be used.

The localisation of the emission points indicates that more attention should be given to the cracks, fissures, vents and slopes, where one finds the major pathways of emitted methane. Apart from these special areas, the fluxes of methane are negligible on well-covered cells with active gas recovery. The examination of the mass balance provides an indication of the performance of the recovery system. Some additional management strategies to reduce methane emissions could be implemented, such as limiting the size of the cell, setting up a temporary cover as quickly as possible, fixing surface discontinuities, and recovering the biogas early, even just to flare it.

Chambers can also be used to estimate the total emissions of a zone depending on the size of the grid. The more it is small, the more precise the evaluation of the total emission of a zone is. It is, though, necessary to apply both the chamber and the tracer methods in order to compare the mass balance calculated with both. In that way, the methane emissions will approach more precisely the most accurate value.

At Montreuil sur Barse site, the thermal anomalies detected didn't systematically correspond to emissions of methane but they are mainly linked to water saturated zones or different thermal transfers following cover configurations. In the winter conditions of the field campaign at Montreuil sur Barse, it appeared that the IR thermography wasn't a good method for determining emission points. As a result, the IRT was not applied at the Lapouyade site. However, other studies have shown better correlation between thermal anomalies and emission of biogas (F. Guigourès, 2000).

The oxidation rates have been calculated using the fractionation factor measured at each site. It appears that in these winter conditions, at the two sites, a global zero oxidation rate occurs in the areas with LFG collection.

These two field campaigns will be complemented by additional measurements at Lapouyade on the same configurations under drier and warmer conditions, as well as on a cell with a geomembrane cover.

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Section XII.

LFG Biofilter on Old Landfills
F.Starka

DEPARTMENT OF THE ENVIRONMENT

Waste Management Paper 26B

Landfill Design, Construction and Operational Practice

London: HMSO

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landfill to the environment in a controlled manner, at a rate which the environment can accept without harm. To be compatible with the Government's policy towards sustainable development, this must be carried out in a manner which minimises pollution control burdens for future generations. Ways in which this can be achieved include

- selection of inert wastes for landfill disposal
- pre-treatment to a quality which will not cause unacceptable harm
- management of bioreactive wastes in such a way that the system degrades to approach a stable, non-polluting state.

1.27 For *inert wastes and wastes of low reactivity*, pollution of the environment should be prevented by appropriate design incorporating passive or simple control measures. Any leachate and gas generation from the landfill will need to be managed proactively to ensure that the site will stabilise according to sustainability criteria.

1.28 *Pre-treatment of wastes* should either result in a less bioreactive waste, or a more predictable material for which it is easier to design appropriate environmental controls. Pre-treatment may also considerably reduce the quantity of waste requiring disposal.

1.29 For *bioreactive wastes*, the achievable rate of stabilisation will dictate the requirements for environmental protection. Achieving a timescale of a generation for the stabilisation of wastes currently presents a number of difficulties, arising from limitations in our current understanding of the rates of many landfill processes, and the ability to achieve rapid flushing of wastes within a bioreactive landfill. The landfill designer must therefore select the approach at the time of design consistent with the BPEO.

1.30 The practical design approach for bioreactive wastes will depend on the waste types and properties proposed for disposal, the characteristics of the site and the proposed afteruse. In selecting the most appropriate approach for landfilling in a particular situation the designer should consider the following approaches in descending order of priority, as illustrated by the decision tree in Figure 1.1.

i) In accordance with the strategy for sustainable development, the designer should first examine the potential for *accelerated stabilisation* of the landfill to achieve degradation of wastes to a stable form within a generation of cessation of tipping.

> To achieve this objective, the landfill will have to be designed and operated to maintain as high a rate of activity as necessary within a *biological reactor*, together with a sufficient degree of flushing to remove the products of decomposition. Fail-safe control measures and a very high degree of management will be needed during the active period of waste degradation. The degree of control required raises issues for the designer and operator which are highlighted throughout this Paper.

> The state of knowledge at the time of the design must be sufficient to give confidence that a particular design objective can be achieved. A summary of the considerations for accelerated

stabilisation is given in Appendix D. For sites which will accept hazardous wastes for co-disposal, reference should also be made to WMP26F.

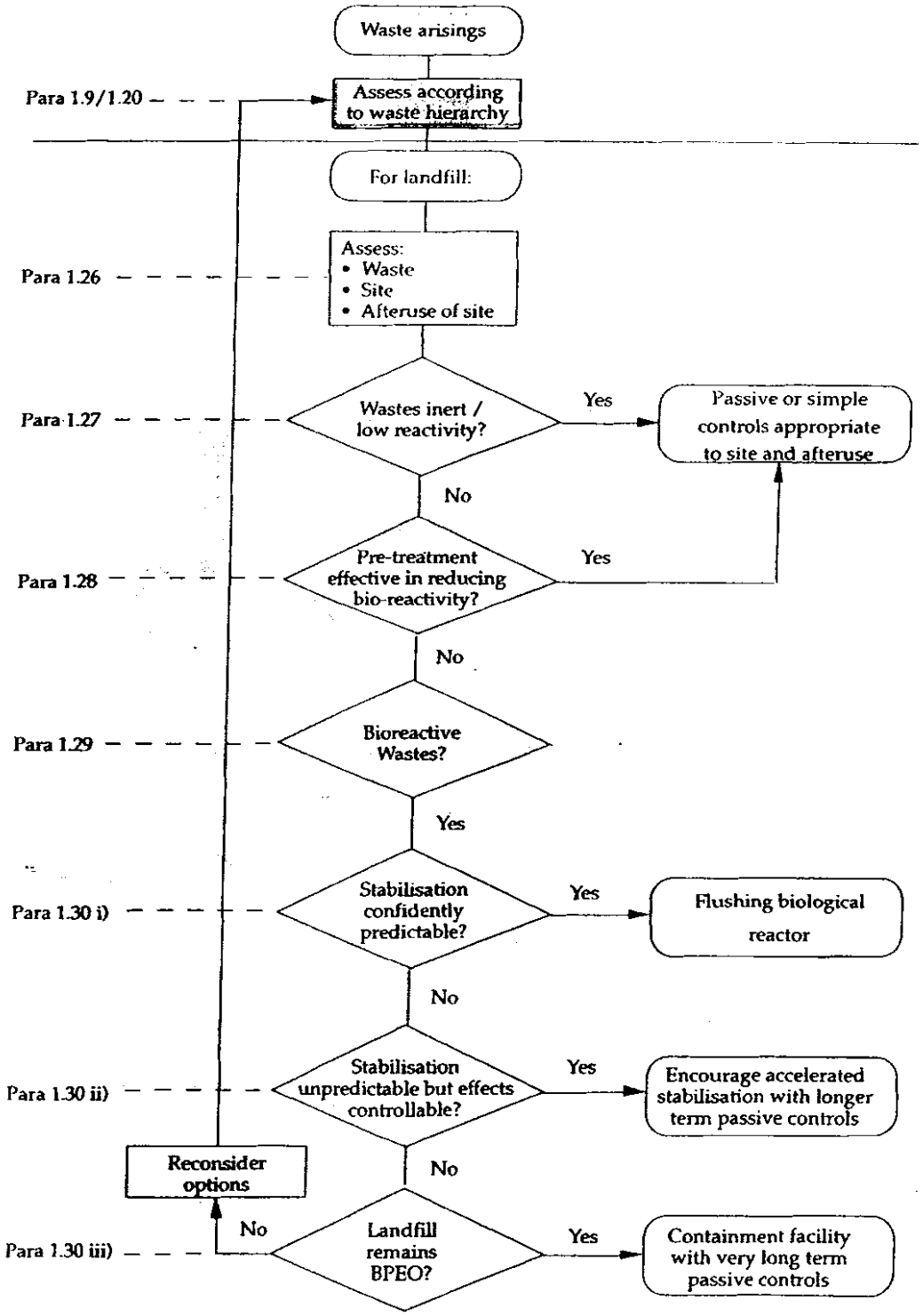
ii) It may not be possible to predict confidently the achievement of stabilisation within a specific period at the time of design. As part of the risk assessment approach and iterative design process, the designer should examine whether accelerated stabilisation should be encouraged, by considering the impact on the environmental controls should stabilisation be only partly successful within the intended timescale.

> Design models will need to either incorporate the ability to install appropriate passive control measures retrospectively or utilise attenuation to minimise the long term burden for future generations. This approach is likely to be the practical option in the majority of situations for the foreseeable future.

iii) Where accelerated stabilisation is not possible but landfill is nevertheless acceptable in a particular location, the design approach should consider the degree of containment required and the incorporation of very long term passive controls.

> In such situations the landfill cap may need to be of high quality and durability, such that the environmental impact should be very low even if the liner failed, and the maintenance obligation, though long-term, should be small and of low technological requirement. Isolation of waste from the environment is not compatible with the aim of sustainable development in the long term because the potential hazards do not diminish with time, even if the risk is low.

1.31 Where the risks are unacceptably high or place too high a burden on future generations, the designer will need to reconsider whether the particular wastes should be landfilled, and may need to seek alternatives for the wastes, site and afteruse under consideration. In all cases, the suitability and mechanism of the approach to landfilling is site specific and should be determined by risk assessment.


Waste arisings
Para 1.9/1.20
Assess according to waste hierarchy
For landfill:
Para 1.26
Assess:
• Waste
• Site
• Afteruse of site
Para 1.27
Wastes inert / low reactivity?
Yes
Passive or simple controls appropriate to site and afteruse
No
Para 1.28
Pre-treatment effective in reducing bio-reactivity?
Yes
No
Para 1.29
Bioreactive Wastes?
Yes
Para 1.30 i)
Stabilisation confidently predictable?
Yes
Flushing biological reactor
No
Para 1.30 ii)
Stabilisation unpredictable but effects controllable?
Yes
Encourage accelerated stabilisation with longer term passive controls
No
Reconsider options
Para 1.30 iii)
No
Landfill remains BPEO?
Yes
Containment facility with very long term passive controls

3 Design Objectives and Considerations

Introduction

3.1 **All landfill designs and changes to design should start with a review of this chapter.** It is essential that the designer has a clear understanding of the approaches to landfilling and defined objectives before commencing design, in accordance with the overall aims and approach set out in Chapter 1

3.2 The principles considered at the design stage must also be embodied in and carried through the construction and operational stages of the development. This chapter describes the fundamental principles to be followed in preparing a landfill design and provides guidance on design objectives, considerations and standards which should be applied.

> The overall approach is based on **risk assessment** rather than **prescription**. It is neither possible nor desirable for all guidance to be prescriptive and **users should not attempt to take recommendations for individual aspects of design out of context.**

> Discussion of design considerations highlights some of the limitations of current knowledge. Understanding and knowledge will develop during the currency of this Paper. **The designer should be guided by the state of knowledge at the time of design taking into account the life of the landfill and its aftercare.**

> The sections on objectives and standards set out clear guidance on design methodology, which is considered in more detail in subsequent chapters.

3.3 The chapter is arranged in the following order

- key principles for the designer, which reiterate the overall concept for the design described in Chapter 1 (paragraph 3.4)
- stages in the design process (paragraphs 3.5 to 3.9)
- design considerations for the overall approach, with reference to the issues for the landfilling of bioreactive wastes in accordance with the aims of sustainable development (paragraphs 3.10 to 3.26)
- risk assessment as applied to landfill design and determination of the acceptability of impacts (paragraphs 3.27 to 3.34)
- design objectives which must be applied consistently throughout the design, preparation, operation, restoration, aftercare and afteruse of the site (paragraphs 3.35 to 3.55)
- design standards including absolute standards, performance standards and guidelines (paragraphs 3.56 to 3.61).

Key principles for the designer

3.4 The following key principles for the designer should be considered at the outset of the design process.

- **The overall concept is the construction of a landform with waste as an engineering project which is appropriate for a particular site and its waste input.**

> This requires consistency in approach to preparation works and environmental controls, operation, restoration and aftercare. All stages must be taken into account by the designer and the design must be understood by the operator.

- **The design model for the site must have regard to the objectives of sustainable development for future landfills.**

  > A decision tree for assessing the approach is given in Figure 1.1 and the design considerations discussed further in paragraphs 3.10 to 3.26.

- **The overall approach to design and the design of each element of the landfill appropriate to its environmental setting are determined through risk assessment.**

  > The risk assessment approach and methodology are described further in paragraphs 3.27 to 3.34.

- **The nature of the wastes that will be used to build the new landform and the processes of degradation and leaching during the life of the landfill are important factors in the overall design approach and methods of operation for a particular site.**

  > A detailed description of the processes of waste decomposition that occur within a landfill is included as Appendix C. This indicates the complexity of the processes and the range of composition of the ensuing leachate and landfill gas. For any given types of waste proposed for use in construction of the landform, the designer should consider its probable decomposition processes and products of decomposition over the whole timescale.

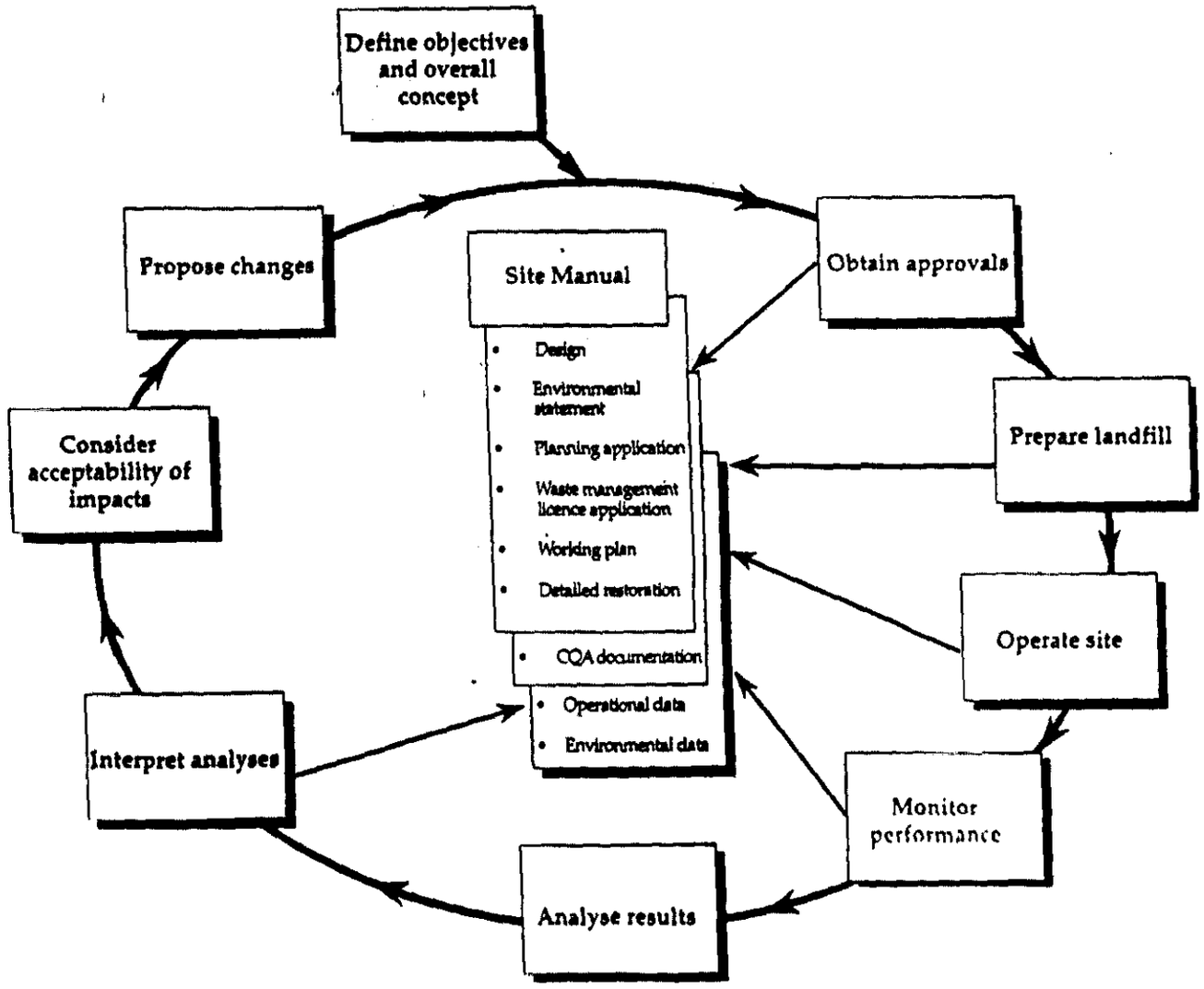
- **Design is an iterative process which should be reviewed both at its inception and before making any changes.**

  > Any amendments to a design should be considered against all aspects of the design, construction and operational processes according to the cycle illustrated in Figure 3.1, and cross-reference made to other sections of this Paper and parts of the WMP26 series as appropriate.

- **Landfill practice is a dynamic science.**

  > Landfill designers must consider probable changes in landfill practice and waste input that may occur over the whole lifetime of the landfill from conception to completion of aftercare and should, where possible, make provision for these changes, or allow for them to be incorporated at a later stage. A process of periodic review should be used throughout the life of the site and prior to the design of later phases[1].

[1] See Chapter 6 for explanation of phases.


Define objectives and overall concept
Obtain approvals
Prepare landfill
Operate site
Monitor performance
Analyse results
Interpret analyses
Consider acceptability of impacts
Propose changes
Site Manual
Design
Environmental statement
Planning application
Waste management licence application
Working plan
Detailed restoration
CQA documentation
Operational data
Environmental data

ages in the design
ocess

3.5 The landfill design process should be the same as that used in other engineering projects where the objectives for proposed use and design of a project are clearly stated at the outset of the design.

3.6 Landfill design should follow a staged approach which can be broadly divided into three key stages, referred to here as *conceptual*, *main* and *construction* design. In each of these stages the holistic principles for the site should be adopted with an appropriate level of detail for each stage.

3.7 At the *conceptual* stage the designer will be principally concerned with the overall feasibility and viability of the site, using experience to determine any fundamental constraints or items of major expenditure. This will result in a notional model for the development of a site, giving approximate volumes, possible design features and proposals for afteruse and setting out the principal aspects for clarification or investigation in subsequent phases.

3.8 At the *main design* stage a detailed site investigation[2] and assessment of environmental issues should be carried out, which will lead to a fully reasoned design for the overall construction, operation and restoration of the site. The main design forms the basis of the planning application for the development and of the working plan for the waste management licence application[3].

> The main design should consider all aspects required for the satisfactory development of the site, including the cost of the development. If formal environmental assessment[4] is required, the level of detail should be suitable for inclusion in an environmental statement.

> The main design is an essential part of the Site Manual[5], which provides a means of transferring information between the design, construction and operation process, and is vital for the attainment of the holistic approach to landfilling.

3.9 When the site progresses to construction, the main design should be developed into a fully documented *construction design* with sufficient detail, specification and contract documentation to permit construction. The construction design should include comprehensive calculations to confirm or qualify the outline calculations and assumptions in the main design, but should not require significant changes in concept. The construction design is likely to be carried out on a number of occasions during the site's life, and should be periodically reviewed.

n considerations

3.10 The overall approach to landfilling described in Chapter 1 is defined by three key elements

- the nature of the waste and prediction of the degradation processes
- site characteristics
- proposed afteruse.

3.11 These should be assessed applying a risk assessment approach at the beginning of the design process to establish a conceptual design and method of

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[2] See paragraphs 5.26 to 5.28 and Figure 5.1.
[3] See WMP4 for guidance on the licensing of waste management facilities.
[4] See Chapter 2 and Appendix B.
[5] See paragraphs 8.19 to 8.21 for further details of the contents of the Site Manual.

operation for a particular site. For bioreactive wastes, the designer should examine the overall approach in accordance with the strategy set out in paragraph 1.30 and illustrated on Figure 1.1 and consider in order of priority

- whether stabilisation within a relatively short timescale can be predicted with confidence, and the site designed and operated fully as a process engineering activity for accelerated stabilisation
- whether accelerated stabilisation can be encouraged even where stabilisation within a generation cannot be predicted with confidence, because provision can be made for longer term passive controls
- where accelerated stabilisation is not feasible, whether a long term containment facility is environmentally acceptable

3.12 In assessing the nature of the wastes and site characteristics, the designer should also consider whether attenuation or passive control measures will provide the required environmental protection for low reactivity wastes or for bioreactive wastes in a particular location. The environmental suitability of such control measures will have to be demonstrated by the risk assessment.

3.13 In determining the optimum approach, the designer will need to consider

i) The prediction of degradation times under different circumstances, taking into account the physical constraints of the waste and how changes in waste composition due to waste minimisation and recycling will affect predictions.

ii) The acceptability of release rates over the life of the site.

iii) The potential mobilisation of residues should the landfill eventually become aerobic.

3.14 These considerations are discussed in turn in paragraphs 3.15 to 3.26 and apply to all sites. Additional details summarising the overall issues for developing the site design and operation as a process engineering activity for accelerated stabilisation are provided in Appendix D.

rediction of waste egradation

3.15 **The landfill designer must clarify at the time of the design the nature of the wastes used to construct the landfill and give consideration to how these are likely to change over the active life of the landfill.** From this, the preparation works and operational methods should be designed appropriately.

> As wastes are progressively minimised, reused, recycled, processed and recovered, the characteristics of waste arriving at a landfill site may change. As it is not possible to predict at the outset the effect that these changes will have on wastes arriving at a particular site, periodic review of the design and operating methods should be carried out as the site is developed.

3.16 Typical untreated household waste is a highly heterogeneous material with variable permeability and water retention properties, which limit access for biodegradation by micro-organisms. The micro-organisms are active at the surfaces of the waste and rely on leachate movement for colonisation and for nutrient supply. The ability to achieve flushing of leachate uniformly throughout the waste is thus a key factor in the prediction of waste degradation rates.

3.17 The hydraulics of landfilled wastes are poorly characterised but often appear to be affected by short-circuiting and by barriers to flow[6]. There is a need for better knowledge of the hydraulic characteristics of wastes under different conditions and the development of engineered techniques for leachate recirculation at high rates in order for landfills to be operated effectively as flushing reactors.

> It seems likely that pre-treatment may be required (see Chapters 1 and 8) prior to landfilling to produce a more uniform waste mass, and placement of the waste carried out with an appropriate degree of compaction, in order to optimise permeability and achieve the required flushing rate.

3.18 Our knowledge of landfill processes will continue to improve with time, such that the potential burden on future generations due to the risk of our not achieving stabilisation within a generation will gradually reduce to less than the burden of long term maintenance. **At the present time we only have the knowledge of factors which might accelerate decomposition, but cannot predict with confidence, and supported by experience, how long it will then take.**

The concept of acceptable release rates

3.19 In the broadest terms, a landfill which fulfils the aims of sustainable development is one in equilibrium with its environment 30–50 years after cessation of filling. This implies that at certain levels of quality and flow rate, leachate and gas may be returned safely to the local environment. These rates will be determined by the risk assessment process.

3.20 Landfill design philosophy in the early 1990s had tended towards the objective of total containment and isolation of wastes. It is now recognised that this is unattainable and that it may be more responsible to design for controlled release than to attempt indefinite isolation, depending upon the nature of the wastes.

3.21 **All liner materials will allow the passage of liquids to an extent determined by their permeability.** Risk assessment methodologies[7] can quantify the probability distribution for a derived seepage rate for a given liner/landfill situation. This should be used either to assess the probable impact on the receiving environment or to determine the performance specification for the liner and landfill operational methods. In this way an appropriate liner specification can be derived incorporating a suitable safety margin. Although the provision of any safety margin implies a degree of deliberate over-design, going beyond an appropriate degree of protection requires an unnecessary use of material resources. ***Excessive* over-engineering should be avoided as this can itself contravene the principles of sustainable development.**

3.22 Any landfill liner is part of a landfill's leachate management system. Systems may need to be designed for a range of seepage rates from very low (the best containment that can be achieved) to high (a controlled form of disperse and attenuate) depending on the degree of environmental protection needed at that

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[6] Technical Overview of Co-disposal, Appendix A in WMP26F.

[7] A summary of a methodology for probabilistic risk assessment for landfill leachate migration is given in Appendix E. This methodology will be published in 1996. The methodology has been developed by the DoE in association with the NRA. It is intended to be simple to apply as a first pass for the early stages of design, with progression to more complex methods where detailed risk assessment is required.

Figure 3.2 Typical comparative seepage rates

FOR ILLUSTRATION ONLY

Calculation of actual seepages rates is complex and dependent upon many variables, and should be carried out using an agreed risk assessment methodology (see text).

A - Rates derived from theoretical studies (based on 1m head)

Case	Material	Thickness (metre)	Conductivity (metre/sec)	Defects	Seepage (l/ha/day)	Source
1	Clay	1	1×10^{-9}	None	1720	Darcy
2	Clay	1	1×10^{-8}	None	17200	Darcy
3	Clay	1	1×10^{-8}	1% of area at 1×10^{-6}	17200	Darcy
4	BES	0.3	1×10^{-10}	None	370	Darcy
5	GCL	0.006	1×10^{-12}	None	145	Darcy
6	HDPE	0.001*		None	3	Gross et al. 1990
7	HDPE	0.001*		5 x 3mm holes/ha	3000	Gross et al. 1990
8	HDPE over mineral	0.001* not stated	1×10^{-10}	5 x 3mm holes/ha	1	Gross et al. 1990
9	HDPE over mineral	0.001* not stated	1×10^{-8}	5 x 3mm holes/ha	30	Gross et al. 1990

* US reference: HDPE used in UK is more usually 2mm thick

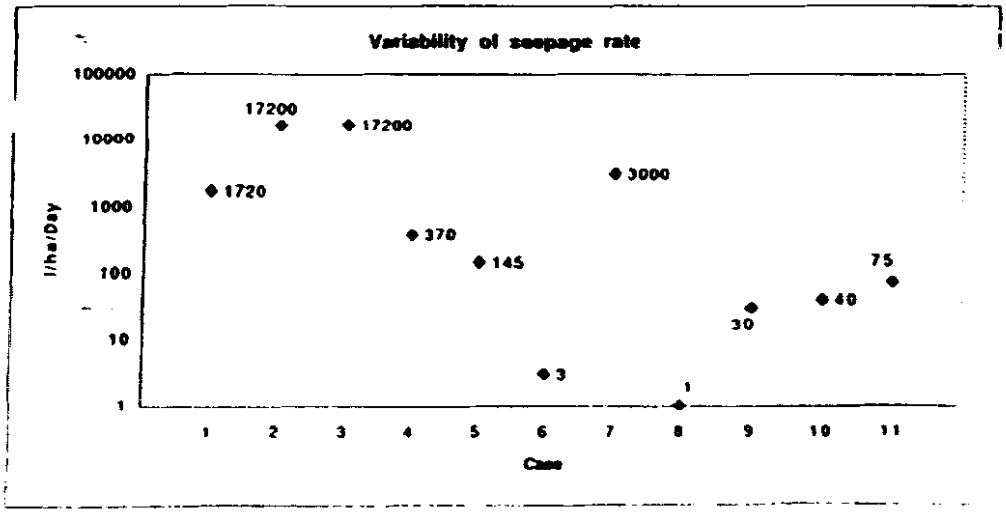
B - Rates obtained by measurement

10	HDPE/mineral	CQA, 50% probability level	40	Allen & Roberts, 1994
11	HDPE/mineral	No CQA, 50% probability level	75	

Notes:

1. Examples 1-9 are based on permeability alone.

2. HDPE is quoted for illustration only. Other materials may also be considered.



- the number of existing licences where Regulation 15(1)(b) applies.

3.25 In the NRA's Policy and Practice for the Protection of Groundwater[10], landfill acceptability is classified by type within zones of travel time to a water source and within resource protection areas. Landfills are defined as acceptable when subject to engineered containment and operational safeguards. If the nature of the waste and the hydrogeological conditions are such that the pollution control authorities in consultation with the WRA judge that its deposit does not pose an unacceptable threat to groundwater, then they may agree to a site being operated on non-containment principles. Acceptable operational safeguards must then be implemented.

bilisation of residue

3.26 When the rate of decomposition slows sufficiently, the rate of gas production may be insufficient to prevent the ingress of air to the main body of the waste. Eventually this could change the decomposition processes from anaerobic to aerobic[11]. The previously reducing conditions which maintained many contaminants in an insoluble state would then disappear, allowing for the mobilisation of many inorganic compounds. This would apply to all landfills containing bioreactive wastes. The designer should consider the possible effects of such a change in source term when carrying out the risk assessment for the site. However it is probable that the diffusion of air into a typical lined and capped modern landfill will be very slow, such that any release rates would be exceptionally slow.

;k assessment

3.27 Landfill design has historically been based on a selection of design features from a menu of alternative measures to achieve an absolute goal. For example, containment has been perceived as an objective which can be achieved either absolutely, or to an equivalent degree, by one of a range of techniques according to availability of materials. It is now understood that all liners will allow some leakage. A probability distribution can be applied to each of the factors governing the rate of leakage for a given liner design, such that its probable leakage rate and consequent impact can be modelled.

3.28 The acceptability of a landfill design in the environment should therefore be assessed by a process which quantifies the probable impact, or the probability distribution of an impact, for each source term on each relevant receptor, that being the persons or features affected by it. This process is known as *risk assessment* and should be used in an iterative way to produce an acceptable design.

3.29 The process of risk assessment leading to an acceptable quantified impact and thereby to an appropriate design is outlined below. An example of a risk assessment process applied to a quantifiable element of the design, and the source/pathway/receptor relationship, are illustrated in Figure 3.4 and Table 3.1. The risk assessment process and a summary of a methodology with an illustration of its application to leachate seepage is given in Appendix E[12].

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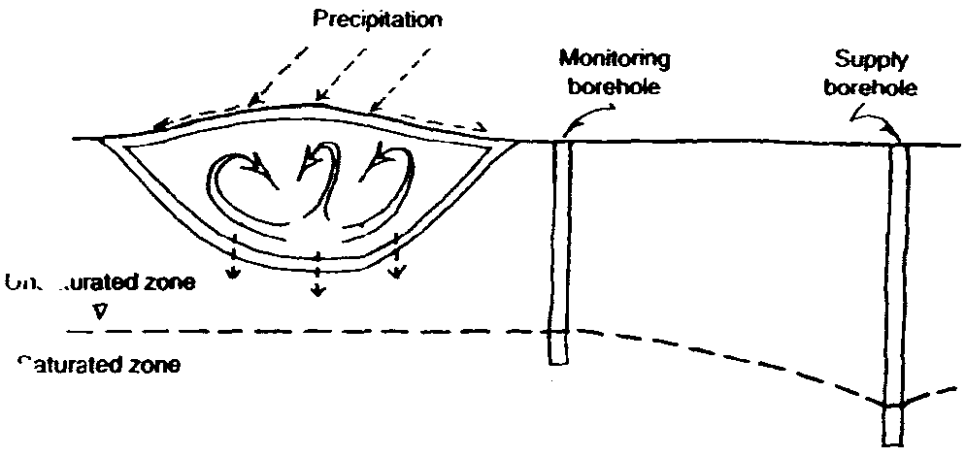
[10] NRA: *Policy and Practice for the Protection of Groundwater*. Bristol, National Rivers Authority, 1992. In Scotland, the *Groundwater Protection Strategy for Scotland* is the equivalent document.

[11] See Appendix C.

[12] Further general guidance on risk assessment is given in DoE (1995): *A Guide to Risk Assessment and Risk Management for Environmental Protection*, London, HMSO. ISBN 0 11 753091 3.

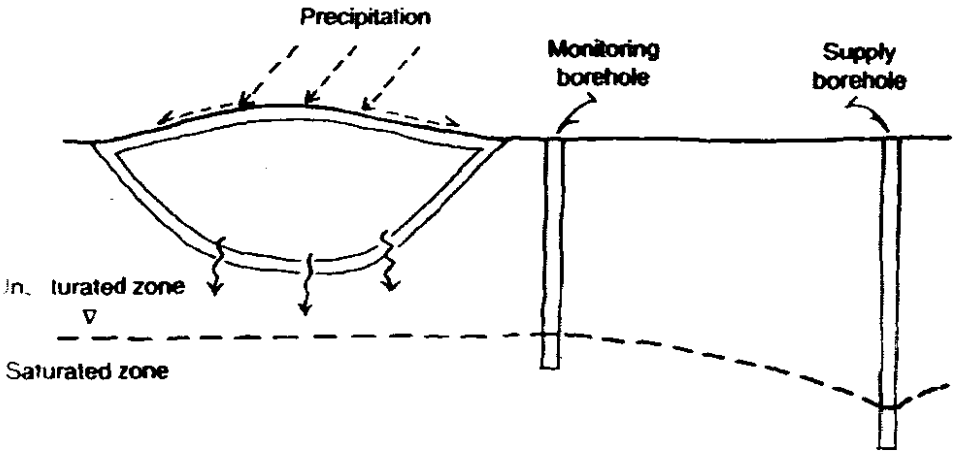
Initially –

ighly active, accelerated decomposition
ndfill contained, leachate recirculated and treated
gh quality capping
ry low seepage
ceptable or no impact at monitoring and supply boreholes



50 years plus later –

ndfill decomposition rate low
ntainment breached
pping maintained intact
w flow rate, low strength leachate
ceptable or no impact at monitoring and supply borehole



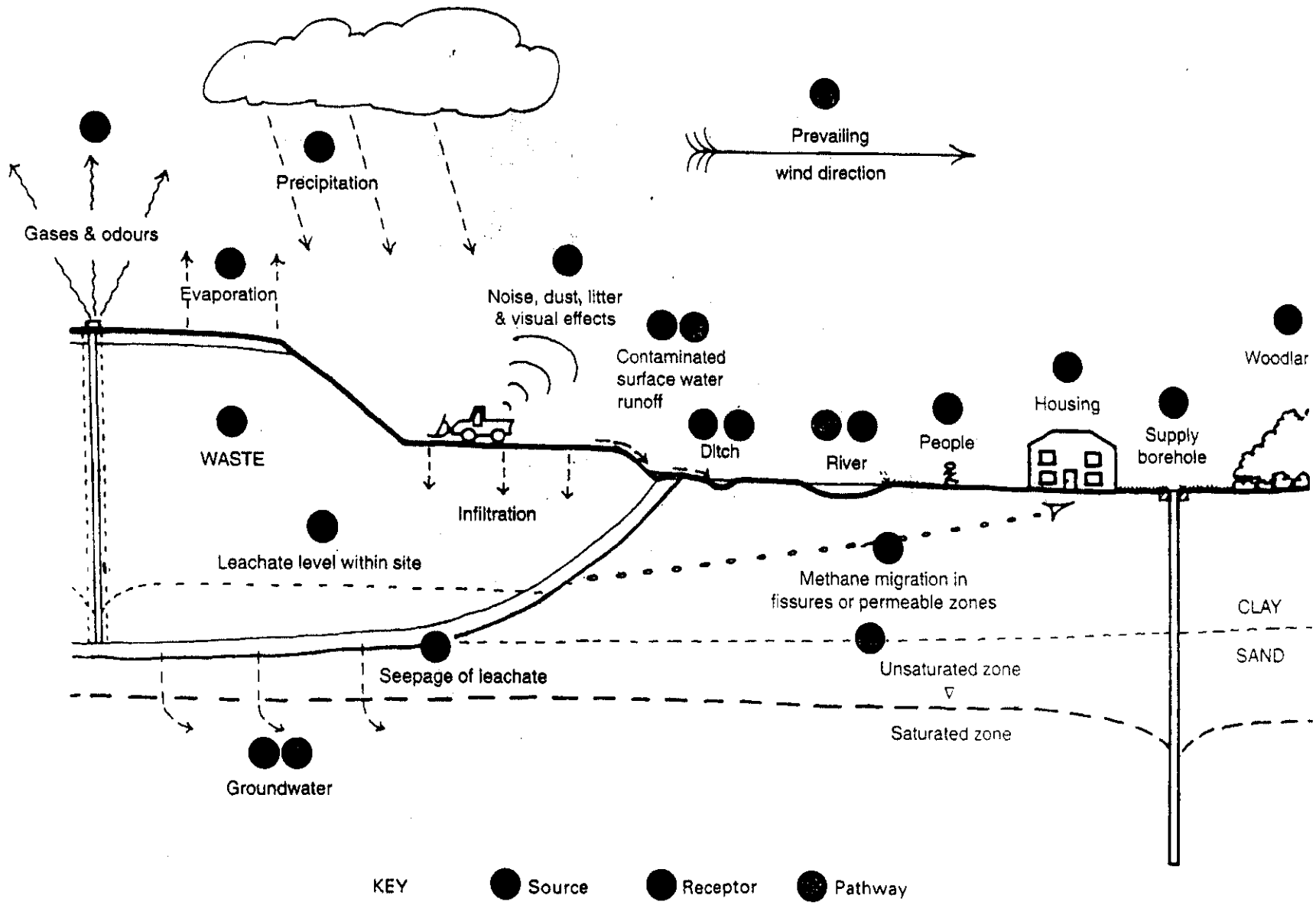

Gases & odours
Precipitation
Prevailing
wind direction
Evaporation
Noise, dust, litter
& visual effects
Contaminated
surface water
runoff
Woodlar
Housing
Supply
borehole
People
River
Ditch
WASTE
Infiltration
Leachate level within site
Methane migration in
fissures or permeable zones
CLAY
SAND
Seepage of leachate
Unsaturated zone
Saturated zone
Groundwater
KEY
Source
Receptor
Pathway

Table 3.1

Example of a risk assessment approach for a quantifiable impact of landfilling

Potential impact	Water pollution
Source	Leachate
Receptor	Groundwater
Pathway	Leakage through liner system, movement through unsaturated zone and groundwater
Establish:	
Sensitivity	Determine water quality objectives
Source term	Quality and volume of leachate
Evaluate	
Relationship between landfill and receptor	Prediction of leakage rates against impact (using agreed methodology)
Adjust design accordingly	Improver liner quality Reduce leachate generation rate Reduce leachate head Improve leachate quality

3.30 The approach may be summarised as

- **identify all potential impacts**
- **for each potential impact identify the *source*, the *receptors* or *targets*, and the *pathway***
- **establish the source term by** geotechnical and other investigations
- **derive a relationship between the landfill and the receptor using an** agreed methodology and probability distribution for the source term and for each element of the pathway[19]
- **establish the sensitivity of the receptor by** consideration of background levels, statutory limits or policy
- **consider the impact on the receptor and its acceptability**
- **repeat this process to obtain a satisfactory design for the landfill** consistent with an acceptable impact.

3.31 **The process should be repeated iteratively** for each potential impact until both an acceptable overall impact and an appropriate design for environmental protection is produced. A risk assessment process should be applied to any quantifiable impact including, for example, leachate, landfill gas, traffic and noise, providing that the effects of mitigation can also be quantified.

[19] A summary of a methodology for probabilistic risk assessment for landfill leachate migration is given in Appendix E. This methodology will be published in 1996. The methodology has been developed by the DoE in association with the NRA. It is intended to be simple to apply as a first pass for the early stages of design, with progression to more complex methods where detailed risk assessment is required.

20%[11]. Values of 15-20% are accepted as being typical of the surcharge allowance that may need to be made when considering the void capacity and final pre-settlement contours of a household waste landfill. The effects of settlement need to be considered in quarry landfills or in landfills whose base is non uniform (or stepped) and measures taken to avoid problems due to differential settlement which can lead to stresses and breaks in the engineering cap, and possible drainage problems.

> The precise effect that controlled bioreactor landfilling techniques may have on settlement is unknown. It is likely that there will be no overall increase in total settlement resulting from loss of mass; however, the rate of settlement is likely to be accelerated. Further guidance is given in Appendix D.

6.14 An example of a detailed analysis of settlement is given in Figure 6.1. This considers the composition of the waste as received, by origin, and sub-divided by degradation rate. Each component is then considered against an individual pattern of degradation and aggregated to give an overall settlement curve. Much of the settlement is manifested as a loss of mass of carbon, hydrogen and oxygen, through gas generation. The results in Figure 6.1 are derived from a mathematical model of a small landfill, but the approach is valid generally and can be used with either measured parameters, or assumed data based on current published research.

Waste density

6.15 The density of waste in a landfill varies widely because of the large variations in waste constituents, the degree of compaction, the state of decomposition, the amount of daily cover, the total depth of waste and the depth from which a sample is taken. Reported densities range from lows of 0.4 tonnes/m^3 recorded in the United States[12] to highs of 1.23 tonnes/m^3 recorded in the UK[13], with more generally recorded values of 0.65 to 0.85 tonnes/m^3[14] For planning purposes, a density range of between 0.65 to 1.0 tonnes/m^3 for bioreactive wastes should be assumed unless there are overriding reasons for departing from these values. Inert wastes may have higher densities[15]. Waste density may change with age as significant mass may be lost by the formation of landfill gas and leachate.

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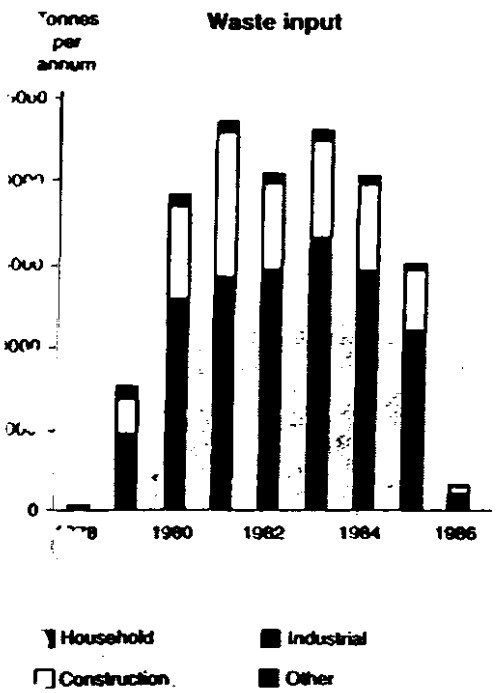
[11] RPS Clouston and Wye College (1993): *Reclamation of Landfill Workings to Agriculture.* Phase 2 DoE. Other reports have suggested settlement values in excess of 25%: see Bjarngard A and Edgers L (1990): "Settlement of Municipal Solid Waste Landfills". Thirteenth Annual Madison Waste Conference, pp 192-205; Di Stefano, A B (1993): "Settlement of Beddingham Landfill" in pre-prints of papers for the 29th Annual Conference of the Engineering Group of the Geological Society of London, ed S P Bentley; Wall D K and Zeiss C (1995): "Municipal Landfill Biodegradation and Settlement". J Environmental Engineering, Vol 121 No 3, pp 214-224.

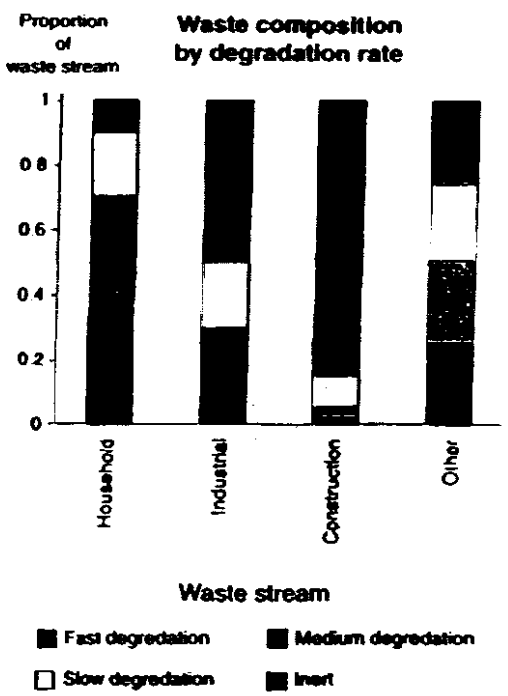
[12] Oweis I S and Khera R P (1990): *Geotechnology of Waste Management.* Cambridge, University Press, 1990.

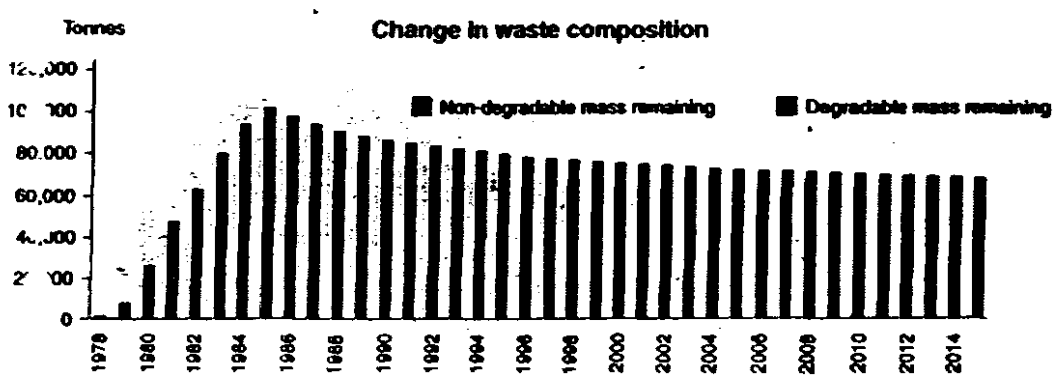
[13] Biddle A (1985): *Evaluating Landfill Compactors.*

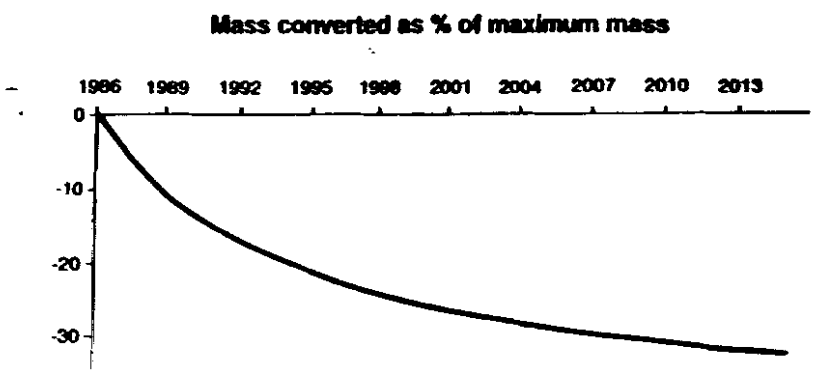
[14] Harrison N H (1985): "Compaction and effective densities in landfill sites." Proc Inst WM. North West Centre Meeting, Leyland, February 1985.

[15] The South East Waste Regulation Advisory Committee (SEWRAC) use conversion factors of 1.5 tonnes/m^3 for Type A (inert/low reactivity) wastes and 0.8 tonnes/m^3 for Types B and C (non inert) wastes. See SEWRAC (1994): *Waste Disposal in the South East Region: Results of the 1993 Waste Monitoring Survey*, page 2.


Tonnes per annum
Waste input
0
1980
1982
1984
1986
Household
Industrial
Construction
Other


Proportion of waste stream
Waste composition by degradation rate
1
0.8
0.6
0.4
0.2
0
Household
Industrial
Construction
Other
Waste stream
Fast degredation
Medium degredation
Slow degredation
Inert


Tonnes
Change in waste composition
Non-degradable mass remaining
Degradable mass remaining
80,000
60,000
0
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014


Mass converted as % of maximum mass
1986
1989
1992
1995
1998
2001
2004
2007
2010
2013
0
-10
-20
-30

6.59 The preferred means of pumping will be determined on site specific basis. Submersible pumps have been used satisfactorily for many years. Eductor pumps are increasingly used, particularly where there is a large number of leachate removal points.

6.60 Temporary pipework is acceptable during site operations but is prone to damage and is unsightly. The design should allow for the use of permanent pipework as soon as is practicable to carry leachate from the removal manholes to the treatment or disposal facility.

6.61 *Manholes* should be classified as permitting or not permitting entry.

> Manholes and wells may be constructed of many materials. Precast concrete is convenient but prone to physical damage. HDPE is also commonly used. The minimum size should be c. 300 mm to facilitate pump insertion if necessary. Manholes, including temporary pumping chambers, should be fitted with heavy lockable covers which cannot be removed by one person. Entry to any manholes or chambers should only be undertaken where it is unavoidable, and in accordance with appropriate written safety procedures which are incorporated into the site safety plan.

> The discharge pipe/manhole function at any pumping manhole should accommodate settlement of the waste around the manhole. The manhole should itself accommodate potential down-drag effects. With all manholes care must be taken to ensure that any foundation loads do not cause damage to the liner system.

6.62 The management of collected leachate is considered in detail in paragraphs 9.118 to 9.156. At the design stage, the designer should consider with the site operator whether treatment of leachate will be required, and if so, should ensure that sufficient area is available at a suitable location. The designer should also consider whether or not easements or agreements are necessary for the routing of pipelines connecting the site to a discharge point.

Accelerated stabilisation

6.63 Recirculation of collected and possibly treated leachate is likely to be a key consideration where accelerated stabilisation is to be achieved. It will only be possible where there is an effective leachate collection system. There will be a need to consider the means of distributing the recirculated liquids through the waste to ensure that there is overall wetting of the wastes and flushing of the leachable contaminants, that preferential pathways are not established, and that downward flowing leachate does not impair the landfill gas collection system. Accelerated stabilisation is discussed further in Appendix D.

Landfill gas management

6.64 The primary objectives of the landfill gas management system are

- to minimise the risk of migration of landfill gas beyond the perimeter of the site such that risk of explosion, combustion, asphyxiation, odours or vegetation damage on adjoining property are eliminated as far as possible
- to avoid unnecessary air ingress into the landfill and minimise the risk of underground fires
- to minimise damage to soils and vegetation within the restored landfill area

- to minimise the impact on air quality and the effect of greenhouse gases on the global climate.

6.65 The risk assessment will determine the appropriate level of landfill gas management. All aspects of design, construction and operation of any landfill gas control system should be to the highest standards, and commensurate with the requirements of the risk assessment and WMP27. This assessment should include harm to the global climate and air quality. The design should also take account of the planned afteruse for the site (see WMP26E).

Features of a landfill gas management system

6.66 The following features should generally be incorporated in a landfill gas management system to meet these objectives, as indicated by the risk assessment

- a containment system which will retain gas within the site and prevent off site migration
- a system for landfill gas collection and utilisation or flaring with adequate back-up facilities (see paragraphs 9.169 to 9.184)
- a separate system to control gas migration at the site perimeter which can operate independently of gas collection from within the body of the waste
- gas monitoring boreholes outside the waste boundary
- use of safe practices to avoid hazardous concentrations of gases within temporary or permanent working areas of the site.

> These features are illustrated in Figure 6.5.

6.67 As the control and management of landfill gas is rapidly evolving, the designer and site operator should ensure that full advantage is taken of changing theory and design. The designer should assess the likely landfill gas generation pattern having regard to the waste types and the rate of filling, and the intended mode of operation.

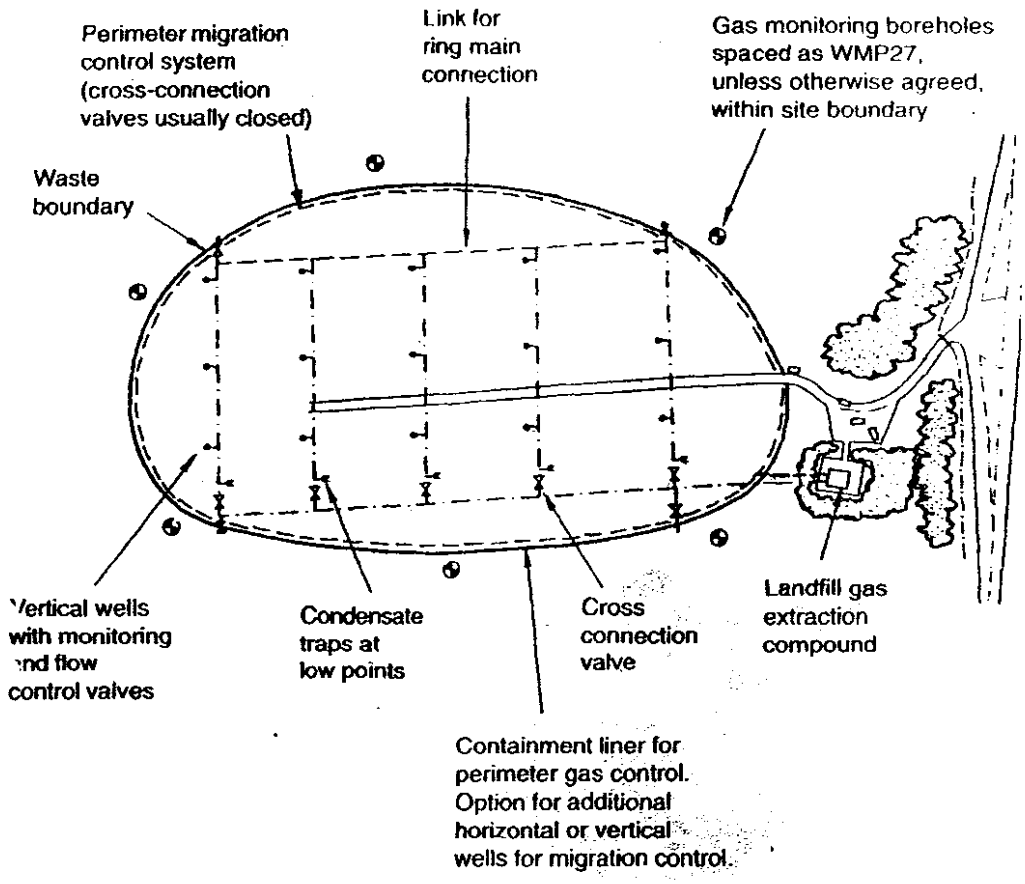
> Where accelerated stabilisation is an objective, a substantially greater rate of gas production is likely. This may necessitate larger plant and provision of a high degree of standby plant facilities. This will enable the control system to be sized and appropriate collection and flaring or utilisation equipment to be specified.

> The designer should ensure that an appropriate location is available for gas plant, generally one that is screened or hidden from view with minimal visual and noise impact. The impact of flare and exhaust emissions from landfill gas plant should be assessed.

Gas wells

6.68 Gas wells may be either vertical boreholes passing through the waste or horizontal pipes laid in the waste lifts as landfilling progresses. Horizontal wells constructed in deep landfills can suffer blockage and dislocation due to differential settlement. Their use is generally restricted to shallow landfills (less than about 10m deep) or to existing landfills with high water (leachate) tables where there is little dry waste between the surface and the leachate table. Where vertical wells are to be used the potential effects of settlement on the well should be assessed, including the possibility of damage to the lining system.

re 6.5 Landfill gas management



Three tier landfill gas management system:

1. Gas extraction
2. Liner barrier (plus migration extraction if necessary)
3. Monitoring wells

extraction wells in the waste linked by pipework in the capping system to a gas pumping and flaring compound. The wells may either be constructed as waste filling progresses or drilled retrospectively - this will be determined in consultation with the site operator. Possible damage to the lining system must also be considered if wells are drilled after waste filling is completed. The layout of the collection wells should be considered at the design stage using best current practice, and the design should also consider the positioning of any perimeter migration control system. The layout of the connection of extraction pipes to wells should be considered so that, where possible, permanent sections can be installed in stages and the extraction and migration control systems can be cross-connected for security.

Gas control at the perimeter

6.70 At the perimeter of the landfill the leachate containment liner will provide a deterrent to off-site migration. Because of differences in the viscosity of gas and liquids clay and bentonite barriers are orders of magnitude less effective at restricting the flow of gas than that of leachate. The designer should consider whether the proposed leachate containment liner is sufficient for gas control or whether a higher specification liner is required for gas control purposes.

Interface with other design [illegible]

6.71 The detailed design of the landfill gas control system should be undertaken in conjunction with the site operator and specialist landfill gas contractors/engineers. The designer should consider the integration of the various components of the gas management systems with other elements of the landfill design, for example whether it will be affected by the leachate management system or whether there is sufficient depth in the restoration layers[31] to accommodate well heads, extraction pipes and pipework required for leachate extraction. Settlement can disrupt the cap around the well or cause down-drag to push the well against the lining system.

> Additional materials above the barrier layer may be required to accommodate landfill gas pipes in a pipework zone within the capping system[32].

> The layout of the gas control system to minimise disruption to the planned afteruse should also be considered.

Gas pumping compounds

6.72 In assessing the design of the gas pumping compound the designer should consider

- the environmental impact (for example, noise, visual intrusion and effects on the atmosphere)
- land availability
- access for maintenance
- utilisation options
- the electricity supply to drive pump equipment
- the likelihood of trespass and vandalism
- operator safety.

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[31] See WMP26E.

[32] See paragraph 10.20 and Figure 10.1.

- access roads
- earthworks cut and fill areas
- area to be lined initially
- location of landfill gas and leachate management facilities
- site drainage including surface water, leachate disposal routes or irrigation plots
- site screening, including tree and shrub planting.

Monitoring requirements

6.76 Processes in a landfill are dynamic. There is a need to monitor the behaviour of a landfill continuously to determine

- its impact on its surrounding environment
- its rate of reaction and its progress towards stabilisation (see also WMP26A).

6.77 The data required by the designer to monitor the performance of the landfill design elements is shown in Table 6.2. Monitoring is described in detail in WMP26D.

6.78 The performance and regulatory monitoring will enable the designer to determine whether or not the landfill is behaving in the manner anticipated at the design stage. The designer should always seek to alter elements of the design to accommodate changes required by actual field experience.

Table 6.2

Performance monitoring of landfill design

Item	Data requirements
Earthworks	Whether the assumptions used in the earthworks balance have been borne out by construction and operational experience, which is generally related to void use
	Will demonstrate whether predicted site life and materials import/export requirements are correct
Fencing	Whether the fencing systems provided are proving effective or whether specifications should be relaxed or strengthened
Groundwater drainage system	Check on efficiency and performance
Landfill gas	The designer will wish to know details of practical experience gathered by the operations team
Leachate collection system	Efficiency of designed removal system, monitored at secondary monitoring points located away from the removal sumps
	Durability of materials used in manholes, pumps and pipelines
	Leachate generation assessment should be checked against operational data
Liner system	As licence requirements
	Designer may wish to monitor the performance of the component parts of the liner system including materials but this may require intrusive investigation and generally should only be considered as part of a research programme
Maintenance schedules	The landfill designer and the site operator should monitor maintenance schedules to determine whether these are realistic, whether they are being followed, and whether they are in need of revision
Odour	Refer to paragraph 9.96
Settlement	Topographical surveys to check on actual settlement and test predictions
Stability	Checks on stability of temporary and permanent slopes to determine whether design assumptions were correct

6.73 A description should be given of the likely equipment that will be provided at the pumping compound, for example

> pumping and flaring equipment, duplicated if necessary for back-up facilities

> condensate traps

> pipe layout

> flare design.

6.74 The pumps and flares should be designed with appropriate performance standards. Consideration should be given to the possible need for VOC destruction even for landfill gas of low combustion potential. The Environmental Protection Act 1990 and its associated regulations have extended waste regulators' responsibilities more widely. Those responsibilities take in the control of gas flares. Until guidance is available the waste regulatory body should take account of best practice and emission standards for comparable industrial processes.

> The components of best practice are likely to include, depending on the site, some or all of the following

- the probable variation of gas volumes and gas composition, including trace components, during the life of the site
- the landfill gas collection and pumping system
- the interrelation of the flare system with landfill gas utilisation
- flare design
- combustion temperature and residence time
- flare capacity, including the effects of turn-down on flare operations and emissions performance
- standby provisions
- continuous combustion monitoring
- process control of flare operation
- exhaust gas recycling
- emission monitoring
- safety
- maintenance.

're_ aratory works

6.75 The design of the preparatory works required before the actual deposit of waste commences should be shown on a single plan. This can be developed in more detail at the construction design stage. Early drawings can be used to prepare estimates of the initial expenditure required to develop the site. The works will include the following elements, as described in the preceding sections

- highway improvements
- site fencing
- waste reception areas including weighbridges, wheel wash, offices, garaging

Control of landfill gas

Importance

9.157 Uncontrolled landfill gas poses risks, through its explosive asphyxiant and greenhouse gas characteristics. Virtually all landfill sites will produce gaseous emissions for a long period of time. The extent to which this will occur, the composition of the gases and the control and monitoring arrangements which will be needed will have been considered as part of the landfill design process. Landfill gas management and monitoring are discussed in detail in WMP27.

9.158 The quality and quantity of intermediate and top cover used in operations and restoration will influence the extent of lateral gas migration.

> For example, the specification of a low permeability cap as part of the restoration may well encourage lateral migration by effectively preventing gas escape through the landfill surface.

Problems arising from landfill gas

9.159 Potential problems arising from landfill gas fall into the following categories:

- explosions or fires due to gas collecting in confined spaces, such as buildings, culverts, manholes or ducts on or near landfill sites
- asphyxiation of people entering culverts, trenches, manholes or buildings on or near landfill sites
- ignition of landfill gas when released through fissures at the surface, with a risk of setting fire to the waste
- detrimental effects on crops and vegetation on or adjacent to landfill sites
- risks to human health
- nuisance problems, especially odour.

9.160 Migration pathways and receptors will be identified during the desk study phase of the design process and the effect of external factors such as sharp changes in barometric pressure should be considered during risk assessment. To be able to design and operate landfill gas control systems effectively it is necessary to understand that two largely independent mechanisms for migration exist:

- gaseous diffusion (concentration gradient)
- advection (pressure gradient).

9.161 For this reason, as well as the need to build in a design safety factor, it is usually necessary to have more than one level of control at any site, specifically designed to meet the requirements of that particular site.

> Landfill gas systems designed to control vertical and lateral migration must take priority over, and must not be confused with, any utilisation systems which may be installed. Nevertheless, a well designed system for landfill gas utilisation can and should complement a migration control system where practicable.

Trace components in landfill gas

9.162 A large number of minor constituents have been identified in household waste landfill gas at low concentrations. Some of these compounds are responsible for unpleasant odours and some of them may represent a health hazard. Odours from landfill gas differ from those from leachate since the smell of the latter is predominantly due to carboxylic acids which are only present at low concentration in landfill gas.

9.163 Landfill gas is typically diluted in the air above a site by a factor of between a thousand and over a million. The numerous organic compounds which may be present at significant concentrations at source are usually diluted to below the toxicity threshold. Measurements of metals as volatile derivatives or in particulate matter have shown that concentrations in landfill gas are very low at both household and industrial waste sites. At sites taking chemical wastes, care must be taken to ensure that toxic gases are not generated by the reaction between incompatible wastes or do not volatilise from the waste itself.

Landfill gas odours

9.164 Landfill odours can cause considerable nuisance, as sufficient dilution to eliminate the smell may not be achieved under some weather conditions. Potential sources of odour and control options are discussed in paragraphs 9.93 to 9.96.

Greenhouse gas emissions

9.165 Both methane and carbon dioxide are greenhouse gases. Methane is estimated to be about 20-30 times more damaging than carbon dioxide. Therefore conversion of methane to carbon dioxide is less damaging to the environment than allowing the landfill gas mixture to be discharged to the atmosphere unchanged.

9.166 The combustion of landfill gas either in flares or as part of an energy recovery process converts methane to carbon dioxide, and should be undertaken whenever the landfill gas yield is capable of supporting combustion. When the methane content is too low or too variable to support combustion, consideration should be given to using a support fuel but this should only be implemented if a risk analysis shows that clear benefits can be gained.

9.167 Passive gas venting systems and migration through the surface cover of a landfill site pose a potential environmental hazard. However, the microbial oxidation of methane in soils may offer a powerful means of reducing the methane emissions. Research[24] indicates that in the near future this process may be enhanced or controlled through controlling the soil type and humidity. Operators should maintain an overview of this research so that operational systems can be implemented as soon as possible.

Objectives of landfill gas management systems

9.168 Landfill gas management systems should be part of the site infrastructure and will normally be subject to waste management licence conditions. The objectives of landfill gas management systems are to

- minimise the risk of migration or accumulation off-site
- eliminate so far as possible the risk of explosion or asphyxiation
- prevent unacceptable risk to human health, detriment to the environment or nuisance.

Types of system

9.169 Three types of system may be used to control lateral migration of landfill gas, either individually or in combination

a) passive venting

b) barriers

c) pumping.

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[24] Whalen S C, Reeburgh W S and Sanbeck K A (1990): Rapid Methane Oxidation in a Landfill Cover Soil. Applied and Environmental Microbiology, Vol 56, pp 3405-3411.

a) *Passive venting systems*

9.170 **Passive venting systems should only be used in situations where the rate of gas generation is low, for example biologically old sites, and inert waste sites.** They rely on the inherent property of gases to move from a location with high pressure and/or concentration, to one where pressure and/or concentration is lower. Such systems can be implemented by a number of means including venting columns and drilled vents as set out in Table 9.8 and shown on Figure 9.2.

9.171 Stone-filled venting trenches rely on their acting as a permeability contrast and the importance of such vents admitting oxygen from the air into the ground should not be overlooked. The reduction of efficiency with depth means that simple venting trenches will not effectively prevent lateral migration at depths of more than about 3 metres because gas concentrations reach an equilibrium between the deeper parts of the trench and the surrounding ground. Performance can be improved by installing a low permeability geomembrane on the side of the trench away from the waste.

b) *Physical barriers*

9.172 Physical barriers range from stone-filled trenches to low permeability constructions including flexible geomembranes, bentonite cement, and slurry walls, piled cut off, and combinations thereof. Bentonite cement and other clay barriers are not fully effective against gas migration unless they incorporate a geomembrane. The performance of all physical barriers is considerably improved when combined with a means of removing the gas, such as by passive venting or pumped extraction.

c) *Landfill gas extraction systems*

9.173 These systems depend on suction to remove landfill gas from the waste. They comprise five main components

- gas wells or drains in the waste[25]
- pipework leading from the wells to the pumps
- condensate traps to remove condensed liquid from the system
- pumps which remove the gas from the waste
- landfill gas diffusers, flares or utilisation plant.

9.174 **Gas wells and drains:** Landfill gas wells comprise either drilled boreholes constructed after the waste has been emplaced or stone collectors constructed as part of the waste emplacement process.

- Drilled wells - comprise large diameter boreholes drilled into the placed waste and completed with an inner perforated well pipe surrounded by a gravel packing. The top of the borehole is completed with non-perforated pipe surrounded by a bentonite seal to allow for settlement. A typical well is illustrated in Figure 9.3.
  - > As a general principle, the performance of a well improves with increasing diameter and boreholes are now being drilled up to 1 m diameter. The well pipe is generally about 150 mm internal diameter HDPE with between 10% and 20% open perforated area.

[25] Migration control systems can, in suitable geological conditions, incorporate wells located in natural ground just outside the waste, where ground conditions can provide more predictable behaviour than the waste. The risks of pulling gas out of the site into the surrounding ground must be assessed before adopting this approach.

Table 9.8

Passive and low permeability barrier landfill gas management options

Drilled vents	*Advantages*
These are drilled using conventional percussion or flight auger methods after substantial thicknesses of waste have been emplaced	A relatively cheap method of providing pressure relief
	Do not interfere with day to day operations
	Can easily be converted to a suction system
	Disadvantages
	Risk of drilling through basal liners
	Limited effectiveness when pressure gradients are absent
	Small surface area inhibits diffusion of air into the ground resulting in poor flushing capabilities
Stone columns	*Advantages*
Stone columns built as tipping proceeds, typically 1 m diameter or 1 m square	Relatively cheap to construct
	Effectively relieve positive pressure
	More effective than drilled wells at diffusion venting because of greater surface area
	Promote downward migration of perched leachates
	Disadvantages
	Intrusive in working area
	Liable to damage by mobile plant
	Lack vertical stability
	Promote rainwater infiltration
Vibropiled columns	*Advantages*
An uncased stone column or stone filled pipe is inserted into the site after tipping has been completed using vibropiling techniques	Do not intrude into operational area
	Costs comparable with conventional drilling
	Effective in relieving pressure
	Disadvantages
	Relatively small diameter makes diffusion venting poorly effective
	Same as for drilled wells

Table 9.8 *continued*

Stone filled venting trenches and pits These are excavated into or around the waste and filled with clean graded stone usually as part of the restoration works A geotextile is frequently used to separate the stone from the waste	***Advantages*** Simple to construct Can be cost effective Effective for shallow sites (<5 m deep) Large surface area allows inward diffusion of air hence good flushing characteristics ***Disadvantages*** Difficult to prevent ingress of surface water Lose effectiveness with depth and will not prevent migration at more than 3 m depth Intrude in restoration scheme
Stone filled venting trenches with barrier As above, but with a low permeability membrane such as MDPE or HDPE on the side of the trench away from the waste	***Advantages*** Effectively control migration provided that the trenches and membranes penetrate to the water table or to a low permeability strata ***Disadvantages*** Difficult and expensive to construct at depths greater than about 5 m
Stone filled venting trenches with headwork venting columns	***Advantages*** The surfaces of the trenches can be scaled thus reducing the risk of infiltration of surface water and improving compatibility with some land uses ***Disadvantages*** Reduced surface area of venting columns impairs diffusion mechanism

Figure 9.2 Passive landfill gas venting pit *(not to scale)*

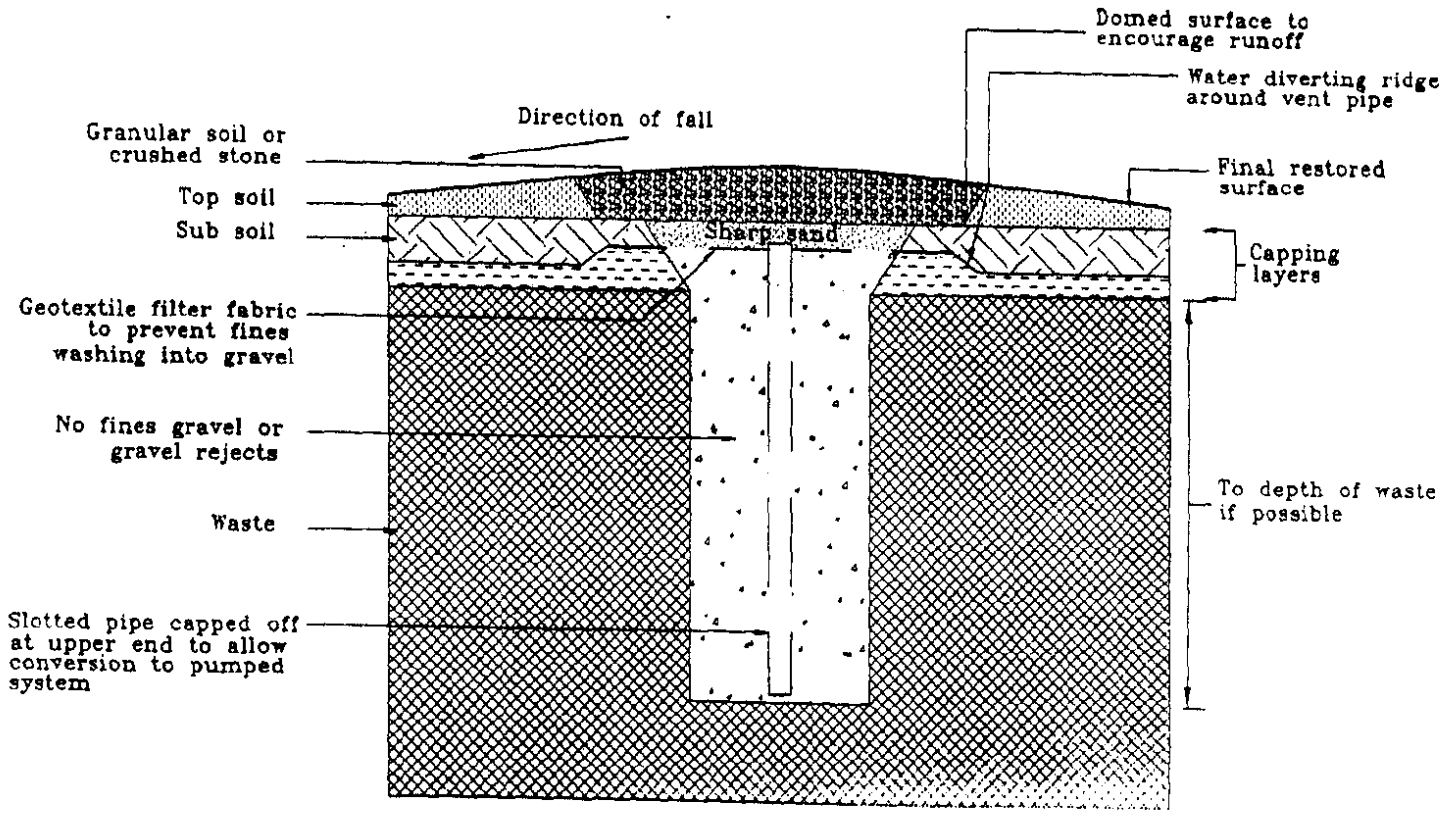
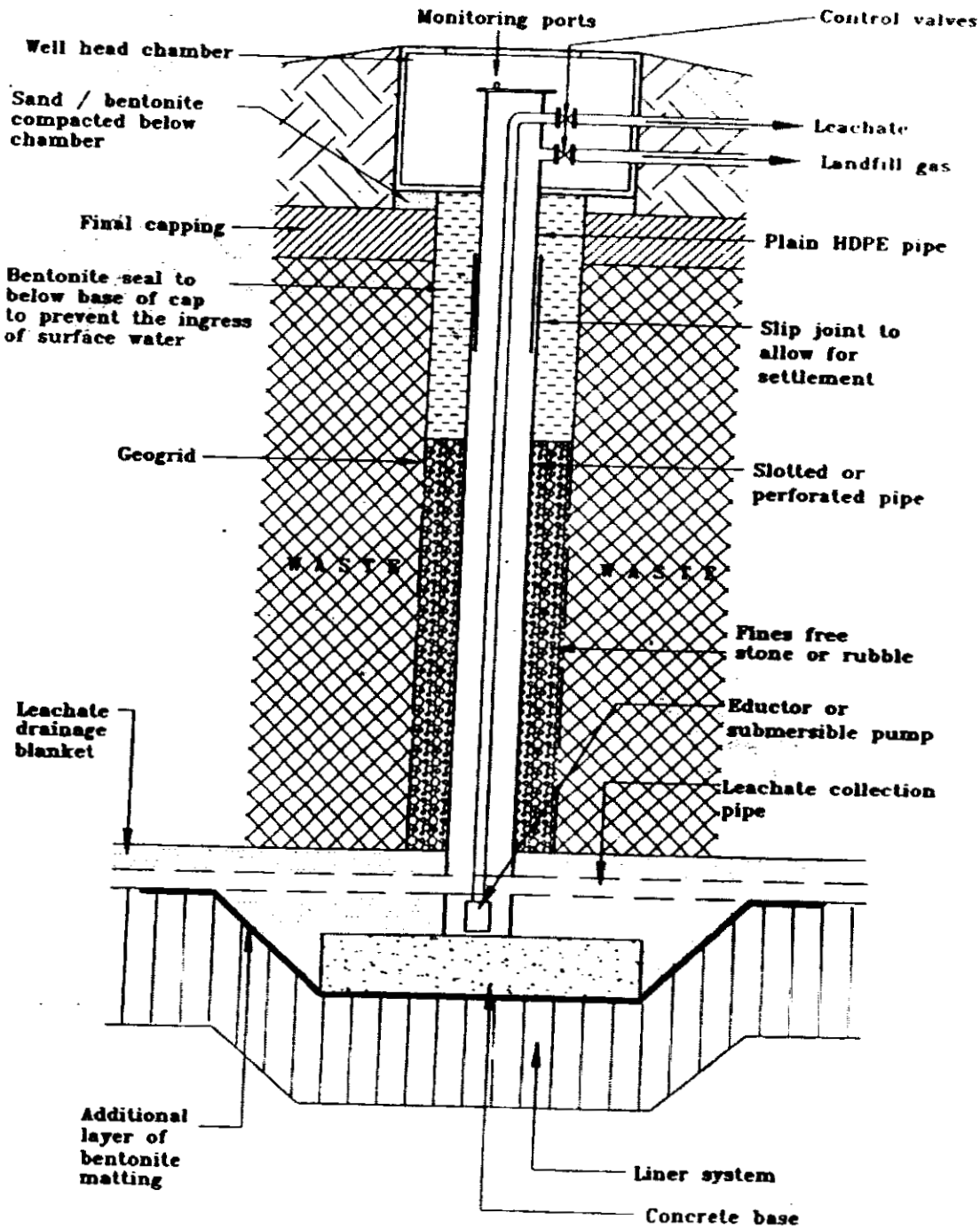


Figure 9.3 Typical combined leachate and landfill gas collection well



- *Horizontal drains* - are usually constructed in the waste as it is emplaced and comprise a horizontal stone bund or a stone-filled trench with a perforated collection pipe which is connected via risers to the gas pumping system.

9.175 Gas collection systems are subjected to very considerable forces as the waste compacts, degrades and settles, and this should be taken into account when the system is designed and constructed. Substantial downward drag forces are imposed on the relatively incompressible vertical wells and stone columns which, in extreme cases could punch the wells or columns through the landfill base liner. Drilled wells should therefore terminate at least 3 metres above the base of the waste in all containment sites and incorporate sliding joints at their upper end. Constructed stone columns should have a substantial foundation pad designed to withstand the forces likely to be imposed.

9.176 Because of the heterogeneous conditions within a landfill, the forces imposed on a vertical structure will be not be confined to the vertical plane. Lateral forces will deflect the structure out of vertical alignment and may crush or shear the well pipes.

9.177 All gas extraction systems are subject to a progressive loss of performance due to the build up of silt, chemical precipitates and biomass. Small diameter wells, ie <150 mm internal diameter, are so badly affected that they can become unserviceable within 3 or 4 years of construction[26].

9.178 Vertical wells will only extract gas effectively from unsaturated waste. The reduced permeability of degraded waste, accumulation of condensate and the physical displacement of pore water often result in a build up of leachate within landfill gas wells to the detriment of their performance.

9.179 As a result, vertical wells are not effective in extracting gas from wet sites. Even in unsaturated sites the operator may well find it necessary to arrange for leachate removal from vertical gas wells using either pumps or ejectors.

9.180 Operators have achieved good results with a horizontal gas collection system installed beneath the capping of saturated sites where vertical wells have failed to achieve good results on account of the high leachate levels. Horizontal collection systems are much more likely to be damaged by loading forces than vertical wells and their use at depth in landfill sites has now been largely discontinued.

9.181 **Pumping mains and pipework:** Landfill gas pipework systems are generally made of smooth bore HDPE piping with fusion welded joints. The pipes should be sized to suit the anticipated flows and may range from 150 mm internal diameter at the well head to 300 mm or more, close to the pumps. Temporary systems are generally constructed from flexible HDPE pipe, typically 150 mm diameter.

9.182 **Condensate traps:** Regardless of whether the pipework is permanent or temporary, careful attention should be paid to the removal of condensate from the system. Landfill gas is saturated with water vapour as it is generated within the waste, and this is carried into the wells and pipework along with the gas. Variations

[26] In situ falling head permeability tests of 150 mm internal diameter wells drilled in waste have shown permeabilities of the order of 1×10^{-8} m/s in household waste emplaced for about 10 years.

in the temperature and pressure within the extraction system cause some of the water vapour to condense and drain to low points in the system where in extreme cases it can cause blockages.

> The pipework system should be designed to drain the condensate to low points which may drain either back to the wells themselves, or to self draining condensate knockout pots which discharge the condensates back into the waste, or to condensate collection tanks.

> Most regulatory authorities take the view that discharging condensate back into the waste from which it originated does not require a separate waste management licence although it may be a condition of an existing licence. Otherwise condensate is a controlled waste and is subject to regulation for its disposal or discharge. Condensate may be a highly contaminated liquid[27].

9.183 **Gas extraction pumps:** Gas extraction pumps now generally take the form of centrifugal compressors driven either by diesel engines or by electricity. They are available in a range of sizes typically between 150 m^3/hr and 500 m^3/hr. The smaller units are available skid or trailer mounted complete with a condensate trap, flare or diffuser and the necessary controls and monitoring equipment. These are generally used for temporary systems either to deal with emergencies or for pumping tests.

> Gas pumping equipment may be required to pump gas/air mixtures which fall within the explosive range (ie 5% - 15% methane, in 18 - 21% oxygen). They cannot be made intrinsically safe and so it is essential that flame arrestors are fitted to prevent ignition within the compressor propagating back through the pipework to the site.

9.184 **Flares and diffusers:** Landfill gas extracted from the waste should be disposed of by combustion in a purpose built flare. Where the gas contains insufficient methane to support combustion, and a risk assessment precludes the use of a support fuel, it should be discharged to the atmosphere through an elevated diffuser stack to ensure adequate dispersion.

> The landfill designer should have estimated the quality and quantity of landfill gas likely to be generated and should design measures to ensure that the emission does not cause a nuisance or health risk to local residents using atmosphere dispersion modelling where appropriate.

> It is not possible to predict the occurrence of malodorous or hazardous trace components in the landfill gas and so it is necessary for the operator to investigate the landfill gas itself and the products of combustion from the flare or utilisation plant to verify that the predicted performance is being achieved. These investigations should be undertaken as part of the plant commissioning trials and should be repeated once a year from then on.

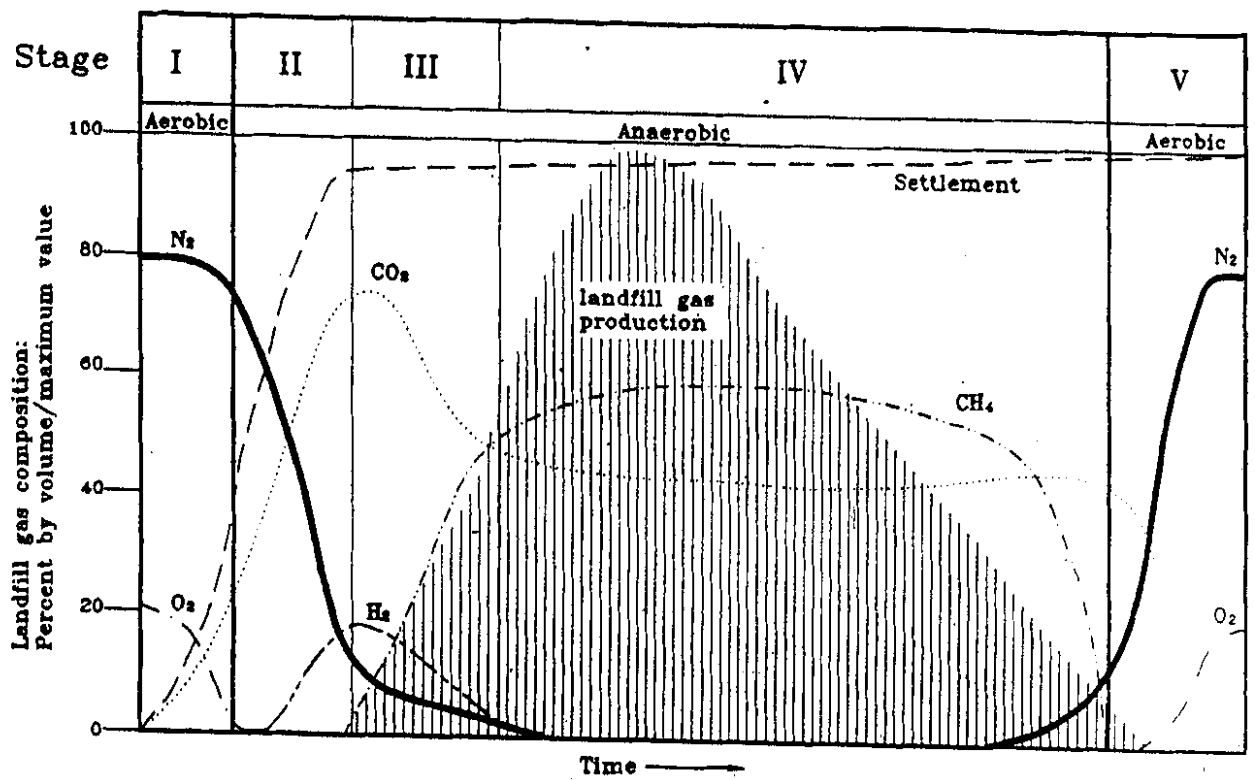
> Operators should be aware that the combustion efficiency of many landfill gas flares is very poor.

andfill gas utilisation

9.185 Energy recovery is a mature, successful technology in the UK and where it

[27] Condensate often forms a two phase mixture; an organic rich 'oily' phase and an aqueous phase. If chemical analyses are required, the presence of the two phases should be taken into account.

Figure C.3 Changes in composition of landfill gas



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Section X.

Microorganisms Against Green House Effects – Suitable Cover Layers for the Elimination of Methane Elimination of Methane Emissions from Landfills

M. Humer and P. Lechner

MICROORGANISMS AGAINST THE GREENHOUSE EFFECT – SUITABLE COVER LAYERS FOR THE ELIMINATION OF METHANE EMISSIONS FROM LANDFILLS

Compost + Cl tm Ox

6+ landfill sp p

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ABSTRACT

Landfills represent an important source of the greenhouse gas methane. This is due to incomplete gas collection on sanitary landfills, abandoned gas collection on older landfill sites with only small gas production, and emissions from unauthorized open dumping. Enhancing microbial methane degradation in proper cover layers could serve as an additional measure to gas collection for operating landfills as well as an alternative for older and smaller landfills. High oxidation rates can be achieved in coarse, ripe waste compost, such as sewage sludge compost or municipal solid waste compost. Laboratory tests reveal that methane oxidation in these composts was clearly better than in natural soils. Apart from a proper compost quality, the design of the cover layer is also very important. In a field experiment on an Austrian landfill, differently constructed cover layers made of compost were tested under real conditions over a two-year period. This paper contains the results from these investigations and proposes a proper design of such cover layers in order to enhance methane oxidation.

INTRODUCTION

Methane, the main component of landfill gas, is an important greenhouse gas. Methan's global warming potential (the infrared radiation absorption potential within the atmosphere) is about 21 times more effective than carbon dioxide, calculated over the time horizon of 100 years (IPPC, 1995). Atmospheric methane concentrations have risen steadily from 0.7 ppmv in pre-industrial times to a recent level of approx. 1.8 ppmv (Blake et al., 1988). This is a clear indication of human intervention in natural fluxes (see Figure 1).

Estimates have put total global annual methane emissions from all sources at about 500 - 600 Tg, of which only less than 200 Tg are natural (Grübler, 1998). Thus methane emissions due to human activity, mainly agriculture, biomass burning and landfills, are up to three times higher than emissions due to natural producers (e.g. wetlands, termites).

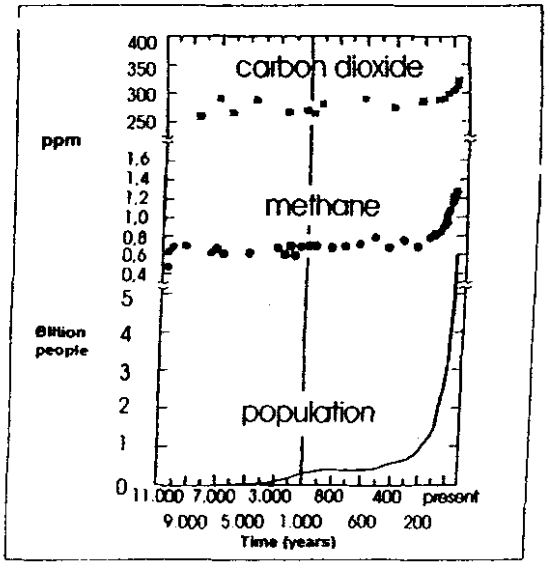

Figure 1: Development of carbon dioxide and methane concentration in the atmosphere in correlation with the global population (Krapfenbauer, 1995)

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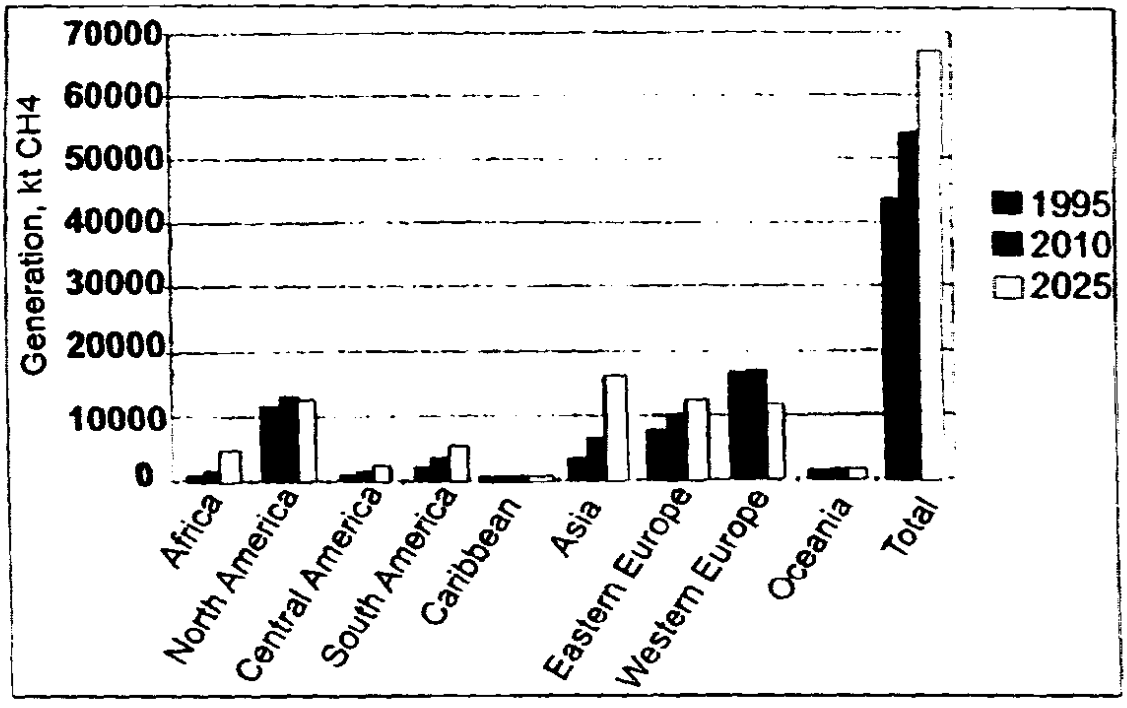

Figure 2: The estimated development of global methane production on landfills by region from 1995 to 2025 (Meadows et al., 1997)

Apart from methane a number of other hydrocarbons, e.g. volatile halogenated carbons, can be found in landfill gas, but mainly up to a level of only <1%. These compounds also have a great impact on the environment and human health. For example, chlorofluorocarbons (HCFCs) have a large global warming potential, a hundred- to thousand-fold higher than carbon dioxide or methane; e.g. vinyl chloride (VC) is carcinogenic.

Although today's sanitary landfills usually operate a gas extraction system, by which landfill gas is collected and burned in flares or used as an energy source, a high amount of gas still escapes into the atmosphere. Methane is also emitted from older and smaller landfill sites, where the subsequent application of a gas collection system is too costly, as well as from open, unauthorized dumps. Landfills contribute about 20 – 70 Tg to global methane emissions each year (Khalil et al., 1989). At the moment Western Europe and North America are the largest producers of landfill methane due to high levels of waste production per capita and the highly-degradable carbon content of the waste. Meadows et al. (1997) estimate that total global methane emissions from landfills will increase significantly by 2025 (see Figure 2). The authors assume that this will mainly be due to growing populations and urbanization in developing countries (such as in regions in Asia or Africa), which most likely will lead to increased waste generation and disposal in landfills. Presumably landfills in these countries will not have gas collection systems because of inadequate or missing technical and financial facilities.

The main global methane sinks are chemical reactions in the troposphere and microbial methane oxidation in soils by methanotrophic bacteria. The scientific community has long known about the presence of methane oxidizing microorganisms in different natural systems, e.g. aerobic soils, water, marine habitats (Whittenbury, 1970). Microbial methane oxidation, that means the turnover of methane to carbon dioxide and water by microbial activity, is very important and accounts for about 80 % of global CH_4 consumption (Kightley et al., 1995). The effect of methane oxidation in natural landfill cover soils has already been described by a number of authors (Croft et al., 1989, Whalen et al., 1990, AERC Ltd. 1991, Bergmann et al., 1993, Kightley et al., 1995; Boeckx et al., 1996, Borjesson et al. 1998). Most of the referenced investigations show that a high methane oxidation capacity could be found in porous, coarse and organic-rich substrates (e.g. Croft, et al., 1989, Bergmann et al., 1993, Kightley et al., 1995).

Based on these reports we initiated investigations in 1996 into several waste composts, including sewage sludge compost or municipal solid waste compost, used as landfill

cover material to enhance the natural potential of methane oxidation. As a first step, we carried out laboratory experiments with soil columns to assess the methane oxidation capacity of compost substrates as compared to natural soils. These tests have proven that ripe compost is a suitable substrate for methane oxidation. As a second step, a field experiment was started on an Austrian landfill during the summer of 1999 in order to investigate the effect of seasonal conditions on methane oxidation in differently constructed compost covers. These investigations have been running for two years.

GENERAL PRINCIPLES

The process of methane oxidation consists of the conversion of methane into water, carbon dioxide and biomass by microbial activity. Methane oxidation is dependent upon a number of determining factors, such as the water content, temperature, soil conditions and nutrient compounds.

Microbial methane oxidation is very effective in many natural systems, such as the aerobic layers of topsoil in wetlands, and it is a determining factor in the natural carbon cycle. For example, in the Florida swamps and in the marsh lands in Germany, it was demonstrated that methane produced in anaerobic zones was reduced by 70-90% in the covering aerobic zones by methane oxidation before reaching the atmosphere (King et al., 1990; Knoblauch et al., 1995). In soil layers with optimum ambient conditions (oxygen-methane ratio) for microorganisms, an „oxidation horizon" of 0.1 to 0.3 m is usually formed. This horizon is where most of the active methanotrophic bacteria accumulate and the major methane oxidation processes take place. Under altered conditions, such as a reduced supply of methane or oxygen, this horizon may proceed vertically in the soil.

Microorganisms which are capable of oxidizing methane have been known since the turn of the 19th century. These microorganisms are mainly so-called obligate methylotrophic (= methanotrophic) bacteria which specialize in the assimilation of C1 compounds (such as methane and methanol). Today methanotrophic microorganisms can be isolated in nearly all limnological, marine, and terrestrial sites. Obligate methanotrophic bacteria use methane and its decomposed compounds, methanol and formaldehyde, as their sole source of energy and carbon. This process is catalyzed by an enzyme called methane mono-oxygenase which can be found in all methanotrophic organisms and is essential to methane oxidation.

Methane mono-oxygenase acts as a non-specific catalyst, which may lead to the co-oxidation of NH_4^+ and other hydrocarbons, such as halogenated ones, which are also found mainly in landfill gas. Methane mono-oxygenase is available in either soluble or membrane-bound form, depending on the concentration of copper available in the substrate (Bender, 1992).

Environmental factors have a decisive impact on the activity of methanotrophic bacteria, i.e. methane turnover rates. Methanotrophic organisms on the whole are fairly adaptive, but some certain ambient factors are required.

Temperature

Most methanotrophic bacteria live and multiply best at temperatures ranging from 15 to 30°C (mesophilic cultures). Heat-tolerant cultures can sustain their growth rates up to a temperature of 55°C (exospores may survive even after short-term exposure to temperatures of up to 80°C). Some psychrophilic cultures have an optimum temperature below 15°C; however, the lowest temperature limit at which their activity ceases is probably slightly above 0°C (Heyer, 1990). There are differing scientific statements concerning the dependency of methane oxidation on temperature. Laboratory experiments conducted by Whalen et al. (1990) show that a temperature increase from 15°C to 25°C causes the methane oxidation rate to nearly double, and the authors indicate that methane turnover rates depend heavily on temperature; however, an investigation conducted by Boeckx et al. (1996) show only a slight temperature effect on methane oxidation. Our laboratory tests indicate the same; in a wide temperature range of 5°C to 30°C we have found rather high and constant methane turnover.

Water content

The water content of the substrate influences methane oxidation in many ways. There is a strong correlation between the actual water content and oxygen respectively methane permeability, which also has a big impact on methane oxidation. Gas permeability decreases with increasing water content.

At a moisture content below 13 % of the maximum water capacity, methanotrophic microorganisms tend to become inactive (Bender, 1992). Tests carried out by Figueroa (1993) on different landfill cover materials show that optimum conditions for methane oxidation are found in areas with a relatively high moisture content. The highest methane turnover rate could be achieved under the same ambient conditions in biowaste composts with a moisture content of approx. 40 - 80 % of the maximum water-holding capacity. Boeckx et al. (1996) indicate that water content widely regulates the activity of methanotrophic bacteria. They found that the optimum moisture content is situated at about 50% of the water capacity. In our laboratory tests the activity of the methanotrophic bacteria was strongly inhibited at a moisture content of <20% w/w in compost (corresponding to <15% of maximum water capacity).

Oxygen supply

Methanotrophic bacteria are obligate aerobes, which can achieve optimum methane oxidation rates even under

microaerophilic conditions, i.e. at very low oxygen concentrations. Bender (1992) carried out experiments on a soil of a paddy field and demonstrated that the microbial activity of methanotrophic bacteria is reduced significantly only below oxygen concentrations of 2 % v/v in the gaseous phase. According to the total formula in stoichiometry, two molecules of oxygen per molecule of methane are required for microbial methane oxidation:

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O + 210{,}8\ kCal/mol$$

(according to Croft and Emberton, 1989)

This equation results in an ideal O_2/CH_4 ratio of 2:1 (2 l O_2/ 1 CH_4 respectively 4 g O_2/g CH_4) in the substrate. This stoichiometric calculation works only if no carbon is converted into biomass. If biomass is accumulated, less oxygen is needed for methane oxidation. Thus Mennerich (1986) indicates that 3.6 to 4.0 g O_2/ g CH_4 is actually needed for methane oxidation, Kjeldsen et al. (1997) indicate 3.5 g O_2/g CH_4 is required.

Inhibitors and co-oxidation

Methane oxidation may be impacted negatively by a number of different organic and inorganic substances. This may be caused indirectly (competing enzymes) or directly (toxicity, unsuitable ambient conditions).

Increasing NH_4^+ concentrations have a decisive effect on the oxidation rate. NH_4^+ is a so-called „competitive inhibitor" to methane oxidation. The methane mono-oxygenase enzyme, which is produced by the methanotrophic bacteria, also acts as a catalyst in the extracellular oxidation (co-oxidation) of NH_4^+ as well as various organic compounds. This leads to the formation of products that cannot be used by the methanotrophic bacteria themselves or may even negatively impact ambient conditions. Bronson and Mosier (1993) carried out special experiments to investigate the inhibiting effect of various inorganic nitrogen compounds on methane oxidation in aerobic soils. The results show that admixture of 25 µg NH_4Cl/g of soil already leads to a 78 - 89 % inhibition of methane oxidation.

Methanotrophic bacteria can also degrade organic compounds, such as halogenated hydrocarbons, which are also present in landfill gas. However on the other hand, the methane oxidation process can be affected negatively as well. Deipser et al. (1997) found that partly halogenated carbons (HCFCs) could be degraded up to a rate of 50% and Vinyl Chloride could be degraded about 90 % by methanotrophic bacteria, but the oxidation of methane was at the same time inhibited at higher concentration of these organic compounds.

Kjeldsen et al. (1997) indicate that in batch experiments, benzene and toluene at high rates and at much lower rates partly halogenated carbons (trichloroethylene, trichloroethan) were also degraded when methane was present.

Soil condition and nutrient supply

Substrates, in which maximum methane turnover rates should be achieved, must have a suitable pore volume to ensure a satisfactory supply of oxygen and methane as well as an adequate retention time for methane in the substrate. The substrate must also be rich in organic matter and provide a satisfactory supply of nutrients.

The nutrient supply and the content of organic matter in a substrate are vitally important in methane oxidation for two reasons. On the one hand, organic matter serves mainly as a carrier for microorganisms and improves the properties of soil and substrate; on the other hand, a satisfactory nutrient supply is a prerequisite to the build-up of methanotrophic biomass. According to investigations by Kightly et al. (1995), the admixture of sewage sludge (2.5 g per kg of soil) to coarse-grained sand raises the specific methane oxidation rate by 26 %, admixture of peat leads to an increase by 27%, and admixture of compost derived from green waste leads to an increase by even 41%. No increase in the turnover rate was achieved by admixing mineral fertilizer.

LABORATORY TESTS

We first conducted laboratory experiments with soil columns to assess the methane oxidation capacity of several compost substrates compared to natural soils. We then tested the influence of differing ambient conditions (such as temperature, water content, oxygen and methane supply). The experiments were carried out at standard temperatures in a climatic chamber using gas-proof, transparent columns of acrylic glass (Figure 3).

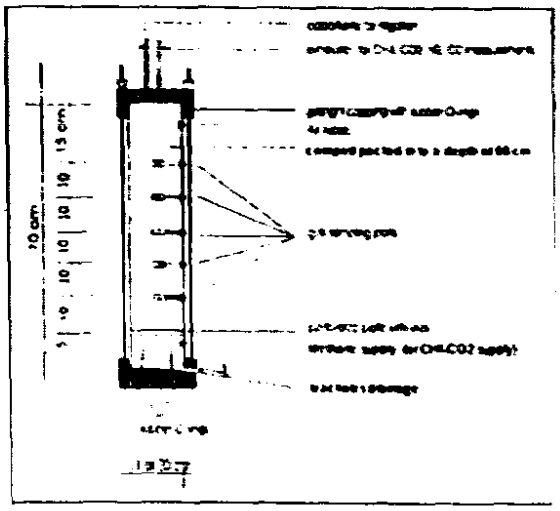

Figure 3: Schematic diagram of a soil-column used in laboratory tests

The testing materials were filled to a depth of 60 cm, and methane or landfill gas mixture was continuously added to the bottom. The methane supply rate ranged at between 3 and 9 ml/min, corresponding to a load per square meter of approx. 150 - 450 l CH_4/m^2d. Air was blown in through an open passage above the built-in substrate. Oxygen had to penetrate the substrate as under natural conditions. Throughout the experiment, measurements were taken for temperature and gas composition (CH_4, CO_2, O_2) at different levels (10, 30 and 50 cm deep) inside the columns as well as for exhaust air. The tests were conducted in duplicate and quadruplicate (tests at different temperature), respectively.

Exemplary results

The following section shows some selected results from these laboratory tests. Figure 4 shows the maximum, mean and minimum methane oxidation rates for some tested composts (municipal solid waste compost = MSW; sewage sludge compost = SS) compared to soil. "Methane load per square meter" indicates the maximum methane load supplied in each of the experiments. The minimum oxidation rates indicate the methane turnover during the adaptation phase. Table 1 shows the analyzed chemo-physical data for the tested substrates prior to starting the experiments.

Mean methane oxidation rates achieved in fully-matured and well-decomposed compost (like MSW 1, MSW 3, SS1, SS 3) were significantly higher than rates in natural topsoil or conventional cohesive landfill covers. In a layer of ripe waste compost of 60 cm in depth and under optimum ambient conditions, it is possible to fully decompose an average methane quantity usually released from a municipal solid waste landfill with an assumed depth of 20 meters.

The adaptation time of the methanotrophic bacteria until a steady state of degradation was achieved, lasted from about 3 to 7 days in the various compost materials, while it lasted somewhat longer in the topsoil and garden soil (about 10 – 14 days). The formation of a methane oxidation horizon within the columns was clearly visible after approximately 3 weeks (with the exception of SS2). This horizon was indicated by a band of intense vaporization, respectively an orange-red band of 15 cm in size, which was clearly distinguishable from the other materials. The reddish slime that covered the compost aggregates was visible with the naked eye. Microscopic examination of the material extracted from this horizon showed a high density of spherical bacteria which seemed to be responsible for the formation of this "biofilm" on the compost aggregates. Within this methane oxidation horizon, there was also a significant increase in temperature of approx. 2° - 4°C as compared to the rest of the column.

The sewage sludge compost SS2 never reached a steady state of degradation within the testing time of about 4 weeks. It showed no considerable methane oxidation because of its high initial ammonium and nitrite concentrations. This is the reason why the test with this compost was stopped after 4 weeks. The compost was subsequently analyzed and the data showed that the ammonia and nitrite in the starting compost material were fully converted into nitrate (full nitrification inhibits methane oxidation).

Figure 5 shows the curve of the methane oxidation rates measured in a fully-matured sewage sludge compost (like SS3) at different temperatures in a climatic chamber. The test started at a temperature of 18°C and after an adaptation time of about six days all of the supplied methane could be oxidised. By reducing the temperature to approx. 4°C the oxidation rates decreased to about 70 – 80% and they increased immediately when the temperature was raised again. In the rather wide temperature range of 5°C to 30 °C, quite constant and high oxidation rates could be achieved. Approx. 150 l of methane/m² d (all of the methane supplied) were oxidised at temperatures of 10°C, 18°C and 30°C, and about 120 l of methane/m²d were oxidised at a temperature of 4°C.

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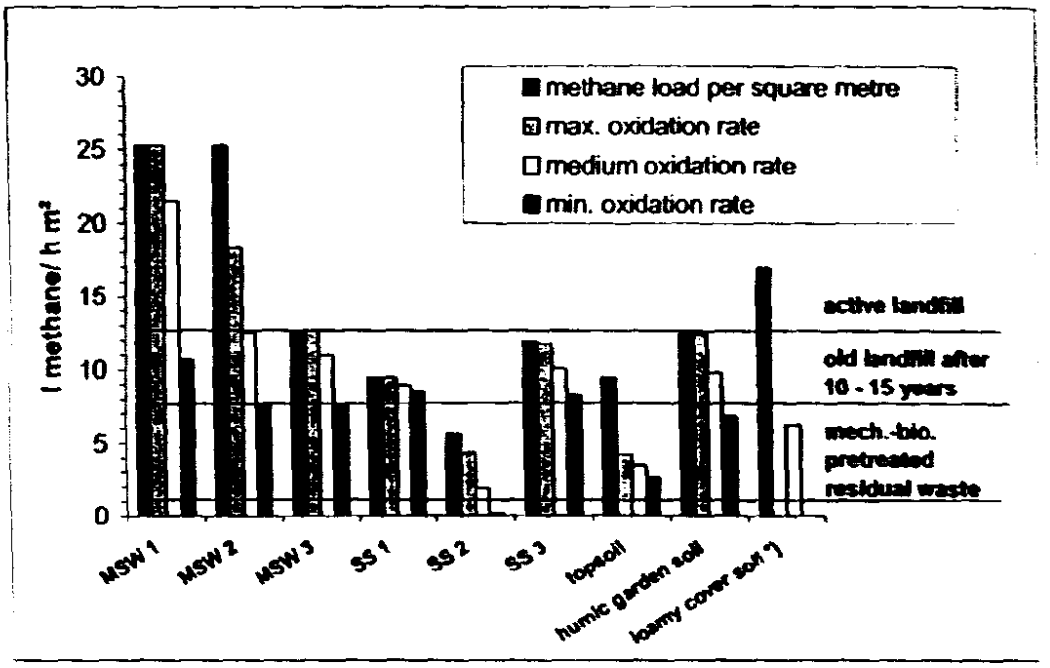

Figure 4. Minimum, maximum and mean methane oxidation rates in the various compost substrates compared to so samples and a loamy cover material; compared to calculated methane rates in a 10-year-old landfill and a landfill fo residual waste after bio-mechanical pretreatment; *) according to Kigthley et al (1994)

Table 1 - Comparison of the analyzed data on the selected compost substrates and soils; MSW = municipal solid w compost; SS = sewage sludge compost; soil 1= topsoil, soil 2 = humic garden soil

	MSW 1	MSW 2	MSW 3	SS 1	SS 2	SS 3	Soil 1	Soil 2
Age of the compost [weeks]	60	20	36	20	34	47	—	—
Bulk density [kg/l]	1.06	0.97	1.02	0.90	0.83	0.90	1.39	1.39
Water content [%]	45.7	44.7	32.4	48.5	46.1	47.6	17.8	17.1
Water capacity [% dry matter]	104	110	89	123	122	121	35	39
Conductivity [mS/cm]	3.8	2.9	2.4	1.2	1.5	0.7	0.9	0.1
pH value	8.0	8.3	8.0	7.0	7.4	7.9	7.0	7.5
NH_4^+-N [ppm dry matter]	348	80	375	8	1200	38	7	1
NO_2-N [ppm dry matter]	0	0	0	0	130	0	0	0
NO_3-N [ppm dry matter]	448	2752	580	279	1070	590	55	29
TKN [% dry matter]	1.29	1.08	0.85	1.14	1.30	1.15	0.21	0.23
Organic content [% dry matter]	24	29	25	26	30	26	7	5
Pore volume within the column [% by volume]	26	27	28	29	37	32	13	25
Respiration activity [mgO_2/g dry matter]	6.8	14.0	6.8	1.9	6.2	6.9	0.6	0.2

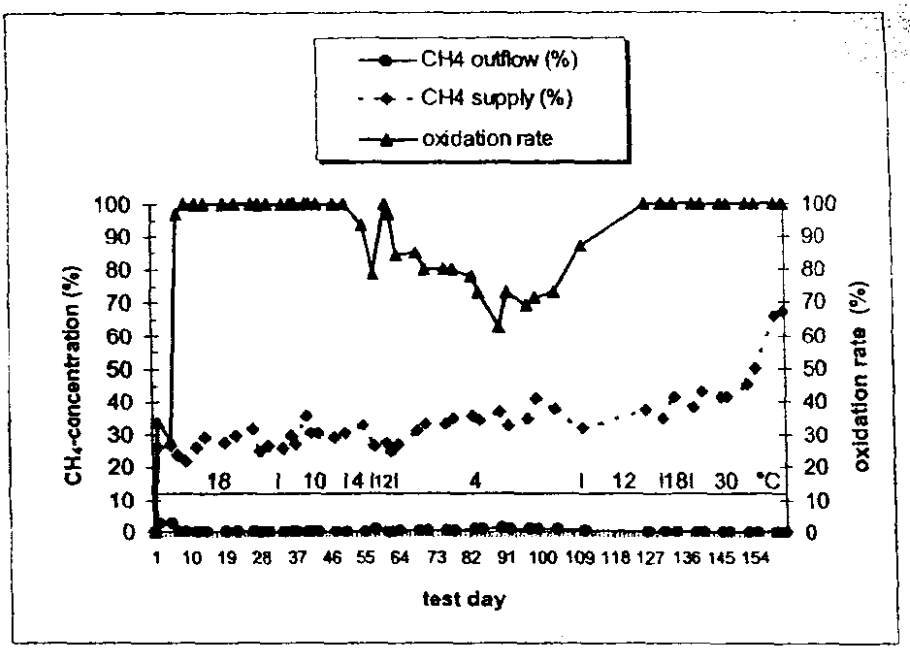

Figure 5: Curve of the methane oxidation rates at different temperatures during the laboratory experiment

Additional laboratory experiments were carried out to assess the co-oxidation of other organic compounds in landfill gas, such as Vinyl Chloride (Obermayer et al., 2001). In duplicate batch tests (in one liter gas-tight glass flasks), sewage sludge compost was used in three different activated stages: "highly-activated sewage sludge compost" (compost taken from a visible methane oxidation horizon in a testing column = haSS), "shortly-activated compost" (compost incubated for one week at a continuous supply of methane = saSS) and a "non-activated compost" (without any prior methane incubation = naSS). 100 grams of these three different activated compost materials were incubated in duplicate flasks in air, 100 ml/l Ch_4 and 0.5 ml/l Vinyl Chloride (VC), and then they were compared against other samples incubated in air and 0.5 ml/l VC without methane.

Figure 6 shows some results derived from these batch tests. Vinyl Chloride was degraded completely in the highly- and shortly-activated compost within less than 24 hours. In the non-activated compost material, only about 45% of the added VC could be degraded (perhaps only adsorbed at the compost material). Only when methane was present VC was completely degraded in this material within five days. There was a strong link with the consumption (oxidation) of the added methane. The results show that in this investigation methanotrophic bacteria mainly were responsible for the degradation of VC, probably cometabolically. Methane oxidation was not inhibited by VC in the activated compost (as it is already adapted to methane oxidation and probably has enough available mono-oxigenase enzyme), but a slight inhibition could be observed in the non-activated material. In further tests the addition of VC was increased up to a level of 1.5 ml/l in order to assess the toxicity level for methanotrophic bacteria. Methane oxidation was strongly inhibited at VC concentration of 1.5 ml/l. Within three days only about 25% of the added methane was degraded.

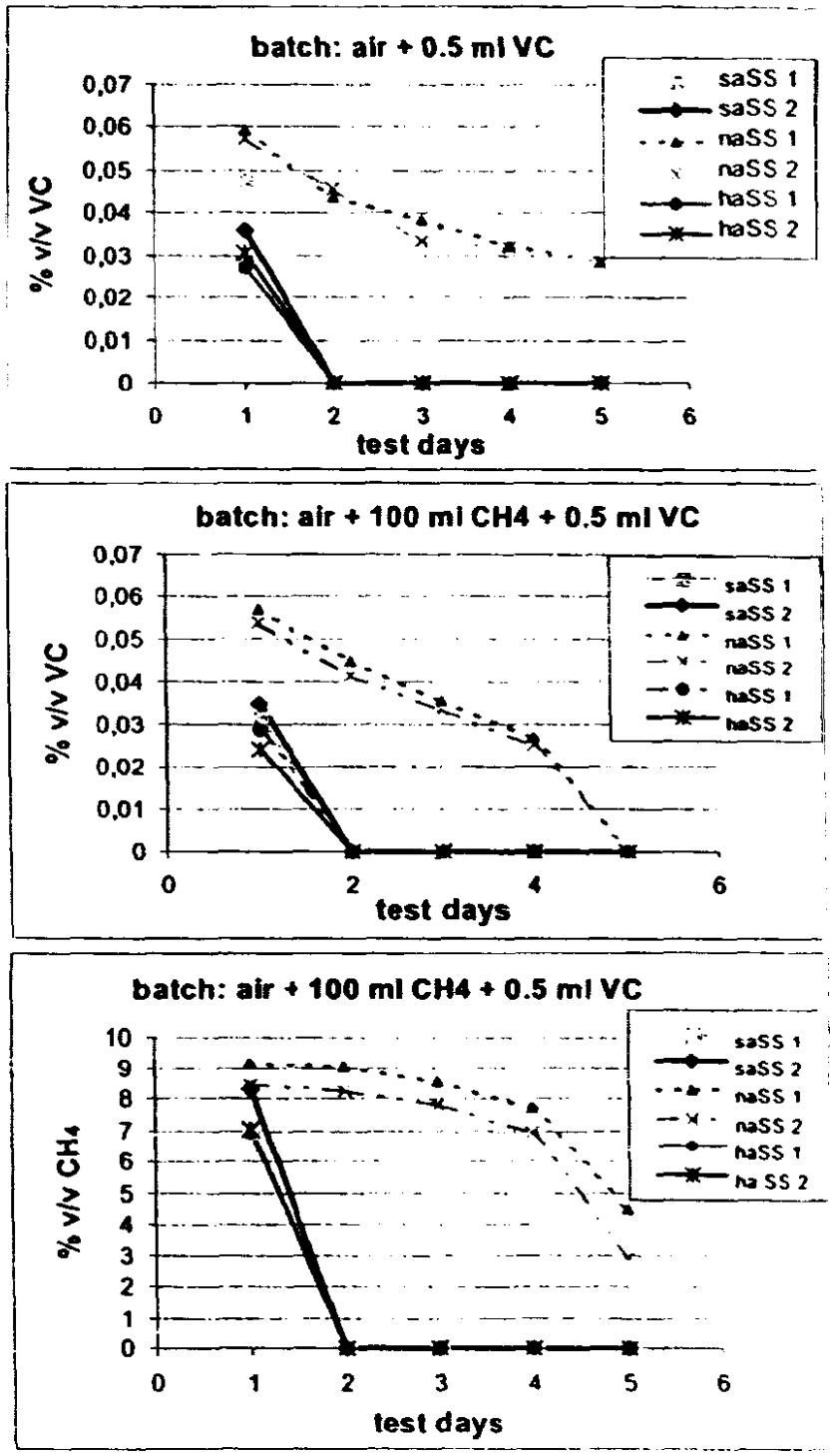

Figure 6: Curve of methane and Vinyl Chloride (VC) concentration in differently activated composts (naSS = non-activated sewage sludge compost; saSS = shortly-activated sewage sludge compost under methane incubation, haSS = highly-activated sewage sludge compost from a visible methane oxidation layer, 1, 2 indicates duplicate batch)

FIELD INVESTIGATIONS

In order to investigate a proper design for compost covers suitable for methane oxidation as well as to verify the methane oxidation capacity under real conditions, a large-scale field experiment was started in June 1999 on a still-operating landfill for municipal solid waste. Several test cells with compost materials of varying thickness and composition were put into place.

Test cells

Five test cells were constructed on the landfill for municipal solid waste in St. Pölten, the capital city of Lower Austria. The landfill is about 14 ha in size and has been operating since 1974 with about 60,000 tons of waste dumped each year, mainly household and biowaste, sewage sludge, demolition waste and some industrial waste. A gas extraction system is in operation on the landfill and the collected gas is used in a gas engine as a source of energy; however, the remaining gas emissions are still high, on average between 0.1 to 0.4 m^3/m^2d (peaks up to 0.8 m^3/m^2d).

Each test cell is approximately 25 x 25 meters in size, was placed on a site where the waste was filled up to a height of about 15 meters. The upper 3 – 5 meters of waste were deposited over 1998 and 1999, shortly before the test cells were put into place, and consist mainly of household waste with a high rate of organics. That means the upper part was filled with fresh, gas-producing waste. The surrounding area of the test cells was made widely airtight by installing geosynthetic clay liners. The various landfill covers on the test cells are designed as shown in Table 2.

Table 2: Designs of the test cells (MSW = municipal solid waste; GD = gas distribution)

Test cell	construction
Test cell 1	- 0.9 m sewage sludge compost - 0.3 m coarse gravel (GD-layer) - about 10 – 15 m MSW
Test cell 2	- 0.9 m MSW- compost - 0.3 m coarse gravel (GD-layer) - about 10 – 15 m MSW
Test cell 3	- 0.4 m sewage sludge compost - about 10 – 15 m MSW
Test cell 4	- 0.3 m sewage sludge compost - 0.3 m compacted loam - about 10 – 15 m MSW
Test cell 5	open landfill body (10 – 15 m municipal solid waste) as a control cell

Ripe (about two year old) sewage sludge compost (50 % by weight of stabilized sewage sludge from a municipal water treatment plat composted with 50 % per weight of wood chips) and municipal solid waste compost (mechanical-biological treatment) were used as cover materials. A coarse gravel (corn size >63 mm) deficient in lime was applied for the gas distribution layer (below the compost layers on test cell 1 and 2) Table 3 shows some data on the used composts as analyzed at the start of the experiments.

Table 3: Data on the waste composts used as landfill cover materials in the field experiment; n.d. = not detectable

	Sewage sludge compost	Municipal solid waste compost
Conductivity [mS/cm]	1.0	2.3
pH value	7.2	7.8
Water capacity [% dry matter]	120	90
NH_4^+-N [ppm dry matter]	5	100
NO_2-N [ppm dry matter]	n.d.	n.d.
NO_3-N [ppm dry matter]	230	230
TKN [% dry matter]	1.11	0.97
Organic content [% dry matter]	27	27
Respiration activity in 7 days [mg O_2/g dry matter]	1.4	2.2

The compost was put into place without any artificial compaction, and we took care not to compress the deposited compost with heavy work machinery in order to achieve sufficient porosity and satisfactory gas permeability.

Local spontaneous vegetation scattered by the wind and weeds sprouted from the compost have been growing on the test cells.

Measurements

A close net of fix installed gas-probes and temperature-probes measure the gas composition and temperature within the cover layers at different depths as well as in the landfill. Methane emissions at the surface of the cover layers are also measured in periodic intervals (every two weeks) in a close screen of about 1.5 x 1.5

meters using a portable Flame Ionization Detector, which is capable of detecting very small concentrations of hydrocarbons (0.5 ppmv – 50.000 ppmv).
Quarterly compost samples are taken from different depth of the cover layers, and the water content, some chemical parameter (e.g. Nitrate, Ammonia, TOC, respiration activity) and the composition of the microbial community (using Polymerase Chain Reaction (PCR) and Denaturing Gradient Gel Electrophoresis (DGGE)) are then analyzed.
Since the winter of 2000/01 emissions have also been quantitatively calculated using a specially-adapted open wind tunnel (Röder et al., 2000). A semicircular tunnel, total open at the front and rear, is placed downwind on the test cells covering an area of 1.5 m². The flow inside the tunnel, induced by natural wind velocity, as well as the temperature, methane and carbon dioxide concentration at the front and the rear of the tunnel are continuously measured. The emission rate is calculated from these parameters using following equation (adapted according to Denmead et al., 1993):

$$F = \frac{v \cdot A_q \cdot \rho_{CH4}}{A \cdot 10^6} \cdot (C_{aus} - C_{ein})$$

F ... emission flow [g/m²s]
v ... velocity [m/s] measured within the tunnel
A_q ... cross-sectional area of the tunnel [m²]
ρ_{CH4} ... density of methane [g/m³] depending on temperature
A ... base area of tunnel [m²]
C_{aus}, C_{ein} ... inflow and outflow concentration [ppmv]

These quantitative measurements are carried out about twice per month.

Exemplary results

No methane emissions were measured by using FID throughout the entire year at the surface of Test cell 1 and Test cell 2, regarded as the "optimal variants" with a gas distribution layer and a sufficient thickness for the compost layer. In contrast, inhomogeneous but at times reasonably high methane emissions were detected on Test cell 3 (only 0.4 m of compost layer direct on the landfill) and Test cell 4 (combination of 0.3 m of compost layer and 0.3 m of compacted loam direct on the landfill) and certainly on Test cell 5 (control cell without any cover). In the latter case (Test cells 3 and 4) methane probably escapes through cracks because of a missing gas distribution layer. There flow velocity and pressure are too high for efficient microbial oxidation.

Sometimes also high methane emissions appeared on the slops of the surrounding area in connection with wind direction and velocity. For example, methane emissions could be detected with a higher wind velocity (> 25 km/h) on the leeward side of the slopes, as opposed to the windward side.
Measurements at the fix installed gas probes indicate the gas concentration within the cover layers as well as the location of the methane oxidation horizon. In Test cells 1 and 2 methane oxidation takes place between a depth of 0.4 to 0.9 m depending on the density and porosity of the two different compost substrates. Figure 7 shows the air-filled pore volume measured at several depths and the corresponding water content in the compost layers. In the coarse sewage sludge compost mixed with wood chips, oxygen penetrates deeper into the cover layer than in the finely-sieved municipal solid waste compost (Ø ≤ 20mm). Therefore the methane oxidation horizon is situated deeper in Test cell 1 than in Test cell 2.
During the winter the methane oxidation layer shifted downwards in both test cells. Figure 8 shows the concentration and temperature profiles of Test cells 1 and 2. Most of the methane is already oxidized at the interface of the gas distribution layer and the compost cover. Also during the winter no methane was detected in the upper 0.8 m of the cover layer, and temperatures were still reasonably high within the cover layer due to the exothermic process of the microbial activity of the methanotrophic bacteria. Dependent on the density and porosity of the different composts, the heat could be stored better in the coarse sewage sludge compost all throughout the year. This is due to the lower thermal conductivity in coarse substrates with a high amount of air space. The field investigations show that within the compost covers from a depth of 50 cm downwards, the temperature (> 10°C) is high enough for microbial activity during winter as well. In our laboratory experiments in a climatic chamber, most of the methanotrophic bacteria in the compost show no loss in their activity down to a lower temperature limit of about 10 °C.

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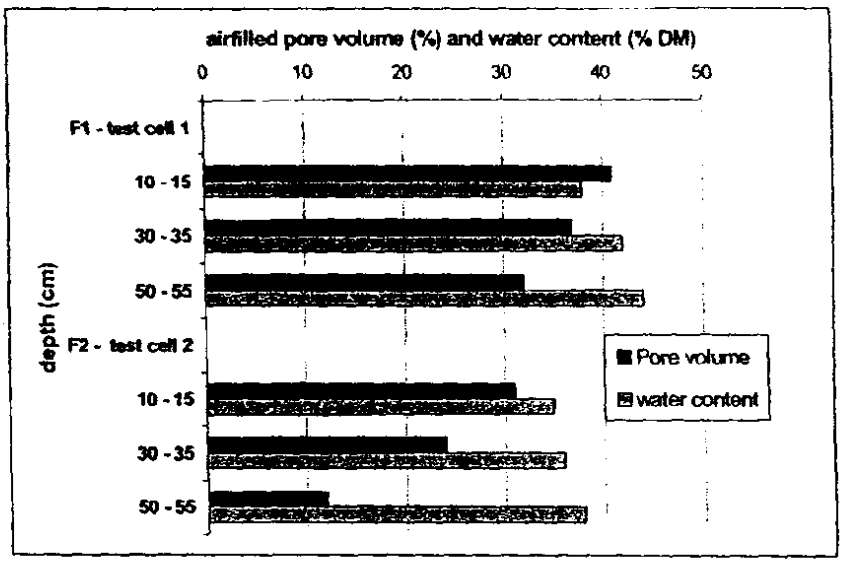

Figure 7: Air-filled pore volume and corresponding water content measured at several depths of the cover layers of Test cells 1 and 2 in March 2001 (mean values of triplicate samples are shown)

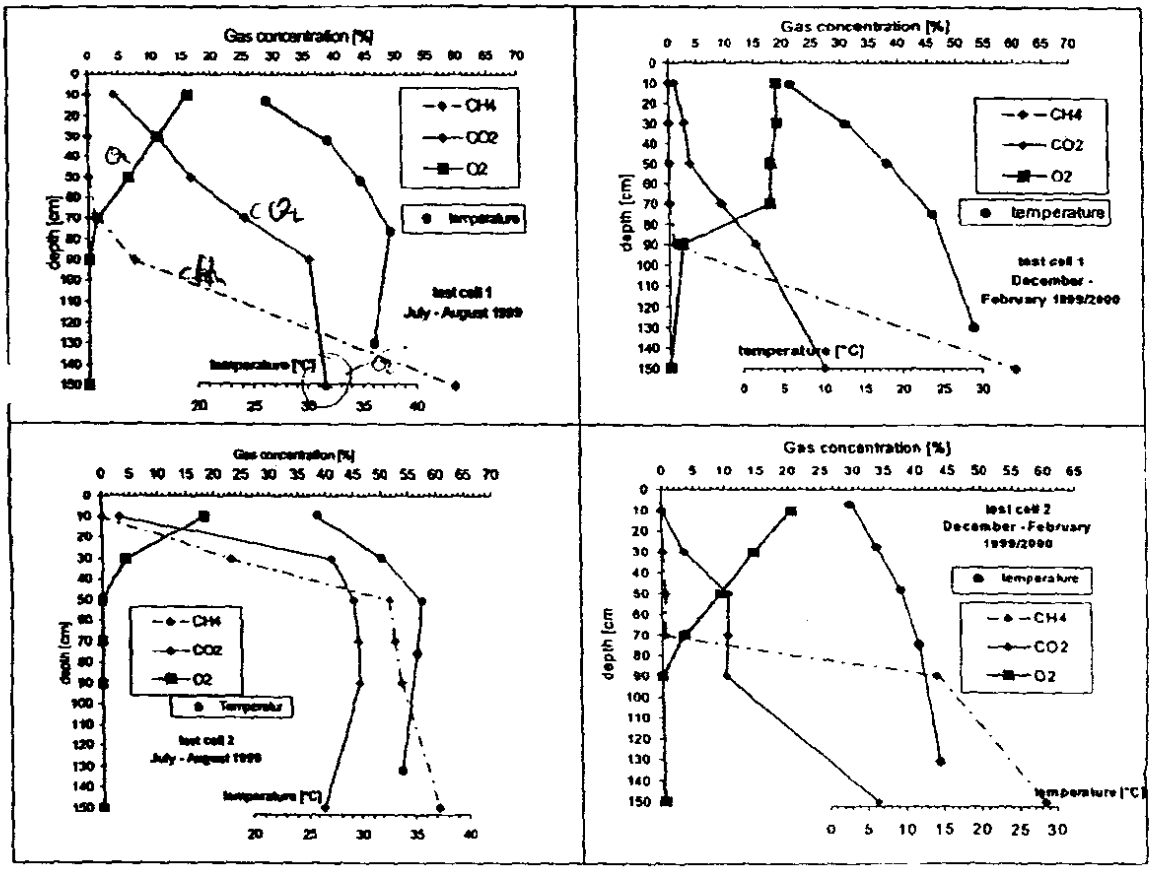

Figure 8: Gas concentration and temperature in Test cell 1 (0.9 m sewage sludge compost and 0.3 m coarse gravel) and Test cell 2 (0.9 m municipal solid waste compost and 0.3 m coarse gravel) during summer and winter

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CONCLUSIONS

The results of our experiments reveal that the method of microbial methane oxidation in compost cover layers can be used as an application for gas emission control on old landfill sites and on landfills of mechanically biologically pretreated waste. Likewise this method can be used in landfill aftercare or as an additional measure to technical gas extraction systems on operating landfills. In order to achieve high oxidation rates, the oxidation layer must ensure optimal ambient conditions for methanotrophic bacteria. Ripe waste compost is a suitable substrate for these processes. The organic matter of the compost must be stable (respiratory activity in 7 days at least <8 mg O_2/g DM) and the compost must provide microorganisms with an adequate and easily-available supply of nutrients (particularly Nitrogen, Phosphor); however, the ammonia concentrations must be low (< 350 ppm). Nitrogen should already be bounded in stable compounds such as humic compounds. Further the structure of the compost must have long-term stability and an adequate porosity even at a high water content, in order to guarantee satisfactory permeability of oxygen and methane.

In addition to the correct quality of the compost material, there must be a proper technical design for such cover systems. Figure 9 shows a simple but effective proper design for such a cover layer. When drawing up the dimensions for the compost layer, various factors must be considered, for example, the oxygen-penetration depth, settling behavior and the dependence of the temperature inside the landfill cover on ambient temperature. The minimum thickness of the compost should be 1.2 m at the beginning stage and the compost should be put in place without any artificial compaction, in order to achieve sufficient porosity and satisfactory gas permeability. Crucial is the installation of a gas distribution layer, e.g. made of coarse gravel deficient in lime, below the compost layer to reach a homogenous load of landfill gas. Landfill gas migrates horizontally much better than vertically. Therefore the surrounding area of the oxidation layer, in particular the zone of the gas distribution layer, has to be sealed carefully against the atmosphere.

It was not necessary to irrigate the test cells during our field investigations. Under the local climate of the landfill site (with annual precipitation about 650 mm), the moister content in the compost covers was always high enough for microbial activity, at least from a depth of 30 cm downwards. Compost materials usually have a high water-holding capacity. The water can be stored over a long period of time in the cover, due to the "isolation-effect" of the compost. This happens when the outer stratum of the compost cover (10 – 20 cm) dries up. As desiccation produces a hydrophobic effect in the layer and disturbs the capillary rise of water, the compost material underneath is protected against evaporation and a barrier forms to prevent temperature loss in the lower compost layers. This guarantees favorable ambient conditions for the methanotrophic microorganisms, to prosper in a moist and warm environment.

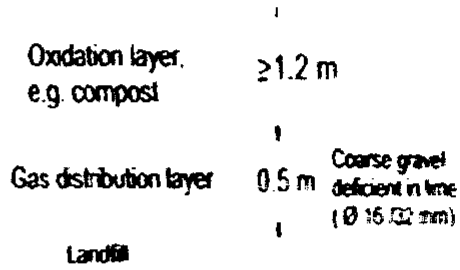

Figure 9: Suggested design of a cover layer for methane oxidation

Under optimal terms (proper design and compost quality), all of the remaining methane emissions from an operating municipal solid waste landfill (about 0.1 – 0.5 m^3/m^2d) could be oxidized throughout the course of the year. The activated compost covers with enriched methanotrophic bacteria also show a high potential for degrading other environmentally hazardous compounds such as Vinyl Chloride or halogenated hydrocarbons as well as odorous substances (e.g. H_2S)

The use of waste composts as a substrate for cover layers on landfills to enhance methane oxidation represent an ecologically- and economically-viable alternative to waste management. Furthermore, this simple and low-cost method help to reduce greenhouse effective gas emissions from landfills and provide a small contribution to the protection of our global climate especially in developing countries where technical landfill gas collection systems are too expensive or too technically impractical to implement in the near future

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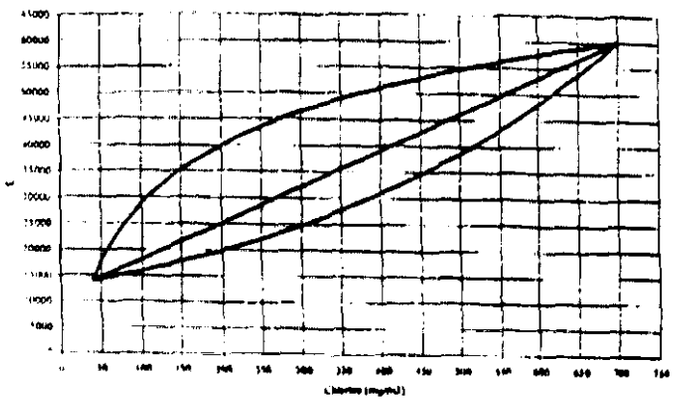

Figure 5 Potential yearly savings on valve failures per engine at various chlorine levels in the landfill gas.

ACKNOWLEDGEMENTS

It would be impossible to list everybody who has been involved in the project – technicians, fitters, electricians, engineers, laboratory staff and senior management. The authors wish to thank all involved directly and indirectly for their help, patience and support shown in regard to the success of the project.

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GUIDANCE ON BEST PRACTICE FLARING OF LANDFILL GAS IN THE UK

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SUMMARY: Regulation of landfill gas in the UK has historically been focused on the need to control migration and flares have been operated in the absence of any emissions standard. In recognition of this, the Environment Agency's National Landfill Gas Group commissioned a technical review of emissions from different types of landfill gas flare. This work has resulted in a document entitled "Interim Internal Technical Guidance for Best Practice Flaring of Landfill Gas". The current paper summarises some of the key aspects of this guidance

1. INTRODUCTION

1.1 The development of the Environment Agency's position

Regulation of landfill gas in the UK has historically been focused on the need to control migration. Flares have been operated in the absence of an emission standard. In recognition of the lack of flare emissions monitoring and the absence of a UK standard, research was commissioned by the Department of the Environment (Frost et al, 1996) in the form of a technical review of emissions from different types of landfill gas flares. The Controlled Waste Management R&D Programme of the Department of the Environment transferred to the Environment Agency and became the Waste Regulation and Management Research Programme on the Agency's creation in April 1996.

The Environment Agency's National Landfill Gas Group commissioned work to develop this further and has released internal guidance based on the initial review, predominantly for use by its waste regulators. The aim of this guidance is for the Agency to move towards landfill gas emission control on a site-specific, risk assessment basis in preparation for the EU Landfill Directive.

It was estimated in 1994 that approximately 20% of total UK methane emissions could be attributed to landfill gas. This is believed to represent between 1 and 2 million tonnes of methane per annum (Environment Agency, 1998). Increased control of landfill gas emissions is therefore an essential part of the UK Climate Impacts Programme to reduce methane emissions in accordance with the Kyoto Protocol. It is expected that the contribution of methane emissions from landfill will continue to decrease as an increasing number of modern landfill sites will be required to have effective full-site landfill gas collection systems

precipitation, stratospheric ozone depletion and global warming.

5.2 Air dilution

As an indication of the type of long-term impacts that may be encountered it is useful to consider dilution factors around a typical flare installation. The results of a long-term air dispersion study for two typical installations in the United Kingdom showed that long-term dilution factors exceed 10,000, except within the close vicinity of the flare, and very rapidly reach 50,000. In terms of typical trace gases emissions from flares this implies that in the long-term risks to health and the environment will be small. The output was based upon mathematical modelling of atmospheric conditions.

By contrast, however, a study carried out in Germany (Gerhardt, 1993) estimated the degree of dilution of gas leaving a landfill site at night. It was found that landfill gas plumes were travelling a distance of up to 1 km with very little dilution whatsoever. This disparity clearly indicates the need to treat such information with caution.

6. RECOMMENDATIONS CONTAINED WITHIN THE INTERIM INTERNAL TECHNICAL GUIDANCE FOR BEST PRACTICE FLARING OF LANDFILL GAS

Against the above background of increasing awareness about the issues involved in the flaring of landfill gas, and based upon substantive advice from the National Environmental Technology Centre (NETCEN), the following recommendations have been agreed as applicable to the question of assessing landfill gas flaring systems.

Recommendation No. 1. No more open flares should be installed on UK landfills except for test and emergency purposes, and then only for limited periods of not greater than six months.
There are a number of specific problems with open flares that militate against their continued use. There is ample evidence to indicate that the conditions within an open flare are favourable to the formation of by-products of incomplete combustion. These include a wide range of compounds and include dioxins and furans. Carbon monoxide is a good indicator of incomplete combustion.

Recommendation No. 2. Existing waste management licenses at landfill sites should be modified so as to effect the replacement of open flares with enclosed flares (or techniques offering equivalent performance) over a period of five years, particularly at sites that:

- produce large amounts of landfill gas; and/or
- are close to population centres or other areas of environmental importance.

The period of five years, starting from January 1st 1999, has been chosen to permit adequate time for this standard to be adopted. It is specifically acknowledged that other technologies may exist or be developed that will dispose of landfill gas in an acceptable manner. It is not the intention of these guidelines to be exclusive of such alternatives.

Recommendation No. 3. The combustion air supply should be controlled so as to achieve a minimum of 1,000°C and 0.3 seconds retention time at this temperature whatever the landfill gas composition and throughput (within expected design limits).

In an open flare the presence of cool zones at the flame's periphery results in incomplete combustion and, therefore, less heat release than is theoretically possible: radiative and convective heat losses are also substantial and uncontrollable.

Precise calculation of retention time is difficult to achieve. Retention time calculations should be assessed on the basis of satisfactory compliance with the intention of holding combustion gases at the design temperature for an adequately long period of time. Further research work is being carried out to define a method for obtaining a more accurate measure of this variable.

Recommendation No. 4. To ensure that flare systems are operating correctly they should not exceed the following emission concentrations when referred to Normal Temperature and Pressure (NTP=0°C and 1013 mbar) and 3% oxygen:

- Carbon monoxide (CO) - 50 mg/m^3
- Oxides of nitrogen (NO_x)- 150 mg/m^3
- Unburned hydrocarbons - 10 mg/m^3

Complete combustion may not be achieved in flares operating outside their design conditions, and partially burned fuel may show up as carbon (smoke, soot, particulates) and/or intermediate reaction products such as CO. Incomplete combustion may result from:

- lack of oxygen caused by poor mixing of fuel and air or an overall air deficiency;
- cooling of the flame by, for example, radiation or its impingement on cold surfaces;
- inadequate time at high temperature for the complete oxidation of carbon - the limiting factor for gases being the oxidation of CO to CO_2.

Recommendation No. 5. Inlet gas concentrations should be analysed to determine if there are any incombustible substances contained within the inlet gas that may require to be removed prior to entering the flare stack.
Certain substances, such as chlorines and fluorines, are not destroyed thermally at the temperatures found with landfill gas flares. In large quantities such substances may lead to difficulties in their own right.

Recommendation No. 6. Enclosure design should:

- permit an homogenous temperature distribution across the combustion chamber.
- be lined with refractory material on the interior
- contain the flame within it; and
- be maintained in an effective manner

Recommendation No. 7. Operators of landfill sites should undertake - or commission - an environmental assessment of the emissions from existing and proposed flares which:

- should use either measured or reported emissions data, flow rate data and local meteorological data;
- consider the impacts of the dispersed emissions in the vicinity;
- determine whether flaring is required for migration control and/or pollution prevention; and
- be approved in writing by the Environment Agency.

Given the highly site-specific nature of landfill sites and the pollutants emitted from landfill sites, it is recommended that an environmental assessment be carried out to ensure that a proposed or existing flare will meet with the environmental criteria for which it is designed. The Environment Agency should approve in writing the findings of such studies.
Recommendation No. 8. Flares should be positioned and sized so that potential health and environmental impacts are minimised.

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The optimum location for a flare will come out of the environmental assessment recommended above. This should be such as to minimise potential health and environmental impacts.

Recommendation No. 9. Guidance is given in the guidelines as to the level of monitoring that should be recommended by Environment Agency officers.

Recommendation No. 10. Flares should be maintained in accordance with the manufacturers' recommendations. Full records should be available for inspection.

Recommendation No. 11. All results obtained by flare-system managers should be the subject of a formal review. Such reviews must accompany results and reports when communicated to Environment Agency officers.

7. CONCLUSIONS

The introduction of a UK best-practice flaring standard has many benefits to the local and global environment and in minimising potential human health risks. The associated Environment Agency's landfill gas policies represent a paradigm shift towards landfill gas emissions control with the clear message that large-scale passive venting of landfill gas can no longer be considered as an effective control option. The design of open flares makes emissions monitoring that has any degree of accuracy difficult and the replacement of such flares will ensure that current UK best practice is maintained and becomes widespread. It will also provide the confidence that enclosed flares can be monitored, assessed, optimised and correctly maintained.

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Section XII.

LFG Biofilter on Old Landfills
F.Starka

LFG - BIOFILTERS ON OLD LANDFILLS

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SUMMARY: The passive landfill gas venting system combined with filtering unit was tested and applied. This system is used on small remedied old landfills, where the commercial utilization of gas is impossible and where an active system of gas pumping and flaring would be too expensive. The venting and distribution of LFG via biologically active filtering units brings more environmental successes than only odor removing. Methanotrophic bacteria are able to oxidize methane from 25 % to almost 100 %. The unit of biofilter is very simple and its operation is sufficiently effective, cheap and safe.

1. INTRODUCTION

Numerous old sanitary landfills are now closed and treated to completely remedied areas. In the process of landfill closure belongs construction of the upper insulating barrier between the main points of interest. Protecting cover stopping all water in-flows closes also the whole body of wastes as a gas tight volume. Impermeable covering of such landfill, which is still producing a significant amount of biogas, needs to be accompanied by a relevant degasification system. Properly designed degasification system enables completely controlled collection of gas from whole area of landfill and prevents all kinds of danger associated with pressurising of gas in internal spaces:

- undesired gas migration from bottom parts
- ballooning of covering membrane
- covering layer rupture and sliding on slope parts.

There are generally no doubts about the necessity of landfill gas controlled collection and its treatment by an environmentally acceptable process.

The positive results about the biological oxidation of methane and other organic compounds from landfill gas are older than 20 years (Tabasaran, Affoyon & Rettenberger, 1979) and practically the same results are continuously confirmed (Dalton, 1988; Bergman, Jacobsson & Lagerqist, 1993; Figueroa, 1993, 1996). Regardless to numerous published articles about biooxidation of methane we can meet the technology of gas flaring as a still very frequent recommendation for landfill gas treatment.

Evaluating the knowledge of research and analyses we can see, that landfill gas burning may be vindicated only there, where the gas is either used for energetic purposes or there, where the gas production is very high. Nevertheless, the incineration of landfill gas on flares as a way of "environmental gas treatment" will be in many cases not more defendable. Trace impurities from landfill gas are also during biofiltration captured and oxidised with better or same results as thermal processes are offering. Good results of biooxidation for mitigation of trace components

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[illegible] are reported by many authors (Tabasaran, Affoyon & Rettenberger 1979; Figueroa 1993, 1996; Kjeldsen, Dalager &Broholm 1997, Munoni & Cossu 1997). In all those presentations is confirmed, that in the process of biooxidation are by methanotrophic or methylotropic bacteria completely consumed not only the typical odour carriers (sulphur compounds and volatile fatty acids) but also other harmful constituents of landfill gas (benzene, toluene, formaldehyde etc.).

Very important question concerns the emissions of oxides of nitrogen. During biological processes the only nitrous oxide (N_2O) can be produced, nevertheless last results of field testing show that landfills are not the significant source of this gas (Boerjesson & Svensson 1997). But at every type of gas incineration harmful oxides either NO or NO_2 are produced. Comparing only the papers of Sardinia 97 dealing with methane oxidation by bacteria and papers carrying new informations about gas flaring, we recognise, that biooxidation is slowly reaching its supremacy over thermal processes, especially if the gas is treated only for purposes of environmental protection. Even if there are new and better gas flares, the single LFG incineration without any other purpose of its energy utilisation is not more recommendable.

If we are evaluating the conditions for closing and remediation of small old landfills, the economic view has a very important influence, especially when the "cold" way of biooxidation offers significantly lower needs in either investment or operational costs against the gas pumping and flaring. In majority of cases the economic evaluation shows the highest priority for local counties (as owners or responsible for landfill areas) and is also used as the basic point of decision.

The landfill gas flaring system needs to be accompanied by an active degasification while the biological filtration of gas can be installed on a passive systems without any consumption of electricity. Considering the facts, that a passive system with biofilters is about 10 fold cheaper than active gas flaring and considering that the resulting level of environmental protection is quite comparable or better, we need not any other argument to support the processes of biooxidation.

Of course, between the landfill gas "treatments" we can sometimes meet also very simple venting of gas from open gas drainage or through open pipes or ventilation heads.

The main problem of such LFG venting is rooted basically in missing end-treatment of escaping gas. Simple open pipes leaving the gas out of the landfill are not recommendable, because:

- the odour of LFG is not captured
- the trace components (many of them are harmful ones) are not captured
- methane is not oxidised and increases the volume of anthropogenic "greenhouse gases"
- nearby the ends of such pipes or venting heads it is a danger of fire or explosion
- during periods of fast rising of the barometric pressure the air can be driven inside the landfill, where than an undesired aerobization and acidification are started
- air intrusion can also create the internal explosive mixtures inside the gas drainage

2. LANDFILL GAS BIOFILTER

During our praxis of testing of various old landfills we observed in many cases the disagreement between the estimated productivity of gas and surface gas flow, analysed by the flux-box method. The successful explanation to lower observed migration velocities of methane from landfill surface is just the biooxidation. In very good agreement with all mentioned references we confirmed that active methanotrophic cultures in soil or cover layers are able to mitigate high volumes of methane penetrating upwards from the body of landfill. Those results were used as a

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key decision to the extensive application of biofilters as an effective tools for treatment of from small and old landfills.

The general strategy of design of the passive degasification system equipped with biologica active filtration unit is based on the one-directional flow of biogas through the filter out to atmosphere while the whole internal parts of gas drainage are kept in an anaerobic sta protected sufficiently against the air intrusion.

2.1 Biofilter Structure & Design

The filtration unit contains two different spaces, filled with solid porous media. Lower part filter is used as a volume compensating space, where the counter flow of air is terminated, wh may happen during sudden rises of barometric pressure. The volume of lower part of filter calculated from the void volume of all gas drainage in the body of landfill.

As a filling for this part of filter was successfully tested coal coke, in granulomet composition about 15 - 35 mm. At this place, of course, we can use also other porous materi with similar porosity and with good physical and chemical stability. This part of filter is used a volume buffer, where the gas can be partially replaced by air driven inside the landfill b counter pressurising when the pressure rise in atmosphere is higher than internal overpressu given by production of biogas.

During our field tests we found that the outer barometric pressure is in majority of cases risir or falling with the time gradient about 0.2%/hr and the same was also confirmed by Registe Scauflaire & Piessens (1997). The capacity of compensating (coke) part is calculated fi uninterrupted rise of barometric pressure for 20 hours, e.g. for the total rise about 4%.

$$V_F = V_D \cdot \frac{\sigma_D}{\sigma_{CF}} \cdot 0{,}04$$

Where:

V_F = Volume of the lower part of filter (coke filling) [m^3]
V_D = Volume of gas drainage in the landfill body (drainage wells, drainage trenches, collectin pipes) [m^3]
σ_D = Mean porosity of drainage fillings
σ_{CF} = Mean porosity of coke filling in the filter

This lower part of filter is designed as a box for subsurface installation (see Figure 1) and is welded from polyolefinic wall plates (for example polypropylene). The box of the filter is created from units whose can be easily transported by the standard road trucks and are sufficiently resistant chemically and mechanically too, even if during operation the internal temperatures can sometimes rise to the values about 50°C. The polypropylene box or assembled group of boxes, buried in the landfill, are connected to the gas drainage and carefully filled with coke, which is than covered by a sheet of filtration geotextile as a separator between both parts of biofilter (the coke compensator and upper biologically active part).

The upper part of filter is filled over the separating geotextile as a layer where the processes of biooxidation are proceeding. As a material achieving good porosity and biological activity were tested for this purpose mixtures of compost with cutted bark or wooden chips.

The detail design of the filter is selected after local conditions and its typical crossections are presented on Figure 1. The height and area of upper compost-wooden chips part is calculated after measured values of free gas outflows from gas drainage. The area and volume of filtering layer is than corresponding to desired maximal load of the filter. The specific loads of

from LFG are reported by many authors (Tabuzaran, Affoyon & Rettenberger 1979; Figueroa 1993, 1996; Kjeldsen, Dalager &Broholm 1997; Muntoni & Cossu 1997). In all those presentations is confirmed, that in the process of biooxidation are by methanotrophic or methylotropic bacteria completely consumed not only the typical odour carriers (sulphur compounds and volatile fatty acids) but also other harmful constituents of landfill gas (benzene, toluene, formaldehyde etc.).

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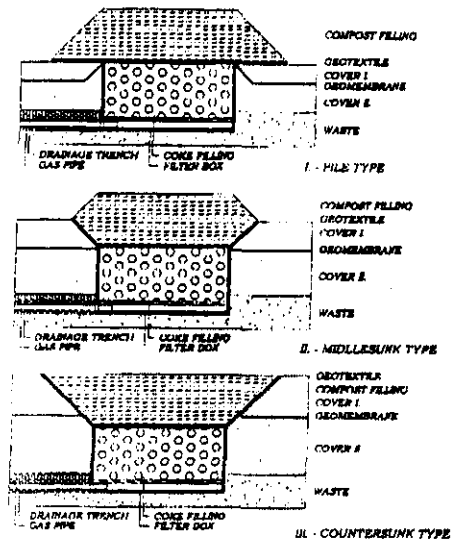

FIGURE 1 - TYPICAL ARRANGEMENT OF BIOFILTERING UNITS

biologically active filling is calculated with the maximum about 10 m^3 of methane per each m^3 of compost filling and hour. As the filter boxes are designed in various lengths (from 2 to 8 m) and various heights (from 0.8 to 2 m), there are many possible combination for parallel arrangement of filtering units if the capacity of one box is insufficient. For large landfill bodies, may be, of course arranged more filtering installations at distant places.

2.2 LFG – biofilter in practical application

The system of passive degasification with biofiltration of gas for completely closed old landfills was until now installed on four landfills with successful results. On one of those bodies is venting of landfill gas via countersunk biofilter in full operation for more than 2 years. This landfill contains the mixture with of sanitary and inert wastes and was equipped only with horizontal subsurface drainage network with the system of gas collectors. The surface of wastes after termination of landfilling was cutted by lines of drainage trenches. Profiles of trenches are 60 x 60 cm, trenches in distances 10 – 15 m are filled with coarse gravel with central collection (perforated) pipes. Side trenches and pipe ribs are connected to the main gas collector carrying the gas to two filtering units. In front of each filtering unit there are installed closing points (see Figure 2.) enabling the check of the internal pressure and gas composition. The most distant parts of drainage ribs on the degasification system are equipped with similar check-points.

The analyses of gas flow and composition on completed degasification system confirmed that the vented gas volumes are in range 9 to 36 m^3/hr depending on the changes of barometric pressure. The gas composition was in methane content 55 % vol. and oxygen content 0.6 % vol.

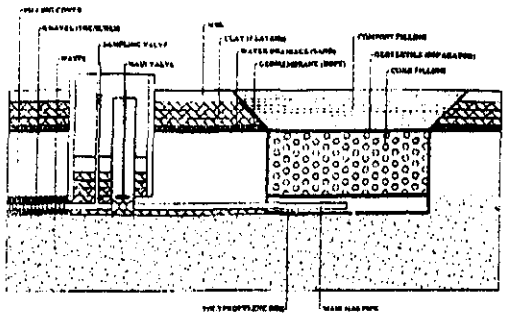

Figure 2 - LFG-biofilter and its connection and check-point

This landfill was covered by triple layer of compacted clay and was on its surface completely recultivated. Since that moment the composition of gas starts to improve. The content of nitrogen was decreased significantly and oxygen content reached the zero value. Methane in internal gas raised simultaneously from 55 % vol. to 61% vol. Just after the filter filling the temperature in the central part reached about 51 °C, but this exothermic processes can be considered as a primary oxidation of the compost biomass and not only as a result of methane oxidation. After consumption of oxygen in internal drainage and in the waste body, the temperature in the filter unit was decreased to 16 °C during the winter period .Since the next spring the more detail testing of landfill was performed and than the rise of internal temperature in filter was observed.

3. RESULTS AND DISCUSSION

The influences of seasonal temperature changes observed by Boerjesson & Svensson (1997) and Maurice & Lagerkvist (1997) was also confirmed. During the summer – autumn period of 1998 the temperature in the depth of 1 m in filtering unit slowly raised, reaching at the end of November 1998 value about 22°C. First testing made at the end of March 1999 shows that internal temperatures in depth 60 to 90 cm were decreasing to about 14°C. This is of course the temperature inside the filtering unit, the same depth out in the landfill in distances 15 m from the unit shows at the same time had temperatures only +2.8°C to +3.6°C (temperatures of covering layers). The distribution of temperatures in the filter and its surroundings shows Figure 3.

The most important results, obtained during the tests on filtering unit are in gas flow and composition. Three days before the main test there were only very negligible fluctuations of barometric pressure (lower than 0.08%) and therefore the internal pressures were corresponding to the stabilised gas flow.

The overpressures on two distant check-points were +20 resp.+28 Pa. the overpressure in front of filtering unit was + 36 Pa. Low values of over pressures confirm good permeability of whole system and filtering unit itself.

Analyses of gas sampled from those check-points confirm the status of anaerobic conditions in the landfill (see Table 1).
Over the filter surface were everytime found the methane concentrations only lower than 0.1% vol.

Nevertheless, the flow of gas upwards can be followed with the highest consumption of

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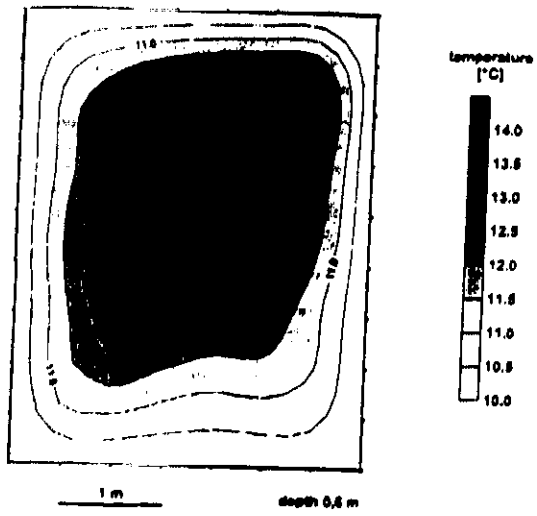

Figure 3 - Temperature distribution in biofilter

Table 1 - LFG composition in drainage system

Sample	gas composition [vol. %]			
	CH_4	CO_2	O_2	N_2
Check-point - west	63.2	24.5	0.0	12.3
Check-point - east	62.8	23.5	0.0	13.7
Filter 1 (N)	65.1	23.9	0.0	11.0
Filter 2 (S)	58.1	25.8	0.0	16.1

methane between 40 and 20 cm of filter depth. The processes of methane oxidation can be described on contour maps of methane and oxygen concentrations in various depths (Figure 4 and Figure 5). Remaining methane escaping from the filter surface was measured using flux-box method. Even of the contours of local migration velocities (Figure 6) are not quite identical with the distribution of methane concentrations, there can be confirmed a distinct similarities, with main stream of gas in the central part of filter.

The contour maps are for simplification showed only for 3 resp. 2 various depths, the mean profiles of methane and oxygen concentrations and mean profile of temperature across the depths from 0 to 60 cm are presented on Figure 7. (The atmospheric temperature at the time of test was -1 to +5.9°C)

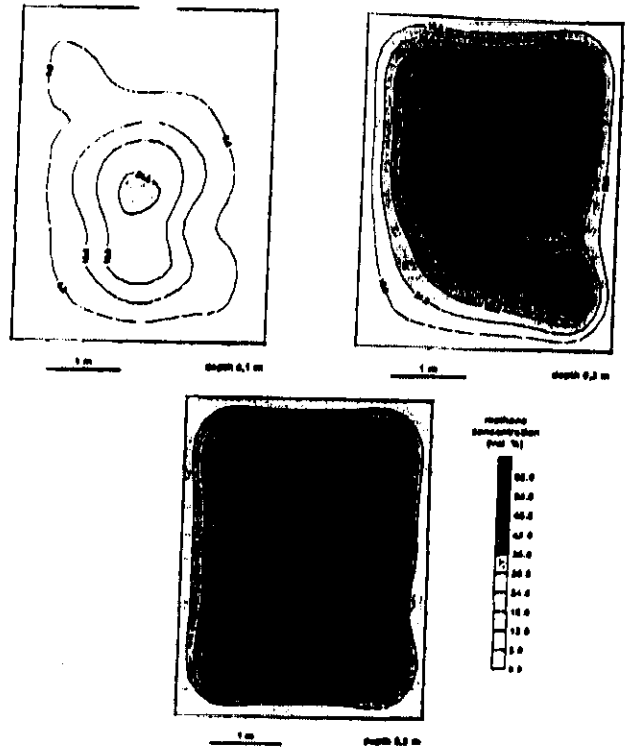

Figure 4 - Methane concentration map in biofilter (depths 0,1 - 0,3 - 0,8 m)

The rapid decrease of methane content in gas during its transfer through the filter is accompanied by distinctly higher temperature inside the unit and confirms the successive level of gas mitigation. Over the filter there are no the smallest traces of typical smell of landfill gas, even if its characteristic and intensive odour can be immediately recognized after opening gas sampling valves. Gas of course can not be ignited anywhere on the surface of the filter. The tested unit treats more than 90 % of all methane produced in the landfill with specific filter loading about 1.1 to 2.5 $m^3/m^3.hr$.

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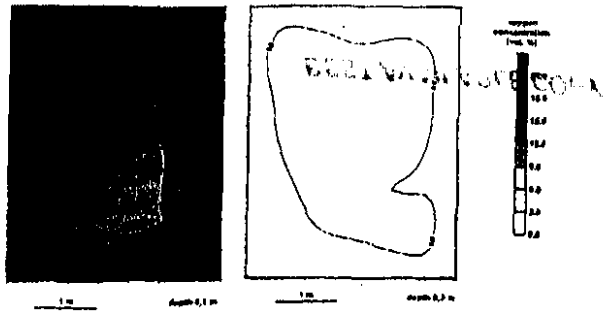

Figure 5 - Oxygen concentration map in biofilter (depths 0,1 - 0,3 m) (0,6 m depth is completely oxygen-free)

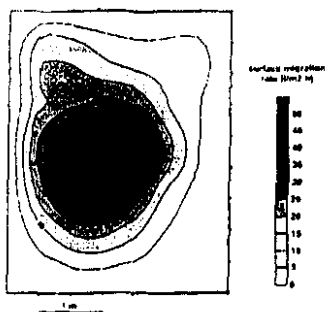

Figure 6 - Surface methane migration velocities on biofilter

The system of landfill gas biofiltration designed as a passive one needs no regular daily maintenance. The testing of gas overpressures inside the drainage can inform the operator about the situation, when filtration layers will show decreased permeability. For such a case we suppose to change the upper (compost) part of the filter and to change the separating geotextile too with a frequency about one times per 3 - 4 years.

4. CONCLUSIONS

Landfill gas escaping from old landfills can be mitigated by the biofiltration in passive venting systems. This method is much cheaper than active gas extraction and incineration and is advantageous especially for smaller and old landfills.

Passive venting systems need neither electricity, nor the frequent personal control and maintenance. Vented gas is free of odour and is carrying only negligible volumes of remaining

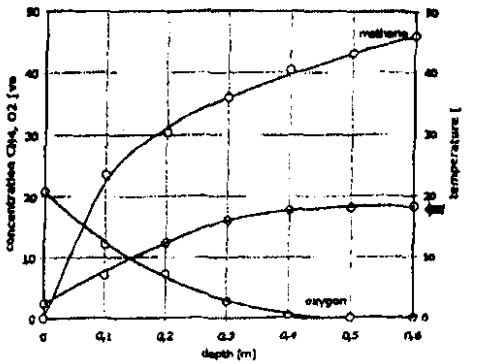

Figure 7 - Methan, oxygen and temperature profiles of biofilter across the depths from 0,0 to 0,6 m

methane. Application of biofiltration is keeping the internal structures of landfill in anaerobi conditions and excludes any danger of fire or gas explosion. Unit of biofilter is generally saft even if the activities of unauthorized persons can not be excluded. Implementation of filter unit into the remediated environment of *landfill is simple and acceptable.*

ACKNOWLEDGEMENTS

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Section XIII.

Microbial Oxidation of Methane from Landfills

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MICROBIAL OXIDATION OF METHANE FROM LANDFILLS IN BIOFILTERS

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SUMMARY: Since the quality and quantity of landfill gas gradually decreases with time, an alternative method to flaring the gas will be necessary at a certain stage, because the gas flow rate or the methane content is too low. Biofiltration is a process to degrade methane at low costs and energy consumption. The principles of microbial methane degradation differ from those of classical applications of biofiltration, like odor treatment, so basic data for dimensioning and operation must be worked out. The first results in a research project were obtained from a bench scale plant of two 12 l compost biofilters, which degraded about 10-25 g/m³h, in one case up to 53 g/m³h methane at an inlet concentration of 1.7 % by volume. Inoculation of one biofilter with methanotrophic bacteria showed no effect. The methane degradation is highly temperature depending; a temperature decrease from 29 °C to 24 °C caused a 50 % lower degradation rate. In a pilot plant, further investigations with real landfill gas shall be carried out in order to obtain an efficient and stable standard method for methane degradation.

1. INTRODUCTION

The gas production of landfills decreases over the years, so that one day the thermal utilization of the methane or the combustion in a flare are not possible any more. This is caused either by a poor gas quality (CH_4-content < 30%) or a too low gas flow rate (<30 m³/h). In those cases, the landfill gas usually is emitted into the environment and acts as a greenhouse gas.

To dispose of the landfill gas, natural gas can be added to enable the combustion in a flare. Alternatively, the treatment in a biofilter is [illegible] suitable to widely reduce the methane emissions. The main objective is to [illegible] on the atmosphere since the global warming potential of methane is 26 [illegible] of carbon dioxide (IPCC 1994). Further more, halogenated trace gases [illegible] as well as odorous substances shall be degraded simultaneously in the biofilter. [illegible] filters are mainly used to avoid odor nuisance and degrade organic pollutants.

The emission of greenhouse gases from landfills, [illegible] methane or carbon dioxide, is not regulated by any law or directives yet. In case of methane, only the danger of explosions must be taken into account. So, to dispose of the nonusable methane, the landfill gas usually is diluted with ambient air and then released into the atmosphere. In order to reduce the greenhouse effect, this practice cannot be tolerated any more.

In a co-operating research project supported by the German Federal Ministry of Education and Research (BMBF, see Acknowledgements) the microbial oxidation of methane from gases

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and odors in biofilters is investigated. Two principles of gas venting are examined in two separate projects:

- Active venting and treatment of the landfill gas in a closed biofilter system (Technical University of Hamburg-Harburg)
- Passive venting through an open bed biofilter embedded in the landfill covering (University of Hamburg)

To achieve a transfer from experimental scale into industrial standard, the projects are run in co-operation with the company Wessel-Umwelttechnik (Hamburg, Germany). The main objectives of the projects are the following:

- Determination of basic dimensioning data for construction of biofilters for landfill gas treatment
- Verification of a reliable and efficient applicability of the methods
- Minimization of the labor cost for operation and control
- Cost benefit analysis

In this paper, mainly the microbial methane oxidation in a closed biofilter is described. Both bench scale and pilot scale experiments are carried out to achieve a system which can be applied to landfills with an active venting system.

2. FUNDAMENTALS

2.1 Microbial methane oxidation

Methanotrophic microorganisms use methane as their only energy and carbon source and are able to completely degrade methane into carbon dioxide and water (Dalton, 1980; Haber et al., 1983). In nature, they can be found throughout (Heyer, 1984), being particularly common in soils or marine sediments in which both oxygen and methane occur (Jones and Nedwell, 1993; Boeckx and Cleemput, 1996).

The microbial oxidation of methane occurs stepwise via methanol, formaldehyde and formic acid to carbon dioxide (Hanson and Hanson, 1996). In this process, biomass is produced from formaldehyde. There are two main pathways of carbon assimilation by methanotrophic bacteria, which split the bacteria into two groups, called „Type I" (ribulose-monophasphate-pathway) and „Type II" (serine-pathway) (Green, 1992).

The ambient parameters for microbial methane oxidation, which were investigated by numerous authors, are

- Oxygen demand: At oxygen concentrations above 1%, no effect on the degradation rate was observed (Bender, 1994).
- Temperature: The temperature range, in which methanotrophic bacteria are active, is from 10 °C to 45 °C. The activity is strongly dependent on the temperature. The maximum was found at about 30°C (Bender, 1994; Whalen et al., 1990; Boeckx and Cleemput, 1996; Figueroa, 1993).
- Moisture content: The optimum moisture content depends on the kind of biofilter material. It ranges from 30-70 % of the water holding capacity, which is clearly lower than the optimum for odor and trace gas treatment. (Whalen et al., 1990; Bender and Conrad, 1995; Boeckx and Cleemput, 1996; Figueroa, 1993).
- pH-value: neutral or slightly acidic (Bender and Conrad, 1995).

2.2 Microbial oxidation of odors and trace gases

The microbial oxidation of odorous substances is used for odor treatment in many types of exhaust gases. Mainly biofilters with an organic filter material are used to degrade those substances. Bardtke and Fischer (1986) and Sabo (1991) investigated biofiltration of landfill gas for odor control, where the odor was caused mainly by hydrogen sulfide. This method can be considered as well established.

Halogenated hydrocarbons can also be degraded microbially, partly even under anaerobic conditions (Deipser and Stegmann, 1997a,b). The utilization of biofilters for the degradation of chlorinated hydrocarbons is described by Jäger (1996) and Kobelt (1996).

2.3 Kinetics

A biofilter can be considered a fixed bed reactor. The over-all reaction rate can be calculated from experimental data with the concentrations at the input and output, the volume of the reactor, and the flow rate using Equation 1.

$$r = (c_{in} - c_{out}) \cdot \frac{\dot{V}}{V} \qquad (1)$$

r	= reaction rate	[mg/m³h]
c_{in}	= inlet concentration	[mg/m³]
c_{out}	= outlet concentration	[mg/m³]
$\dot{V}$	= flow rate	[m³/h]
V	= biofilter volume	[m³]

The reaction rate can also be expressed in dependence on the order of reaction by a term consisting of the medium concentration and one or more coefficients. The order of the reaction depends on the kind of application. For many microbial processes, the order of the reaction varies from "1" at lower concentrations to "0" at higher concentrations, which can be described by Equation 2.

$$r = \frac{k_1 \cdot c_m}{1 + k_2 \cdot c_m} \qquad (2)$$

c_m	= medium concentration	[mg/m³]	$c_m = \frac{c_{in} - c_{out}}{\ln \frac{c_{in}}{c_{out}}}$
k_1	= coefficient 1	[h⁻¹]	
k_2	= coefficient 2	[m³/mg]	

The order of reaction must be elaborated iteratively by comparing the experimental data with the assumed order. Then the coefficients (k_1 and k_2 in Equation 2) can be determined graphically or numerically.

By comparing Equation 1 and 2 and using the coefficients found by experiments, the necessary volume of the reactor (=biofilter volume) for a certain application can be calculated (Equation 3).

$$V = \frac{\dot{V} \cdot \ln \frac{c_{in}}{c_{out}} + k_2 \cdot (c_{in} - c_{out})}{k_1} \qquad (3)$$

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Table 1. Dimensions of the bench scale biofilter plant — microbial methane oxidation

volume	[m³]	0,012
height	[m]	0,27
diameter	[m]	0,24
flow rate	[m³/h]	0,15
specific flow rate	[m³/m²h]	3,3
	[m³/m³h]	12,3
CH_4-concentration (input)	[% by volume]	0,2 – 1,0
biofilter material		compost

3. EXPERIMENTAL PLANTS

The experiments are carried out in two experimental plants:

- A bench scale plant consisting of biofilters with a volume of about 12 l
- A pilot plant situated on a landfill, consisting of five 1 m³-biofilters

In the bench scale experiments, an artificial air flow containing methane is introduced into several biofilters to investigate a wide field of variations of parameters like raw gas concentration, kind of biofilter material, temperature, moisture content, flow rate, etc. The dimensions of the biofilters are listed in Table 1.

The pilot plant is still under construction and will be situated on a closed landfill. Thus, the biofilters will be loaded with real landfill gas containing numerous trace substances (hydrocarbons, halogenated hydrocarbons, and others) as well as odorous compounds (e.g. hydrogen sulfide). A very important subject is the dependence of the methane degradation on the temperature (see Chapter 4).

Figure 1 shows a scheme of the pilot plant. It consists of five parallel biofilter sections, each being divided into three levels. Different materials can be tested simultaneously with the same raw gas quality. At the inlet, the landfill gas is diluted with ambient air in order to add oxygen and to obtain a methane concentration lower than the lower explosion limit (< 5 %CH_4).

The concentration of methane, oxygen, and carbon dioxide will be measured continuously at each measuring point. To determine the odor and trace gas concentrations, samples will be taken weekly and analyzed in the laboratory.

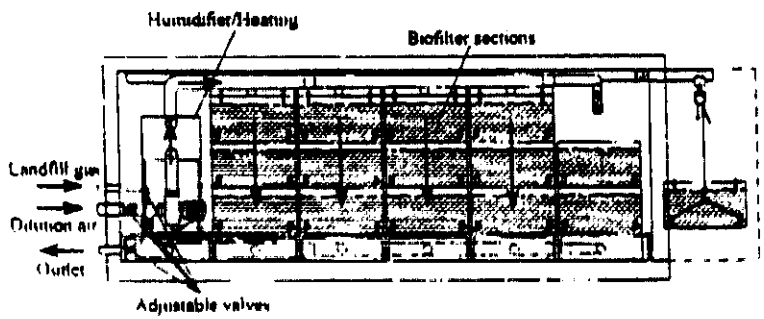

Figure 1. Biofilter pilot plant for landfill gas treatment

4. RESULTS AND DISCUSSION

In the first experiments with the bench scale plant, two compost biofilters were run in parallel with a gas flow of 150 l/h each. The raw gas concentration varied between 2 and 12 gCH_4/m³. Degradation rates up to 25 gCH_4/m³ were measured (Figure 2). The biofilters were emptied, the material was melted and refilled into the biofilters. Then the degradation rate increased slowly up to 53 gCH_4/m³ (raw gas concentration: 12 gCH_4/m³), a value that exceeds the highest degradation rates published before (Figuerna, 1996).

The degradation rates were significantly dependent on the temperature. The rates measured at 29 °C were twice as high as at 24 °C (Figure 2). The temperature dependence can cause problems in outdoor plants during the winter, because the microbial activity will be strongly decreased and maybe reach zero at low temperatures. Heating of the biofilter can solve the problem, but it means an immense increase of energy consumption and therewith higher costs and secondary emissions of greenhouse gases, relativizing the benefit of the methane degradation. This problem will be severely investigated during the pilot experiments under real boundary conditions. It is necessary to minimize the energy consumption by installing an efficient insulation and a partial recirculation of the gas flow. Furthermore the lower temperature range with a still satisfactory efficiency must be elaborated.

One of the two compost biofilters was inoculated with methanotrophic bacteria (*Methylosinus trichosporium* H6). However, no difference in degradation rate between the two biofilters could be detected. Two months after the inoculation, the cell concentrations were measured by most probable number countings. Between $2*10^{10}$ and $2*10^{11}$ cells/g were counted in each biofilter, which is a very high value. So, inoculation of the compost had no effect on the degradation rate. Obviously, methanotrophic bacteria had already been in the compost and were multiplied when methane was introduced into the biofilters. For technical reasons it could not be determined, if the inoculation accelerated the increase of bacteria and therewith decreased the adaptation time, so this might be investigated in the future. Though it seems not necessary to inoculate compost biofilters, it might be reasonable to inoculate other filter materials in which no methanotrophic bacteria can be expected.

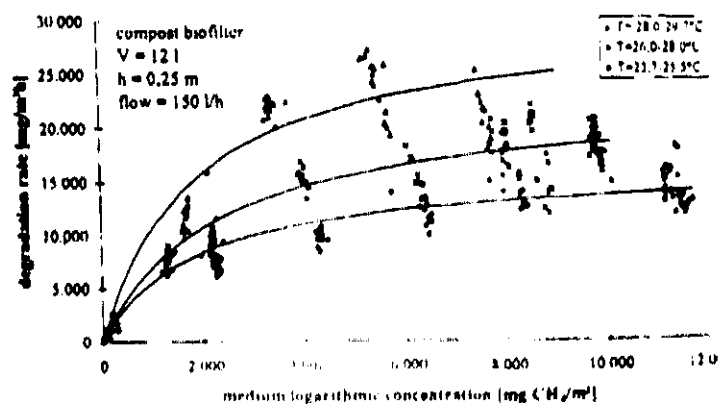

Figure 2. Degradation rate of methane in a bench scale biofilter at three temperature ranges

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