NSW GOVERNMENT

Environment,
Climate Change
& Water

Handbook for the design, construction, operation, monitoring and maintenance of a passive landfill gas drainage and biofiltration system

Disclaimer:

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Glossary

AGO	Australian Greenhouse Office
CORE	Centre for Organic Resource Enterprises
$C_4H_8O_2N$	represents Microbial Biomass
CWWT	Centre for Water and Waste Technology
DEC	Department of Environment and Conservation (NSW)
DECC	Department of Environment and Climate Change NSW (formerly the DEC)
DECCW	Department of Environment, Climate Change and Water NSW (formerly the DECC)
EPA	Environment Protection Authority
EPRD	Environment Protection and Regulation Division (of the NSW DECCW) (formerly the NSW EPA)
IPCC	Intergovernmental Panel on Climate Change
MSW	Municipal Solid Waste
NSW	New South Wales
POEO	Protection of the Environment Operations (Act)
RuMP	Ribulose Monophosphate Pathway
SPD	Sustainability Programs Division (of the NSW DECCW)
TDR	Time Domain Reflectometry
UNSW	University of New South Wales
VOCs	Volatile Organic Compounds
WMAA	Waste Management Association of Australia

Executive Summary

Greenhouse gas emissions and their impact on the climate are increasingly becoming a matter of concern. Whilst emissions from waste management activities in Australia are quite small compared to other sources, emissions from landfills comprise approximately 75% of the total emissions from waste management activities, and equate to approximately 2.0% of Australia's total anthropogenic greenhouse gas emissions (Australian Government, 2008). The Australian Greenhouse Office (2007) reported that the collection and treatment of landfill gas in Australia has increased steadily since 1990 and in 2005 amounted to approximately 17% of total landfill gas generation. One reason for the low level of collection and treatment of landfill gas is the lack of cost effective methods for capturing and treating landfill gas at the many small to medium sized landfills in Australia.

Microbial methane oxidation has attracted significant interest as a process for treating landfill methane and a substantial amount of research effort has been devoted to this topic in recent years, both locally and internationally. This includes a long-term field scale trial undertaken in Bankstown, NSW, which tested a number of passive gas drainage and biofiltration systems and was funded by the Department of Environment and Climate Change NSW (DECC) (see reports by University of NSW and GHD, 2006 and 2008). Two other passive gas drainage and biofiltration trials have also been undertaken by the University of NSW at Horsley Park, NSW (see CWWT 2006 and 2008, and Dever, 2008). These trials have shown that a passive gas drainage and biofiltration system can effectively capture and treat landfill gas, achieving methane oxidation rates greater than 90%. The results of the trials have also shown that the microbial methane oxidation process is dependent on a range of factors including the landfill gas loading, local climatic conditions and their effect on the temperature and moisture content of the biofilter media, and the characteristics of the biofilter media.

There are a number of approaches to using passive landfill gas drainage and biofiltration as a means of reducing landfill methane emissions. These include:

- installing a temporary passive gas drainage and biofiltration system, which is used to reduce landfill methane emissions from inactive areas during landfilling

- treatment of emissions from landfill gas emission point sources e.g. leachate drainage sumps, temporary or permanent passive landfill gas vents, and other landfill gas emission point sources

- a final passive gas drainage and biofiltration system, which is incorporated in the final capping layer of a landfill

- a passive gas interception and biofiltration trench, which may be used to manage subsurface landfill gas migration

- passive biofilters for treating landfill gas collected via a former active gas extraction system, after landfill gas flows have reduced to an extent that flaring is no longer a practical option.

This handbook provides landfill owners, operators and designers with information to assist with the design, construction, operation, monitoring and maintenance of a passive landfill gas drainage and biofiltration system.

1 Introduction

1.1 General

Greenhouse gas emissions and their impact on the climate are increasingly becoming a matter of concern. Whilst emissions from waste management activities in Australia are quite small compared to other sources, emissions from landfills comprise approximately 75% of the total emissions from waste management activities, and equate to approximately 2.0% of Australia's total anthropogenic greenhouse gas emissions (Australian Government, 2008). The Australian Greenhouse Office (2007) reported that the collection and treatment of landfill gas in Australia has increased steadily since 1990 and in 2005 amounted to approximately 17% of total landfill gas generation. One reason for the low level of collection and treatment of landfill gas is the lack of cost effective methods for capturing and treating landfill gas at the many small to medium sized landfills in Australia.

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1.2 Purpose of this handbook

The purpose of this handbook is to provide landfill owners, operators and designers with information to assist with the design, construction, operation, monitoring and maintenance of a passive landfill gas drainage and biofiltration system. It should be recognised that passive landfill gas drainage and biofiltration systems are new methods for treating landfill gas and the information provided in this handbook is based on the results of research undertaken overseas and the results of a number of trials undertaken in Western Sydney. Consequently knowledge on the design, behaviour and performance of the systems is growing as the systems are implemented.

Specifically, this handbook provides the following:

- background information on:
    - the management of landfill gas in Australia
    - the significance of landfill gas emissions in Australia and internationally
    - microbial methane oxidation
    - approaches to using microbial methane oxidation to reduce the emission of methane from landfill sites.

- a description of a range of concepts that use passive drainage and biofiltration as a method for reducing landfill methane emissions

- a discussion of the factors that affect the behaviour and performance of passive gas drainage and biofiltration systems

- a description of the recommended process for evaluating and designing a passive gas drainage and biofiltration system

- recommendations for the design, construction, operation, monitoring and maintenance of a passive landfill gas drainage and biofiltration system

- information on the costs of a passive gas drainage and biofiltration system.

Department of Environment, Climate Change and Water NSW

2 Background

2.1 Management of landfill gas in Australia

2.1.1 Current measures for managing landfill gas

There are currently a range of methods that are commonly used to manage landfill gas generation and emissions in Australia. These include:

- Placement of the landfilled waste within / on a low permeability barrier layer (landfill lining system), which primarily acts to prevent migration of leachate from the landfilled waste, but also prevents subsurface migration of landfill gas.

- Covering of the landfilled waste (during landfilling) with a layer of low permeability soil or other suitable materials, and capping the landfilled waste with a low permeability final cover layer, once landfilling has been completed to:

    - reduce the infiltration of rainfall (into the landfilled waste), thus minimising the moisture content of the landfilled waste and consequent rate of landfill gas generation

    - contain landfill gas within the landfilled waste, thus reducing emissions from the surface of the landfilled waste

    - management of surface water runoff at the site in a manner that reduces the infiltration of stormwater into the landfilled waste thus minimising the rate of landfill gas generation.

Passive drainage and venting of the landfill gas to the atmosphere. Typically, such systems comprise a network of drains constructed within the landfilled waste, under the final capping / cover layer, which direct landfill gas to a selected point (s) for discharge to the atmosphere. Generally the drains comprise slotted plastic pipe placed within coarse aggregate. The systems can also include gas interception trenches and vertical barrier layers / walls installed around the perimeter of the landfilled waste that act to prevent subsurface migration of gas from the landfilled waste.

Active extraction and flaring of landfill gas. Typically, such systems incorporate a network of vertical gas extraction wells or horizontal gas extraction trenches installed in the landfilled waste, under the final capping / covering layer. Landfill gas is actively extracted from the landfilled waste using fans and directed to a flare where the landfill gas / methane is combusted (thermally oxidised). Traditionally such systems have been installed after landfilling at the site has ceased, however, at larger landfill sites these systems are now being installed progressively, soon after landfilling has commenced, to increase the capture of landfill gas and reduce landfill gas emissions.

Active extraction of landfill gas and energy recovery. Typically, such systems include an active extraction system as described in the previous paragraph, with the collected gas being used directly in an industrial boiler or furnace, or being used on site as fuel in an electricity generation plant. Such systems are generally only commercially viable in Australia if there is a potential user of the landfill gas near the landfill site and / or the landfill is large (typically receiving more than 100,000 tonnes per year for a period of at least 10 years) (Falzon, 1998). A general rule of thumb is that a landfill needs to contain at least 1 million tonnes of mixed putrescible solid waste, placed within a period of 10 years or less, have a depth of at least 10 m, and generate more than 600 $m^3.hr^{-1}$ of landfill gas for a period of 10 to 15 years to be commercially viable for electricity generation (Falzon, 1998). This will provide enough methane to produce 1 MW of electricity, which is typically the smallest commercially viable generating unit in Australia.

In 2005 the Waste Management Association of Australia (National Landfill Division) undertook a survey of active landfill sites in Australia (WMAA, 2005). The results of the survey are summarised in Table 1 and show the following:

- less than 40 – 45% of large landfills (receiving > 100,000 tonnes of waste per year) have active landfill gas extraction and flaring and / or energy recovery

- less than 6% of small to medium landfills (receiving < 50,000 tonnes of waste per year) have active gas extraction and flaring or energy recovery.

Table 1: Summary of landfill gas management practices at Australian landfill sites in 2005 (from WMAA, 2005)

Landfill size (tonnes of waste landfilled per year)	Management system / practice			
	Odour control	Landfill gas collection	Landfill gas flaring	Energy recovery
> 200,000	60%	45%	40%	45%
100,000–200,000	56%	44%	31%	25%
50,000–100,000	48%	33%	29%	0%
25,000–50,000	39%	14%	6%	3%
10,000–25,000	31%	3%	0%	0%
< 10,000	13%	0%	1%	2%

Overall the results of the survey indicate that most landfill sites in Australia do not capture and treat landfill gas. The gas (and methane) simply discharges to the atmosphere untreated. Reasons for the lack of landfill gas collection and treatment measures include:

- Currently, in most states of Australia, landfill gas is permitted to be discharged to the atmosphere untreated. There are no regulations requiring the capture and treatment of landfill gas, unless the landfill gas is causing off site odour impacts, the landfill gas is migrating off site, or the landfill gas is presenting a hazard (due to its flammability), on site or offsite.

- Landfill gas extraction and energy recovery, including electricity generation, is only commercially viable at large landfill sites (typically landfills receiving > 100,000 tonnes of waste per year), and this is reflected in the data shown in Table 1.

- The cost of active extraction and flaring of landfill gas can be high (both capital and operating costs), particularly when there is no income stream i.e. after the landfill has ceased accepting waste.

2.1.2 Effectiveness of current management measures

As stated in Section 2.1.1 only a small proportion of landfills in Australia actively collect and treat landfill gas. In addition, traditionally, landfill gas extraction and flaring / energy recovery did not occur until after landfilling had ceased. Such an approach is not very effective as it ignores landfill gas generation during landfilling, which can be significant. Figure 1 shows a typical landfill gas generation curve for a landfill receiving mixed solid waste (generated using the US EPA's LandGEM model (US EPA, 2005)). The results of the modelling show that approximately 30% of total landfill gas generation can occur prior to landfilling ceasing. 50% of landfill gas generation occurs during the first 30 years after landfill closure. And 20% of landfill gas generation occurs 30 to 100 years after landfilling ceases. Thus if active gas extraction is only undertaken for a 30 year

period after closure of the landfill only 50% of the landfill gas will be captured, at best (not allowing for the collection efficiency of the gas collection system).
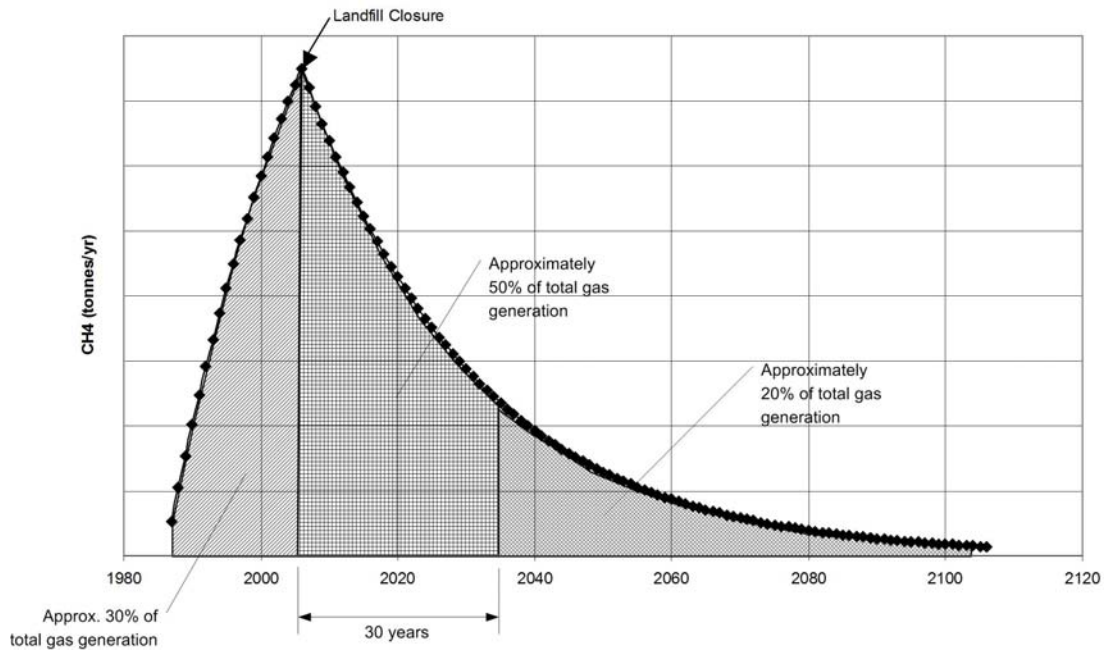
Figure 1: Typical landfill gas generation curve (generated using the US EPA's LandGEM model)

Recently, a study was undertaken at 3 French landfill sites to determine the efficiency of conventional gas collection systems (Spokas et al, 2006). This study endeavoured to determine the total methane balance of the landfills, which used different landfill configurations, including temporary clay covers, final clay covers, geosynthetic clay covers, geomembrane composite landfill covers, and landfill cells with and without an active gas collection systems. The results were used by the French Environment Agency (ADEME) to set default landfill gas recovery values for various landfill situations. These were:

- 35% gas recovery for an operating landfill cell with an active landfill gas collection system

- 65% gas recovery for a temporary covered landfill cell with an active landfill gas collection system

- 85% gas recovery for a landfill cell with compacted clay final cover and active landfill gas collection system

- 90% gas recovery for a landfill cell with a geomembrane final cover and active landfill gas collection system.

Huber-Humer et al (2008) applied the above recovery rates to typical landfill gas generation data to illustrate the overall landfill gas recovery rates for conventional active gas extraction systems – see Figure 2. The figure shows that a significant proportion of the total landfill gas generated is not captured by conventional active gas extraction and treatment technologies and practices (approximately 40 – 50%).
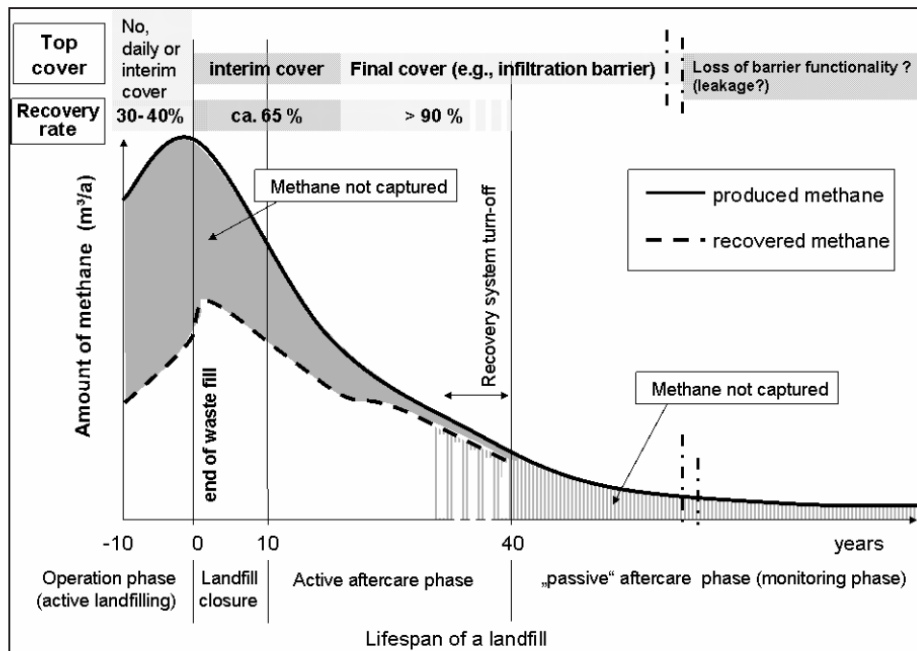
**Figure 2: Effectiveness of conventional active landfill gas extraction systems
(from Huber-Humer et al, 2008)**

According to the Australian Greenhouse Office (2007) the collection and treatment of landfill gas in Australia has increased steadily since the early 1990s (see Figure 3) and in 2005 amounted to approximately 17% of total landfill gas generation, which is quite low but consistent with the lack of active gas collection and treatment in Australia, as identified by the WMAA National Landfill Survey (see Table 1). The data is also consistent with the traditional approach to landfill gas management in Australia, which generally involves not undertaking any active management measures until after landfilling has ceased (see Section 2.1.1).
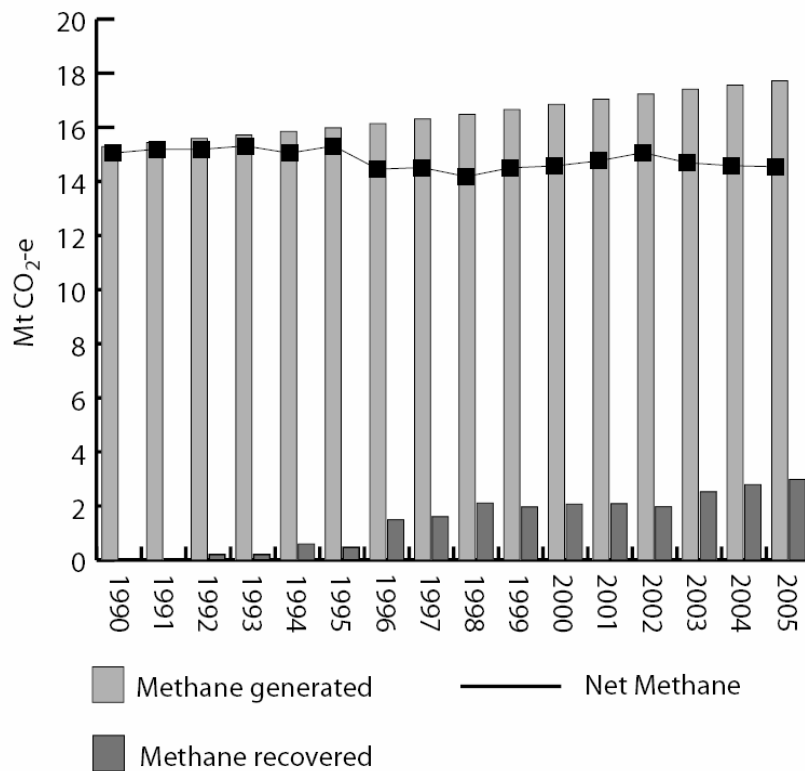
Figure 3: Estimated landfill methane generation and recovery in Australia, 1990 – 2005 (from Australian Government, 2007)

2.1.3   Summary of problems with current practices

In summary, there are a number of problems with current landfill gas management practices in Australia that are contributing to high landfill gas emissions. These include:

- landfill gas collection and treatment system have not been implemented at all large landfill sites (< 40 – 45% of landfills have active gas collection and treatment)

- no / limited landfill gas collection and treatment at small to moderate sized landfill sites (receiving < 100,000 tonnes of waste per year)

- no / limited landfill gas emission measures during landfilling (all landfill sites)

- no / limited landfill gas emission measures at old / closed landfill sites

- no / limited landfill gas emission measures 30 years after landfilling has ceased (all landfill sites).

2.2   Significance of landfill gas emissions

2.2.1   General

One of the primary components of concern in landfill gas is methane. Methane typically comprises a major proportion of landfill gas (45 – 60% vol/vol) (Tchobanoglous et al, 1993), which presents a hazard in relation to explosion potential, and is a significant contributor to green house gas emissions in Australia and elsewhere in the world. According to the Intergovernmental Panel on

Climate Change (IPCC) (2007) methane has 25 times the global warming potential of carbon dioxide over a 100 year period.

2.2.2   Internationally

Data presented by the Intergovernmental Panel on Climate Change (IPCC) (2001) indicates that methane from landfills makes up approximately 10% of global anthropogenic methane emissions (emissions created by human activities).

The IPCC (2007) reported that methane is one of four long lived greenhouse gases that is significantly contributing to global warming. The atmospheric concentration of methane has risen from approximately 700 ppb in 1750 to 1774 ppb in 2005 (see Figure 4), and this increase can be attributed to human activities.
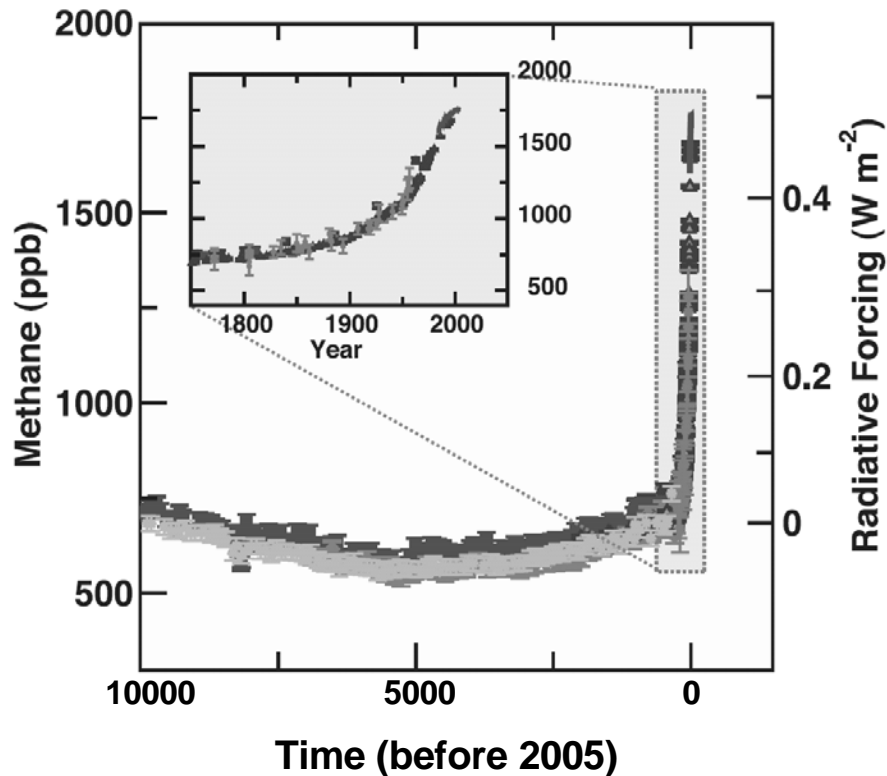
Figure 4: Atmospheric Concentrations of Methane over the last 10,000 years (large panel) and since 1750 (inset). Measurements are from ice cores and atmospheric samples. From IPCC 2007.

The increase in atmospheric methane concentrations is contributing significantly to global warming, as shown in Figure 5, which shows the estimated contribution of various agents and mechanisms to average global warming and cooling in 2005 (relative to 1750). Methane is contributing approximately 16% of the positive radiative forcing (warming).
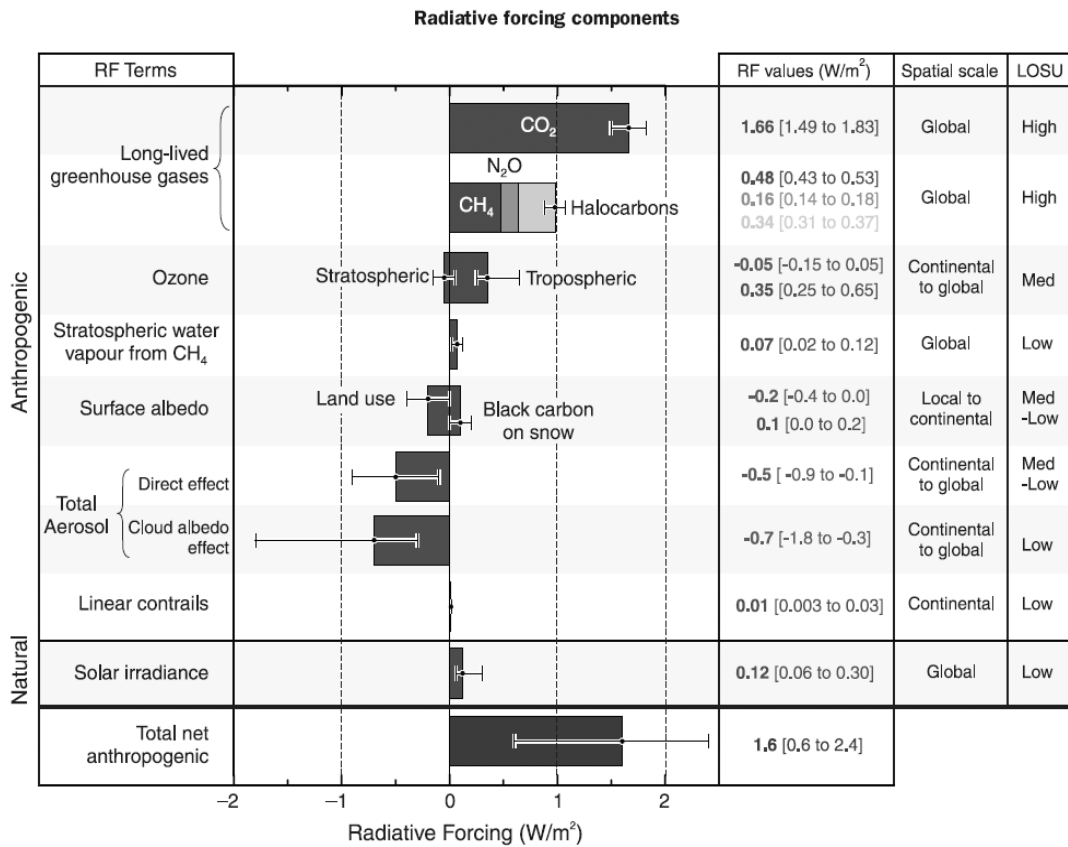
Note: LOSU – Level of Scientific Understanding

Figure 5: Global average radiative forcing in 2005 (relative to 1750)(from IPCC, 2007)

Table 2 presents a summary of greenhouse gas emissions from the waste sector in Australia in 1990 and in 2005 (Australian Government, 2008). The data shows that in 2005 emissions from landfills amounted to 11.9 Mt CO_2-e, which represented approximately 2.0% of Australia's net anthropogenic greenhouse gas emissions. The data also shows that emissions have reduced by 12.6% since 1990. But there is substantial scope to further reduce emissions from landfills due to the low level of landfill gas collection and treatment in Australia, and the lack of other landfill gas treatment measures.

Table 2: Greenhouse gas emissions from the Australian waste sector, 1990 – 2005 (Mt CO2-e) (from Australian Government, 2008)

Activity	1990	2005	Change (%)
Solid waste disposal on land	13.7	11.9	-13.1
Wastewater	3.8	3.4	-10.5
Waste incineration	0.02	0.03	33.7
Total Waste Emissions	17.5	15.3	-12.6
Total Emissions	551.9	584.7	+5.9
% of Total Emissions	3.2	2.6	

2.3   Microbial methane oxidation

2.3.1   General

Microbial oxidation of methane has attracted interest as a process capable of treating methane at landfill sites where current conventional gas management methods are not suitable, and / or as a means of further reducing landfill gas emissions. The following section describes the microbial methane oxidation process and the factors that affect the process. The subsequent section (Section 2.4) describes a range of approaches to using microbial methane oxidation as a means of treating landfill gas.

2.3.2   Methanotrophic bacteria

Methanotrophic microorganisms are able to utilise methane in the presence of oxygen as their only energy and carbon source and are able to convert the methane to energy, carbon dioxide, water and cell material. Methanotrophs and the microbial methane oxidation process has been investigated and reported by many including Whittenbury et al. (1970), Mancinelli (1995), and Hanson and Hanson (1996).

Methanotrophs are a subset of a larger group of bacteria known as methylotrophs, which utilize a variety of different one-carbon compounds including methane, methanol, methylated amines, halomethanes, and methylated compounds containing sulphur (Hanson and Hanson 1996). According to Mancinelli (1995) the majority of methanotrophs are gram-negative, microaerophilic rods, vibrios, or cocci, which form a differentiated exospore or cyst that is desiccation and heat resistant, and can use organic nitrogen compounds, ammonia, nitrate and nitrite as nitrogen sources. Whilst most methanotrophs are strict aerobes, they are microaerophilic, preferring oxygen levels lower than atmospheric levels.

Hanson and Hanson (1996) report that while most methanotrophs are generally mesophilic, some methanotrophs are thermophilic and can grow at temperatures greater than 45°C.

According to Whittenbury et al. (1970) and Hanson and Hanson (1996), methanotrophs are found widely throughout the environment, in both aquatic and terrestrial ecosystems, wherever stable supplies of methane and oxygen are present. Commonly the methanotrophs occur where methane mixes with atmospheric air, as the methane moves away from the methane source.

2.3.3   Process

In simple terms, methanotrophs are able to utilise methane in the presence of oxygen and convert the methane to energy, carbon dioxide, water and cell material. However, the process is in fact not so simple and involves many intermediate steps and processes. Methanotrophs are divided into two basic groups based on the process they utilise to oxidise methane. Those that use the Ribulose monophosphate pathway (RuMP) are called type I methanotrophs while those that use the Serine pathway are called type II methanotrophs. These pathways have been described in some detail by many including Mancinelli (1995), and Hanson and Hanson (1996). According to Hilger and Humer (2003) the stoichiometric equations for the two pathways can be summarised as below (Note: $C_4H_8O_2N$ represents microbial biomass):

Ribulose monophosphate pathway (RuMP):

$CH_4 + 1.5\ O_2 + 0.118\ NH_4^+ => 0.118(C_4H_8O_2N) + 0.529\ CO_2 + 1.71\ H_2O + 0.118\ H^+$

Serine pathway:

$CH_4 + 1.57\ O_2 + 0.102\ NH_4^+ => 0.102(C_4H_8O_2N) + 0.593\ CO_2 + 1.75\ H_2O + 0.102\ H^+$

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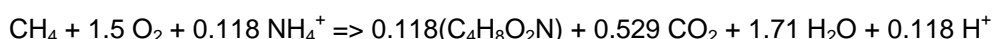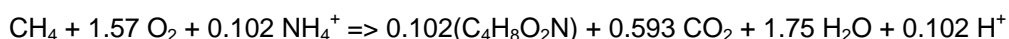
Both pathways commence with the conversion of methane (CH_4) to methanol (CH_3OH), a reaction that is mediated by the methane monooxygenase enzyme (MMO). The methanol is then converted to formaldehyde, which can be used in the electron-transport chain, oxidised to formate, or assimilated by the cell via the RuMP and / or Serine pathway (Mancinelli, 1995).

Methanotrophic bacteria generally possess both dissimilatory and assimilatory pathways of methane oxidation (Mancinelli 1995). In dissimilatory pathways, the methane is oxidised completely to carbon dioxide, producing cellular energy and the carbon dioxide is given off to the surrounding environment. In assimilatory pathways the methane is oxidised and converted to cellular biomass.

Both the (RuMP) and Serine pathways include various reactions that release energy as, initially, methane and then other intermediate carbon compounds are oxidised (Anthony, 1982).

2.3.4   Factors that affect the process

General

Research by a number of researchers (Whalen et al 1990, Jones and Nedwell 1993, Figueora 1993, Bender and Conrad 1995, Kightley et al 1995, Whalen and Reeburgh 1996, Boeckx et al 1996 and 1997, Czepiel et al 1995 and 1996, Börjesson et al 1997 and 2004, Humer and Lechner 1999, 2001, and 2003, Hilger et al 1999, Dammann et al 1999, Gebert et al 2001, 2003, 2005 and 2006, Streese et al 2001, Le Mer and Roger 2001, Reay et al 2001, Hilger and Humer 2003, Streese and Stegmann 2003, Huber-Humer 2004, Schuetz and Kjeldsen 2004, Felske et al 2005, Seghers et al 2005, Haubrichs and Widman 2006, Mor et al 2006, Kettunen et al 2006, and Einola et al 2007) has shown that the methanotrophic methane oxidation process is affected by a number of factors including:

- The supply of methane and oxygen.

- The acidity of the media in which the process is occurring.

- Temperature of the media in which the process is occurring, which may be affected by site conditions e.g. atmospheric temperature, temperature of the gas being treated, rainfall, and the presence / type of vegetation on the media in which the process is occurring, and the exposure of the media to atmospheric conditions.

- Moisture content of the media in which the process is occurring, which may be affected by local climatic conditions e.g. rainfall and evaporation, and the characteristics of the media in which the process is occurring.

- The physical characteristics of the media in which the process is occurring, including porosity, gas conductivity, hydraulic conductivity / drainage and water holding capacity.

- The nature and supply of nutrients, which may affect microbial activity.

- The presence of substances that may inhibit the process including ammonium, nitrite, salt and copper.

- The generation of extracellular polymeric substances (EPS), which may clog the landfill cover layer / biofilter and hinder the methane oxidation process.

These factors are discussed in the following paragraphs.

Methane and oxygen supply

Methane and oxygen are both critical to the microbial methane oxidation process. As stated previously, methanotrophs are commonly found where methane mixes with atmospheric air, as the

methane moves away from the methane source. In such locations there are generally counter gradients of methane and oxygen i.e. near the methane source methane concentrations are high and oxygen concentrations are low, and at distance from the methane source methane concentrations are low and oxygen concentrations are high. An example of this is a landfill cover soil layer i.e. at depth in the soil cover layer, near the landfilled waste, methane concentrations are high whilst oxygen concentrations are low, and near the surface of the soil layer methane concentrations are low and oxygen levels are high (atmospheric). This is important as research shows that the concentration and supply of methane and oxygen affects the microbial methane oxidation process. In general the following principles apply:

- Methane oxidation ($gCH_4.m^{-2}.hr^{-1}$) increases with increasing methane concentrations / loading until a certain point, when the rate of increase begins to declines as the methane load increases, and ultimately the methane oxidation reaches a maximum value.

- Stable 100% methane oxidation until a certain landfill gas / methane loading rate and then reduced methane oxidation (as a % of load) as the methane load is increased.

- Methane oxidation decreases with decreasing oxygen concentrations.

- Oxygen concentrations need to be greater than 0.4 – 0.5% vol/vol to avoid limiting the methane oxidation process.

Acidity

The results of research indicate that methanotrophs prefer fairly neutral conditions and will oxidise methane whilst pH is in the range 5.5 – 8.5.

Temperature

Methanotrophs are generally mesophilic (Hanson and Hanson 1996) and the optimum temperature for methanotrophic methane oxidation has been found to be 25 – 40°C. However, some methanotrophs are thermophilic and can operate at higher temperatures (> 45C). Note, these are temperatures within the soil layer / media in which the methanotrophic activity is occurring, which is affected by the temperature of the landfill gas, atmospheric temperature, the level of methanotrophic activity (as the process is exothermic), and rainfall, which can cool the soil layer / media.

Moisture content

Methane oxidation has been found to occur over a wide range of moisture conditions and it has been found that the characteristics of the media in which the process is occurring is important. Generally, as the moisture content of the media increases the pore space within the media available for gas movement decreases and this affects the transfer of both methane and oxygen to the methanotrophs, which are located in a biofilm on the surface of the solid particles in the media. This occurs because the movement of these gases within the media changes from advection and diffusion through air to diffusion through water, and Whalen et al (1990) report that the diffusion of methane and oxygen through the gas phase is much faster than diffusion through water (10^4 fold faster). Once a soil / media layer becomes saturated the movement of methane and oxygen is substantially reduced as advective flow of gas is prevented and movement within the media only occurs only via diffusion through water within the media.

The optimum moisture content of a soil / media for methanotrophic methane oxidation depends on the physical characteristics of the soil / media in which the activity is occurring. Important parameters include different grain size, porosity, water holding capacity, hydraulic conductivity and gas conductivity, as these characteristics affect:

- the movement of methane through the media

- the diffusion of oxygen into the media (from the atmosphere)

- the infiltration of rainfall into the media

- the drainage of water from the media.

From available research the optimum moisture conditions for a compost biocover / biofilter media typically range from 30 – 100% of the water holding capacity of the media (Huber-Humer 2004). For soils the optimum moisture content typically ranges from 15 – 30% (wt/wt). However, it should be noted that these optimum values are dependent on the characteristics of the media / soil.

At low moisture contents the methanotrophs experience water stress and consequently activity and oxidation rates are reduced. Bender and Conrad (1995) and Boeckx et al (1996) both found substantially reduced / no methane oxidation at low moisture content (at 8% and 5% wt/wt respectively).

Physical characteristics of the media in which the process is occurring

As identified in the previous section, the physical characteristics of the media in which the process is occurring are important as they determine conditions within the media and can affect the methanotrophic methane oxidation process. Important characteristics include soil grain size, porosity, water holding capacity, gas conductivity, hydraulic conductivity / drainage, stability of any organic matter within the media, and structural stability.

Grain size affects porosity, which affects the movement of gas (methane and oxygen) and water within the media, which can affect the methanotrophic methane oxidation process. Generally, methane oxidation rates are higher in coarse textured, porous soils / media.

The water holding capacity of a soil / media is important because the soil / media must have sufficient water for microbial activity to occur, and the difference between water holding capacity and porosity of the media should be sufficient to allow movement of gas (methane and oxygen) within the media when the media is at water holding capacity, and thus allow microbial methane oxidation to proceed.

The stability of organic matter within a soil layer / media affects the availability of oxygen for the methanotrophs i.e. if the organic matter is not stable it may aerobically degrade and consume oxygen, thus competing against the methanotrophs for the available oxygen.

The structural integrity of a soil layer / media and how the media settles / consolidates affects the porosity of the media and consequently gas movement within the media are also important. Ideally, the soil layer / media should not undergo large settlement.

Nature and supply of nutrients

The media in which the methanotrophic methane oxidation process is occurring needs to have sufficient nutrients for the process to occur. The effect of various nutrients has been evaluated by a number of researchers and the following generally applies:

- nitrate and ammonium amendments induced a more rapid onset of methane oxidation, but once the methane oxidation rate had stabilised ammonium can inhibit methane oxidation

- high levels of ammonium strongly inhibits methane oxidation

- nitrate had no inhibitory effect on methane oxidation

- lime addition can enhance methane oxidation in a sandy loam soil

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- organics amendments with a high C/N ratio (wheat and maize straw) stimulated N-immobilization and did not affect methane oxidation

- the addition of organic amendments with low C/N ratio (potato and sugar beet) stimulated N-mineralization, resulting in strong inhibition of methane oxidation

- amending soils / media with an organic fertiliser (compost) is likely to improve methane oxidation compared to soils / media treated with mineral fertiliser

- adding phosphate has no significant effect on the methane oxidation rate.

Presence of substances that may inhibit the process

A number of substances can have an adverse effect on methanotrophic methane oxidation including ammonium (> 14 mg.kg^{-1}), nitrite, salinity (> 6 mS.cm^{-1}) and copper (> 60 mg.kg^{-1}).

Generation of Extracellular Polymeric Substances (EPS)

Some researchers believe that bacteria attach themselves to soil particles using extracellular polymeric substances (EPS), which are self produced, and many take the form of discrete capsules, amorphous slime, or a polymer gel biofilm. Others believe that EPS is excreted to provide protection against unfavourable conditions such as predation, desiccation, and heat. Typically EPS comprises polysaccharides and its production varies depending on the microbial community and environmental conditions.

Methanotrophs are known to produce EPS in both capsule and slime form and typically the EPS generated by methanotrophs comprises sugars and amino acids (Hilger et al 2000). Generally, EPS production increases with increased methane oxidation and can lead to clogging of the soil layer / media in which the process is occurring, which reduces methane oxidation. Consequently, the media in which the process is occurring needs to be highly porous to minimise the effects of EPS production. Alternatively, EPS production can be controlled by maintaining a low methane oxidation rate. Huber-Humer (2005) also suggests that rainfall maybe a factor in full scale field systems as EPS is soluble in water and rainfall may wash (remove) EPS from the soil layer / media.

2.4 Utilising microbial methane oxidation to reduce landfill methane emissions

2.4.1 General

Microbial oxidation of methane in landfill gas has been demonstrated in both laboratory and field studies, and is well documented in the literature (Whalen et al. 1990, Jones and Nedwell, 1993, Figueroa, 1993, Bergman et al, 1993, Kightley et al. 1995, Boeckx et al, 1996, Czepiel et al. 1996, Börjesson and Svensson 1997, 2004, Kjeldsen et al 1997, Haarstad, 1997, DeVisscher et al 1999, Hilger et al 1999, Humer and Lechner 1999, 2001, Schuetz and Kjeldsen, 2001, 2004, Huber-Humer, 2004, Gebert et al, 2001, 2003, 2005, and Abichou et al 2006). Haarstad (1997) concluded that, based upon experimental data, methane oxidation in a landfill cover layer has the potential to be greater than methane production within the landfill, under optimum conditions.

A number of approaches to utilising microbial methane oxidation as a means of reducing landfill methane emissions have been identified and evaluated, including:

- enhanced landfill cover layers and biocovers (temporary and final cover systems) including biotarps

- passive gas drainage and biofiltration systems (temporary and final cover systems) including biowindows

- passive gas drainage and aerated biofiltration systems (temporary and final cover systems)

- active gas extraction and biofiltration systems (temporary and final cover systems).

Table 3 presents a summary of how these approaches may be used to reduce landfill methane emissions. The following sections provide a general description of each of the approaches.

Table 3: Approaches to using microbial methane oxidation to reduce landfill gas emissions

Landfilling phase		
Active landfilling	**Initial 30 year post closure care period**	**Final post closure care period (> 30 years after closure)**
Large landfills		
1. temporary biocover layers and biotarps 2. temporary passive biofilters connected to a passive gas drainage system 3. active gas extraction + biofiltration system	1. a final biocover layer to complement an active gas extraction and treatment system to further reduce landfill gas emissions	1. active gas extraction + biofiltration 2. passive gas drainage and biofiltration system 3. final biocover layer 4. biowindows (old / closed landfills)
Small to medium landfills		
1. temporary biocover layers and biotarps 2. temporary passive biofilters connected to a passive gas drainage system 3. progressive capping + final biocover layer 4. progressive capping and final passive gas drainage and biofiltration system	1. a final biocover layer to complement an active gas extraction and treatment system 2. passive gas drainage and biofiltration system 3. final biocover layer 4. biowindows (old / closed landfills)	1. passive gas drainage and biofiltration system 2. final biocover layer 3. biowindows (old / closed landfills)

2.4.2 Enhanced landfill cover layers, biocover layers and biotarps

During the 1990s a number of researchers investigated and evaluated methane oxidation in landfill cover soils. The focus of much of the research was on identifying and understanding the factors that affected the methane oxidation process and quantifying the rates of oxidation. The research indicated that methane oxidation appeared to be enhanced in media that was porous, had good water holding capacity, was stable, and had a high level of organic matter. This lead research onto methods for improving the rate of methane oxidation in landfill cover layers as a means of reducing landfill methane emissions. Humer and Lechner (1999, 2001) conducted laboratory and field scale experiments that indicated the incorporation a layer of mature and well decomposed compost in a landfill cover layer achieved significantly higher methane oxidation rates than those constructed using natural topsoils or conventional clay landfill cover soils. Humer and Lechner (1999, 2001) also found that the installation of a gravel gas distribution layer under the compost layer (above the landfilled waste) created a more homogeneous loading on the compost cover layer resulting in better overall reduction in methane emissions. In those compost cover layers where a gravel gas distribution layer was not installed, at some locations over the cover layer very high concentrations

of methane were detected (this was not the case where a gravel gas distribution layer was used). Humer and Lechner (2001) suggested that the most effective methane oxidation cover layer should comprise 1.2m of mature compost (sewage sludge compost or municipal solid waste compost) over a 0.5m thick layer of coarse gravel (to act as a gas distribution layer). Subsequently, other researchers have evaluated a range of organic compost materials for use in a 'biocover' layer and various gas distribution layer materials including crushed glass and shredded tyre.

Figure 6 shows a concept of a biocover as proposed by Huber-Humer et al (2008). Note, a range of biocover layer concepts have been proposed including:

Placement of a biocover layer directly over the landfilled waste (as shown in Figure 6);

Placement of a biocover layer over a low permeability barrier layer, which is placed over the landfilled waste and acts to supplement an active landfill gas extraction system; and

Temporary biocover layers that are used as intermediate cover layers during landfilling to reduce landfill methane emissions, or placed over traditional soil intermediate cover layers.
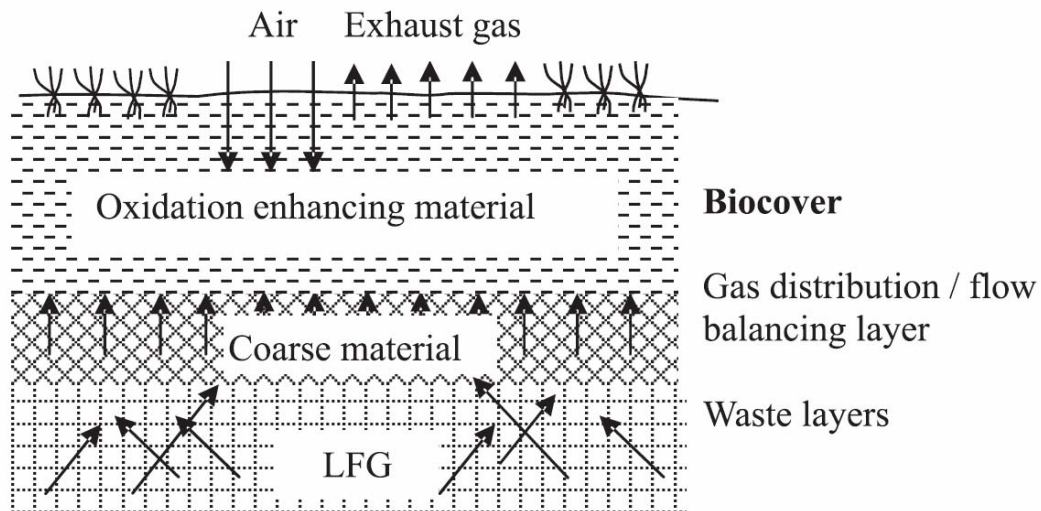
Figure 6: Biocover Concept (from Huber-Humer et al, 2008)

The benefits of a biocover layer as a means of reducing landfill methane emissions include simple construction, no costly low permeability barrier layer (at some sites), very little ongoing operation and maintenance, and low operating costs. However, one significant issue with a biocover layer is the permeable nature of the cover layer. Such a layer could allow infiltration of rainfall into the landfilled waste if no barrier layer is used, and lead to increased leachate generation (and potentially lead to increased groundwater contamination if an appropriate leachate containment and collection system is not in place). Such a permeable landfill cover layer does not comply with current Australian landfill cover design practice, which involves the construction of a low permeability landfill capping layer to minimise rainfall infiltration and landfill gas emissions. To address this issue a number of researchers have investigated combining a capillary barrier layer with a biocover layer as the final capping layer for a landfill. The capillary barrier layer acts as a barrier to rainfall infiltration and acts as the gas distribution layer for the biocover layer. Ettala and Vaisanen (2001) developed a system where the biocover was constructed above a low permeability barrier and was fed by pipework that directed gas from below the barrier layer into the biocover without allowing water / rainfall to infiltrate into the landfill.

Other issues with biocover layers include the lack of control over the process and complexity of monitoring the effectiveness of the biocover layer (Huber-Humer, 2008).

Recently, a group of researchers (Hilger et al 2007) have commenced investigations of a 'biotarp' as a means of reducing methane emissions from the active landfilling area. The concept involves immobilising and fixing methanotrophs onto a suitable layer of material, which is used as a tarpaulin and temporarily placed over the active landfilling area at the end of each working day. At the commencement of filling the next day the biotarp is removed and stored for use again later that day. For further details see Hilger et al (2007) and Huber-Humer et al (2008).

2.4.3   Passive gas drainage and biofiltration systems

A variety of passive gas drainage and biofiltration systems have been proposed and investigated. These include:

- a passive biofilter, constructed within a landfill capping layer, connected to a passive gas drainage system constructed below the landfill capping layer / within the landfilled waste (Straka et al 1999, Gebert et al 2001, 2003, 2005, Park et al 2002, Dever et al 2000, 2003, 2005, 2007, Cabral et al 2007).

- a passive gas interception trench and biofilter (Dever et al, 2005, Swarbrick et al 2005).

- biowindows (Kjeldsen et al 2007).

Other potential approaches include:

- a passive biofilter connected to a former active gas extraction system, once gas flows have fallen to a level where flaring is no longer practical. The biofilter may be installed on or adjacent to the landfilled waste.

- temporary, movable passive biofilters (constructed within a suitable container) connected to a temporary passive landfill gas drainage and venting system, and / or connected to point sources of landfill gas emissions e.g. leachate sumps.

Straka et al (1999) constructed passive landfill gas drainage and biofiltration systems at 4 old landfill sites in the Czech Republic, and one system (where the biofilter was 'countersunk' within the landfill waste) was operated and monitored for more than 2 years. The profile of the countersunk biofilter comprised compost placed over a geotextile barrier, above a coke filling and all contained in a filter box (which received landfill gas flow from a passive gas drainage system). Straka et al (1999) developed and tested several biofilter designs referred to as 'Pile' type (above ground), 'Middle Sunk' type (partly countersunk) and 'Countersunk' type – see Figure 7.

From their testing Straka et al (1999) concluded that a passive landfill gas management system incorporating biofiltration is "much cheaper than active gas extraction and incineration and is advantageous especially for smaller and old landfills". The passive venting system requires no electricity and minimal maintenance and therefore has low operating costs.

Since the work by Straka et al (1999) a number of others have investigated and evaluated passive landfill gas drainage and biofiltration systems including Gebert et al (2001, 2003, 2005, 2006), Park et al (2002, 2003), Dever et al (2003, 2005, 2007), Felske et al (2005), and Cabral et al (2007). Further details of passive gas drainage and biofiltration systems is provided in Section 3.
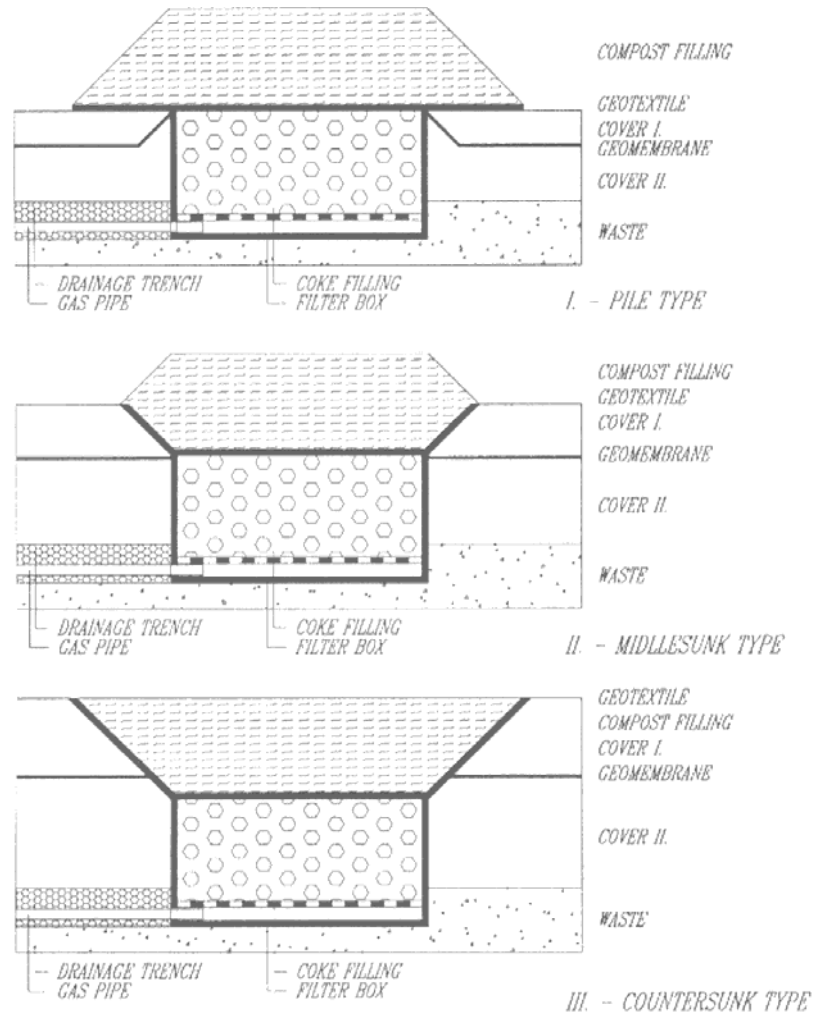
Figure 7: Types of passive biofilters proposed by Straka et al (1999)

Biowindows are a new approach proposed by Kjeldsen et al (2007) for old / existing landfills and are a variation of a passive gas drainage and biofiltration system. It is proposed that biowindows be used at old landfill sites where no gas drainage system exists, and it is impractical, costly, or unnecessary to install a passive landfill gas drainage system. The biowindows are constructed within the existing conventional landfill cover layer as shown in Figure 8 and landfill gas migrates though the landfilled waste (below the landfill capping layer) to the biowindow due to pressure differences and diffusion. Note, the biowindow media is typically compost and consequently has a high permeability compared to the landfill cover layer, and thus landfill gas readily moves through the biowindow to the atmosphere. Kjeldsen et al (2007) are currently assessing the performance and behaviour of a number of biowindows installed at the Fakse Landfill site in Denmark.
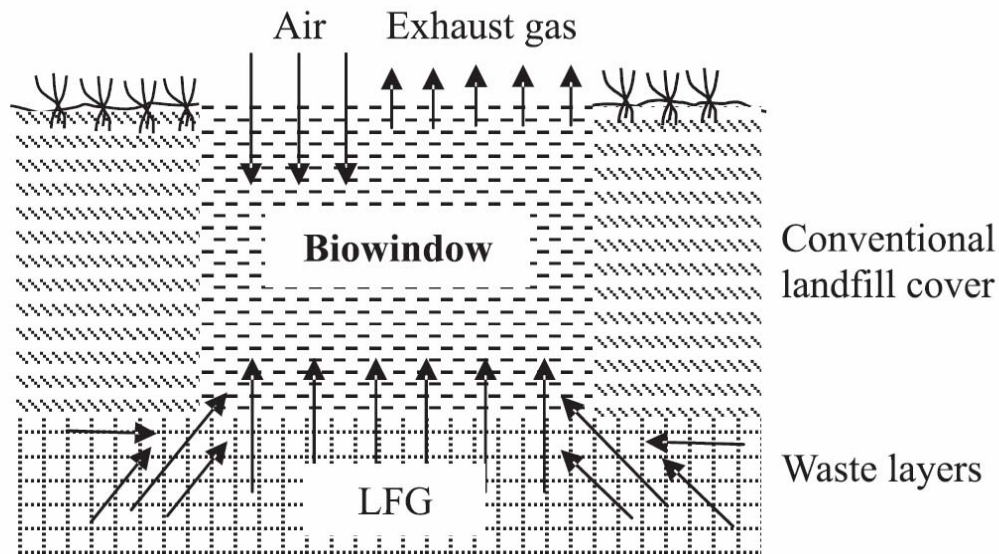
Figure 8: Biowindow Concept (from Huber-Humer et al, 2008)

2.4.4 Aerated passive biofiltration systems

Oxygen is essential for microbial methane oxidation to occur and in a passive landfill gas drainage and biofiltration system the process relies on the diffusion of atmospheric oxygen into the biofilter. However, the higher the flow of landfill gas up through a biofilter the lower the diffusion of atmospheric oxygen into the biofilter, which limits the microbial methane oxidation rate. To test this theory Haubrichs et al (2004 and 2006) tested both a passive biofiltration system and the effect of aerating the biofilter. The testing was undertaken using a laboratory scale biofilter and oxygen was provided throughout the full depth of the biofilter by continuously injecting air into the biofilter. The testing was undertaken for a period of 148 days and the result was a significant increase in the capacity of the biofilter to oxidise methane compared to the passive biofilter (methane oxidation increased from 5.1 $gCH_4.m^{-3}.hr^{-1}$ in the passive biofilter to 28.8 $gCH_4.m^{-3}.hr^{-1}$ when aerated). They concluded that injecting air into the biofilter allows microbial methane oxidation to occur over the full depth of the biofilter, which is not the case in a passive biofilter, where microbial activity is limited to a small zone where oxygen concentrations and supply are suitable. Haubrichs et al (2006) also found that maintaining an oxygen / methane ratio of 2.5 in the biofilter media allowed 100% of the methane to be oxidised. Lowering the oxygen / methane ratio to 2.0 resulted in a reduction in the methane oxidation rate to 88 – 92%.

However, Haubrichs et al (2006) reported the formation of EPS in the biofilter, identified increased drying out of the aerated biofilter media, and the need for an irrigation system to maintain the moisture content of the biofilter media.

2.4.5 Active landfill gas extraction and biofiltration systems

A number of researchers have investigated active landfill gas extraction and biofiltration systems (Dammann et al 1999, Streese et al 2001, Streese and Stegmann 2003, 2005, Nikiema et al 2005, Nikiema et al 2007). Such a system has been proposed as potentially suitable for treating landfill gas from low gas generation landfill sites including:

- old landfill sites where landfill gas generation has declined to such an extent that there is insufficient landfill gas to run a flare.

- landfills that did not receive highly degradable organic waste eg. inert waste landfills and landfills that received mechanically and biologically treated (stabilised) waste.

- an active gas extraction and biofiltration system typically comprises a conventional landfill gas extraction system (of vertical and / or horizontal gas extraction wells and gas pumps / blowers), a system for mixing the landfill gas with air, and a system for discharging the collected gas through dedicated biofilter units constructed on or adjacent to the landfilled waste. Figure 9 shows the pilot scale system constructed by Streese and Stegmann (2003), who tested a variety of biofilter media including:

  - mature garden waste compost

  - a mixture of mature garden waste compost, peat, and squeezed spruce wood fibres (termed a mixed biofilter) and

  - a multi-layer biofilter incorporating multiple layers of mature garden waste compost and layers of wood fibres.
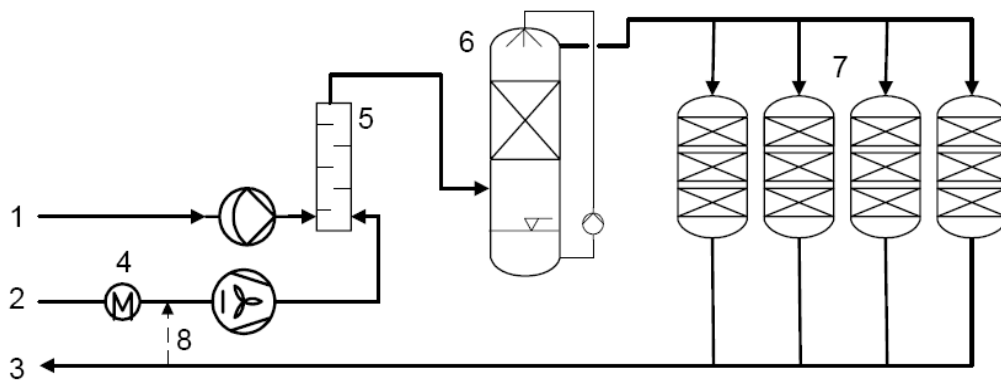
Legend: 1-landfill gas from gas well; 2-ambient air; 3-exhaust; 4-air pre-heating; 5-mixing chamber; 6-air humidifying scrubber; 7-biofilters (12 filters in 4 columns); 8-recirculation

Figure 9: Pilot plant tested by Streese and Stegmann (2003)

Findings of the work by Dammann et al (1999) and Streese et al (2001, 2003) included:

- Methane oxidation rates are typically higher than that in passive systems due in part to the mixing of the landfill gas with air, which overcomes the oxygen limitation of passive systems.

- The biofilter media was subject to clogging by EPS, which reduced the performance of the biofilter.

- To achieve high levels of methane oxidation the flow rates to the biofilters must be much larger than biofilters treating odours or volatile organic compounds.

- Methane oxidation rates increased with temperature.

- There is a need to humidify the landfill gas / air mixture prior to discharge into the biofilter to minimise drying of the biofilter media.

- The biofilter system needs to incorporate an irrigation system to maintain the moisture content of the biofilter media.

- A biofilter media made up of mixture of compost, peat, and wood fibres produced the most satisfactory results due to its high porosity.

- From their studies Streese and Stegmann (2003) concluded that whilst active landfill extraction and biofiltration systems do work, due to the low methane oxidation rates the biofilters need to very large (compared to biofilters for odour control) and require a gas humidification system and biofilter irrigation system. However, Streese and Stegmann (2003) noted that operational costs would be relatively low, so the application of biofilters may be suitable in cases where methane oxidation at low concentrations or low gas flow rates is required.

According to Huber-Humer (2008) other advantages of an active landfill gas extraction and biofiltration system include:

- Monitoring is simple and effective.

- Operational conditions of both the biofilter and gas extraction system can be manipulated and controlled. This is not the case for passive systems.

3   Design concepts

3.1   General

There are a range of approaches to using passive landfill gas drainage and biofiltration as a means of reducing landfill methane emissions. These include:

- installing a temporary passive gas drainage and biofiltration system, which is used to reduce landfill methane emissions from inactive areas during landfilling

- treatment of emissions from landfill gas emission point sources e.g. leachate drainage sumps, temporary or permanent passive landfill gas vents, and other landfill gas emission point sources

- a permanent passive gas drainage and biofiltration system, which is incorporated in the final capping layer of a landfill

- a passive gas interception and biofiltration trench, which may be used to manage subsurface landfill gas migration and

- passive biofilters for treating landfill gas collected via a former active gas extraction system, after landfill gas flows have reduced to an extent that flaring is no longer a practical option.

These approaches are described in the following sections of this Guideline.

3.2   Temporary passive gas drainage and biofiltration systems

A temporary gas drainage and biofiltration system can be used capture and treat landfill gas emissions from temporarily inactive areas of a landfill. Figure 10 shows a concept of such a system.
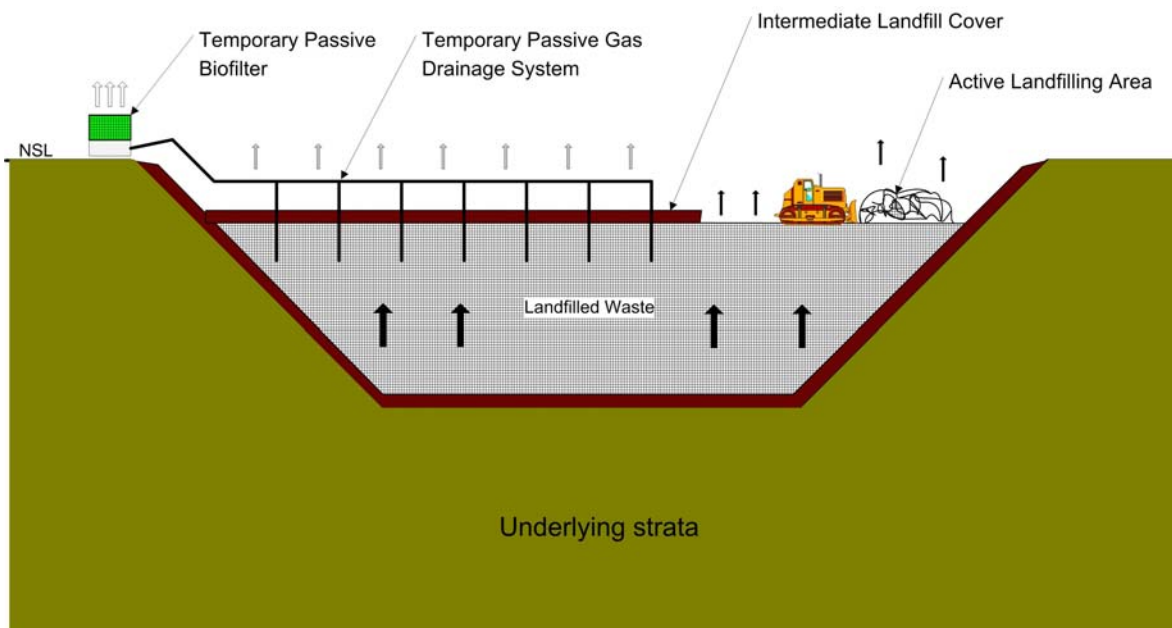
Figure 10: Temporary passive gas drainage and biofiltration system

A typical system may comprise a temporary passive gas drainage system installed in the inactive landfill area, which is connected to a temporary passive biofilter that may be located on or adjacent to the inactive landfill area. The temporary gas drainage system may comprise a series of passive vents installed in the landfilled waste (as shown in Figure 10) or a subsurface gas drainage system e.g. gas drainage layer or network of drains. It should be noted that these drainage systems may be destroyed once landfilling recommences in the area. The biofilter may be a temporary or permanent unit / installation, located on or adjacent to the inactive landfill area being managed. A temporary installation may be movable (see Figure 14) or fixed (see Figure 11 and Figure 12). A permanent installation would be located adjacent to the landfilled waste and used throughout the landfilling process, with various temporary passive gas drainage systems connected and disconnected as the landfilling progresses. The permanent installation may be constructed above or below ground level (see Figure 11 and Figure 12).
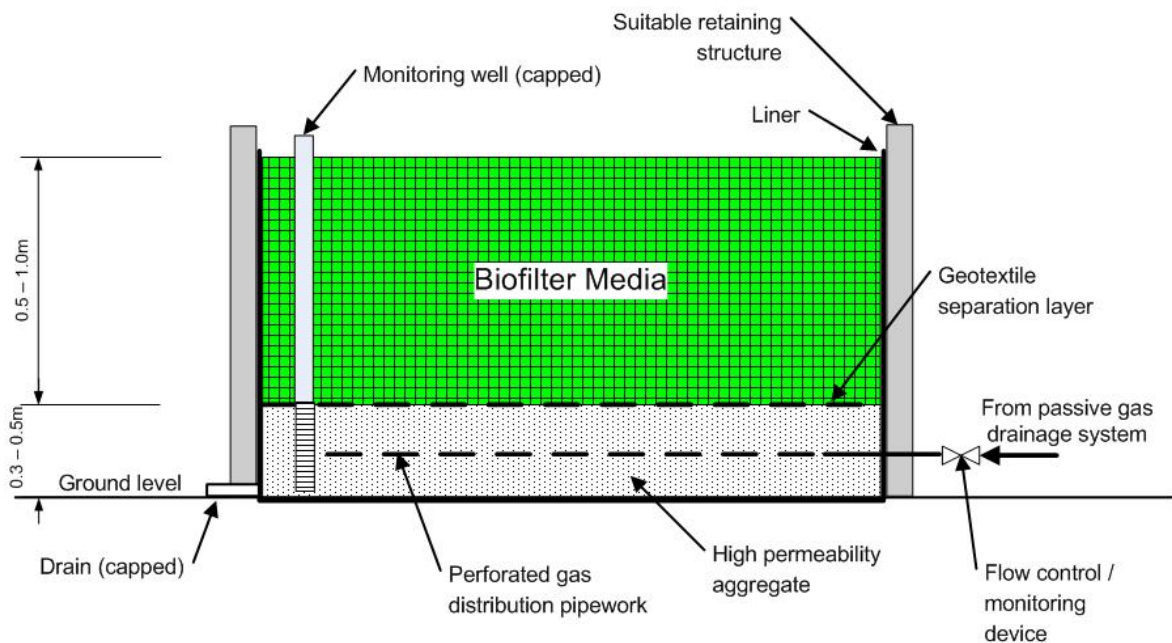
Figure 11: Typical section of above ground passive biofilter
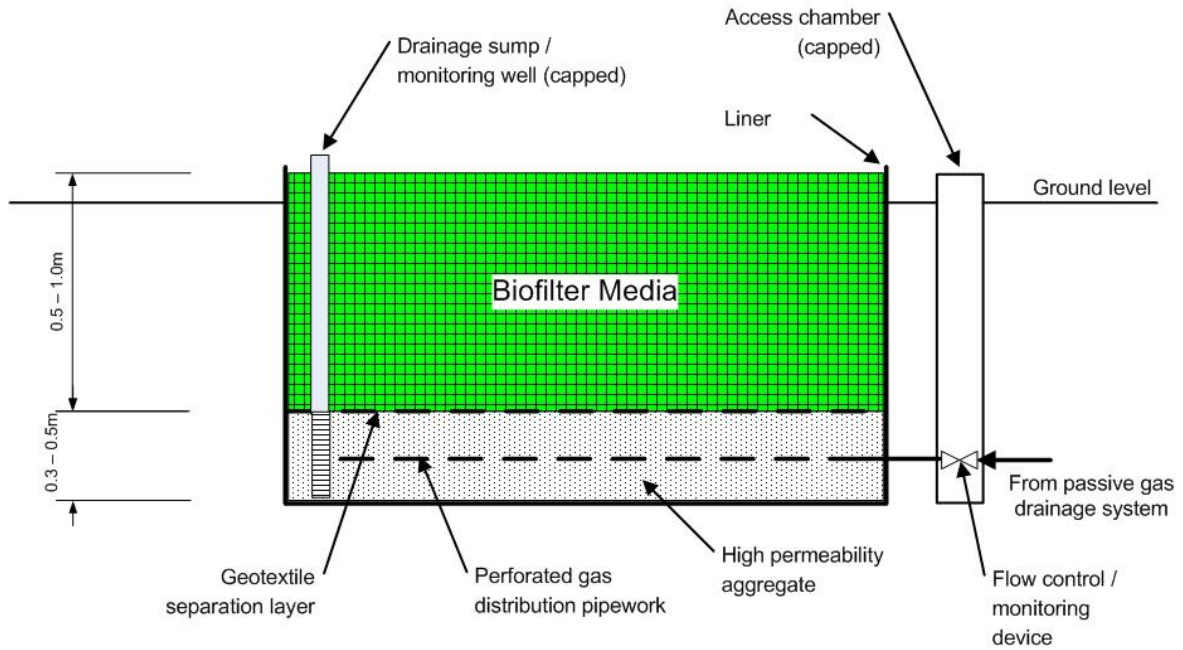
Figure 12: Typical section of below ground passive biofilter

3.3 Passive biofilters for treating point source landfill gas emissions

There are a number of landfill gas emission point sources that commonly discharge landfill gas to the atmosphere that could be connected to a passive biofilter. These include:

- leachate drainage sumps

- uncapped leachate and landfill gas monitoring wells

- temporary or permanent passive landfill gas vents.

Figure 13 shows a possible arrangement for a leachate drainage sump, where a movable passive biofilter is used to treat methane emissions from the sump. Alternatively, the emissions from the leachate sump could be piped to a permanent biofilter located adjacent to the landfilled waste. Figure 14 shows a typical section of a movable passive biofilter. An example of a movable passive biofilter is described in Dever et al (2000).
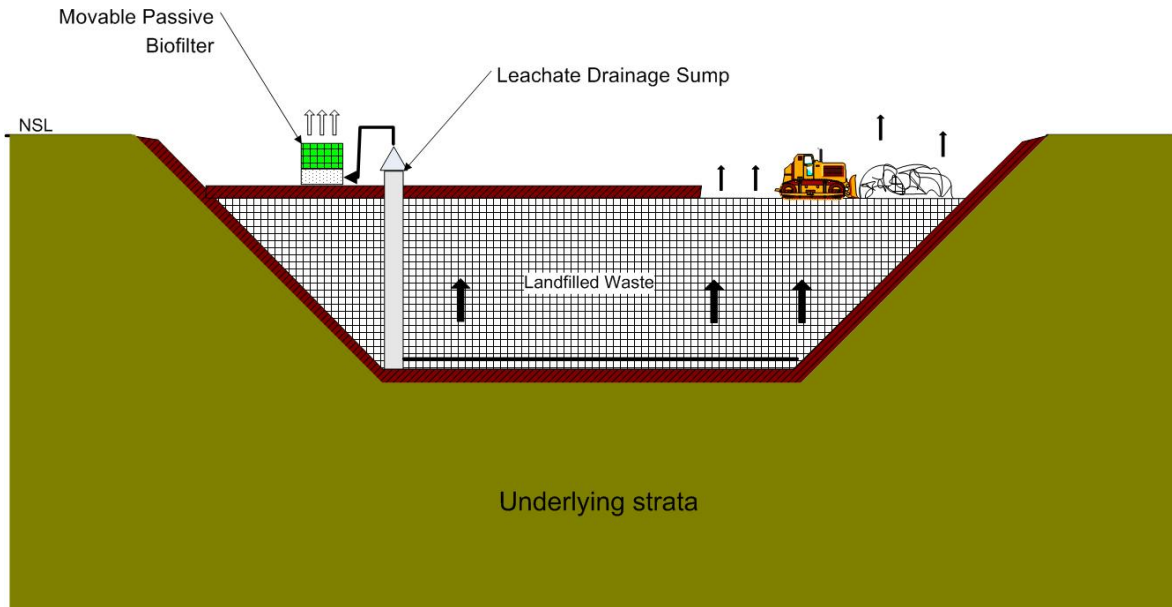
Figure 13: Point source passive biofilter concept
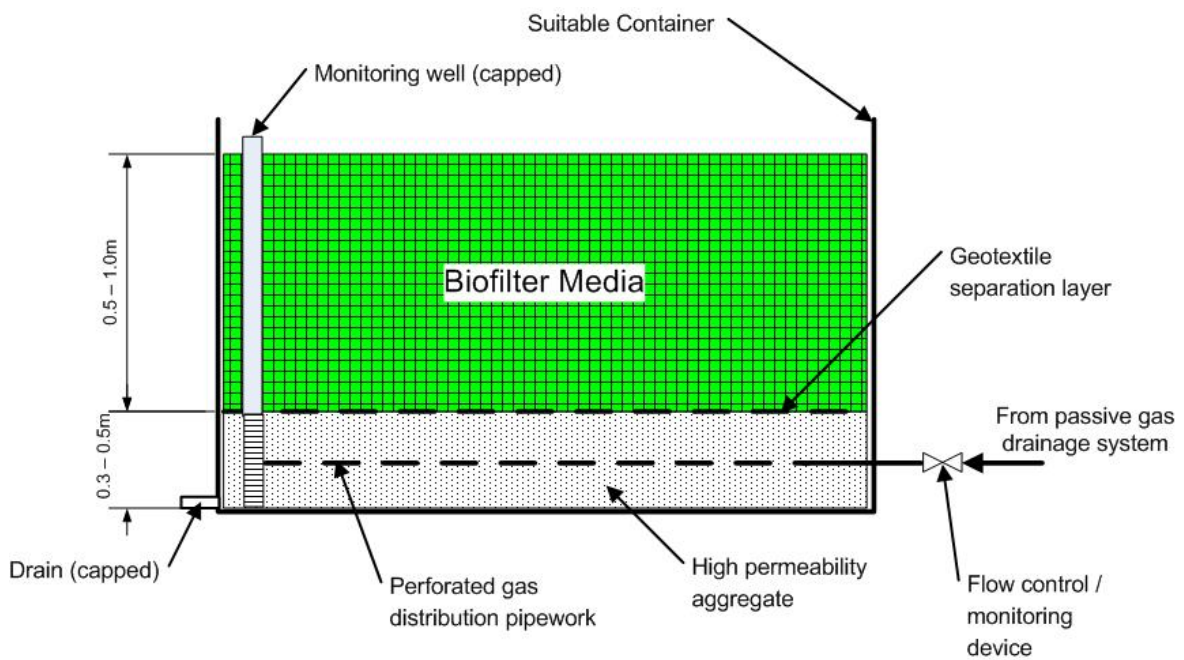
Figure 14: Typical section of a movable passive biofilter

3.4 Final cover layer passive gas drainage and biofiltration system

A passive gas drainage and biofiltration system can also be used once landfilling at a site has ceased. A number of approaches are available:

- Biowindows, for existing capped landfill sites, where it is not necessary or cost effective to install a passive gas drainage system (see Figure 15). Such a system relies on the low permeability of the existing landfill capping layer to contain and direct landfill gas through the upper layers of the landfilled waste to the biowindow (or number of biowindows), which are strategically located on the surface of the landfill.

- Passive gas drainage and biofiltration systems, which may be installed at old (capped) landfilled sites or active landfill sites. Such a system encompasses a passive gas drainage system installed below a low permeability landfill capping layer, to direct landfill gas to a biofilter (or number of biofilters), which are strategically located on the surface of the landfill (see Figure 16 and Figure 17). The passive gas drainage system may comprise a layer of aggregate or a network of gas drainage trenches installed below the low permeability landfill capping layer, depending on a number of factors (see following paragraph). Figure 18 shows a suggested typical section of a passive biofilter installed in a landfill capping layer. Further details of a passive gas drainage and biofiltration system trialed in Sydney can be obtained in UNSW and GHD (2006 and 2008).
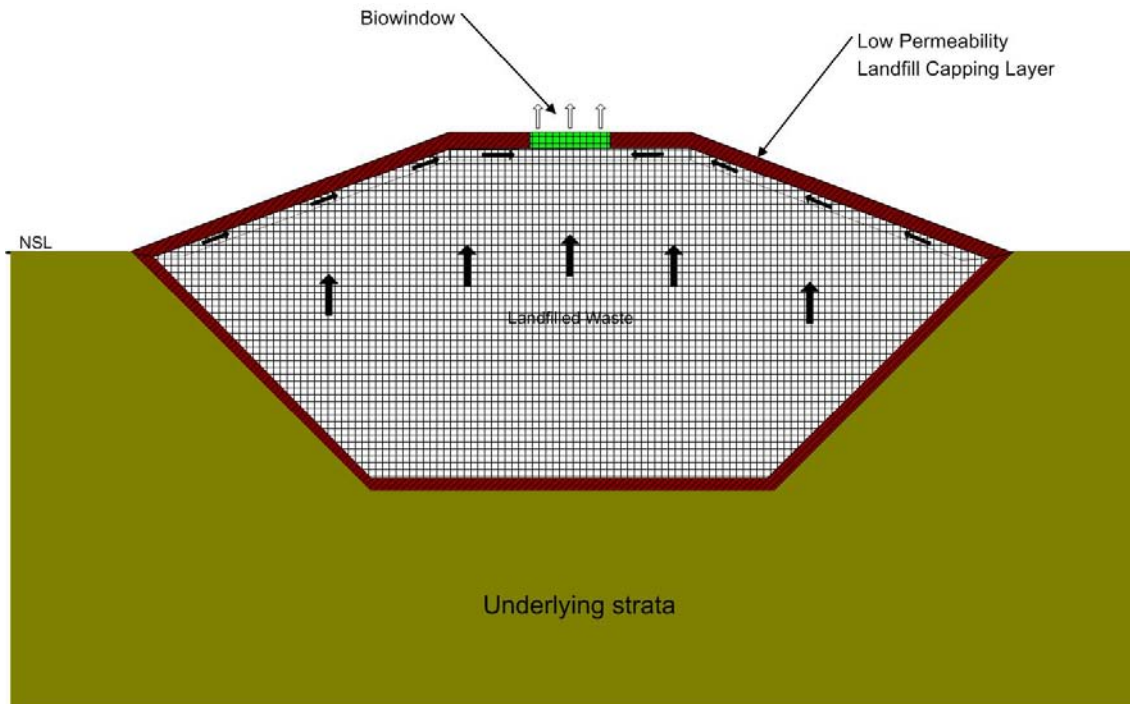
Figure 15: Final cover biowindow for existing capped landfills
(adapted from Kjeldsen et al 2007). Note, no passive gas drainage system.

The need for a passive gas drainage system to direct landfill gas to a biowindow or biofilter is dependent on a number of factors including the quantity (rate) of landfill gas generated at the site, the characteristics and condition of an existing landfill capping layer (profile, soil types, barrier layer, permeability, cracking, erosion, vegetation), the design of a landfill capping layer (profile, soil types, barrier layer, permeability), the characteristics of the landfilled waste (in regard to movement of landfill gas), the characteristics of the aggregate used in the gas drainage system, the distance between biowindows or biofilters, and the risk and consequences of surface methane emissions. All these factors need to be considered when developing the design of a passive gas drainage and biofiltration system.
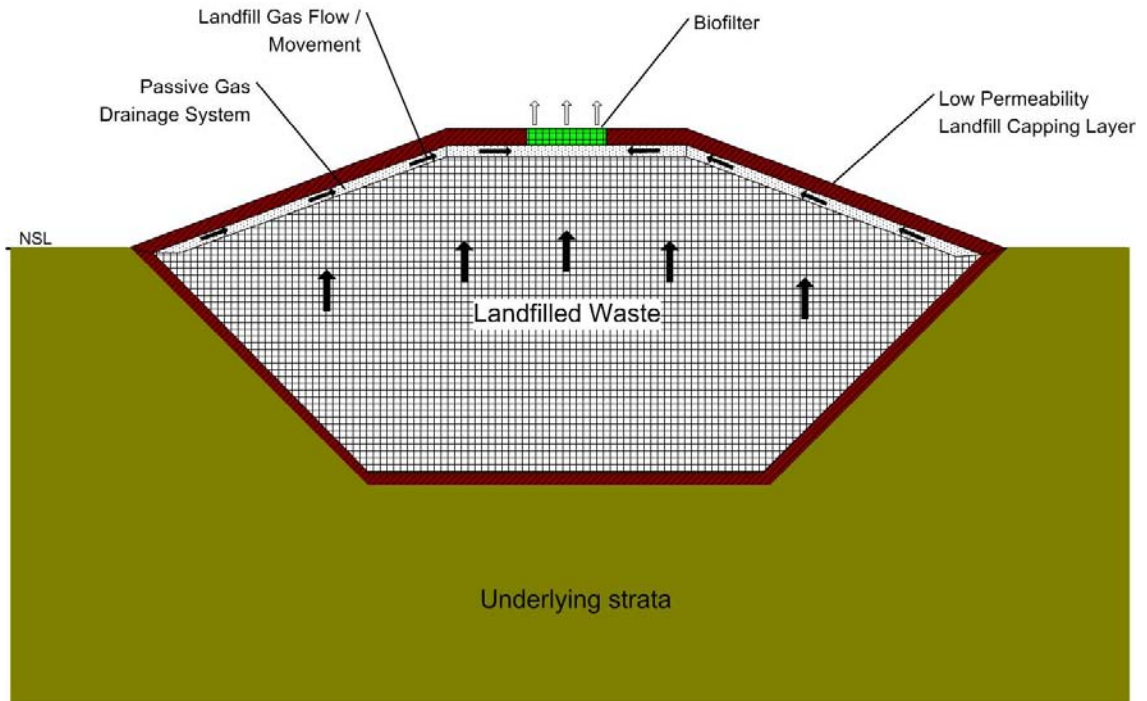
Figure 16: Final cover passive gas drainage and biofiltration system
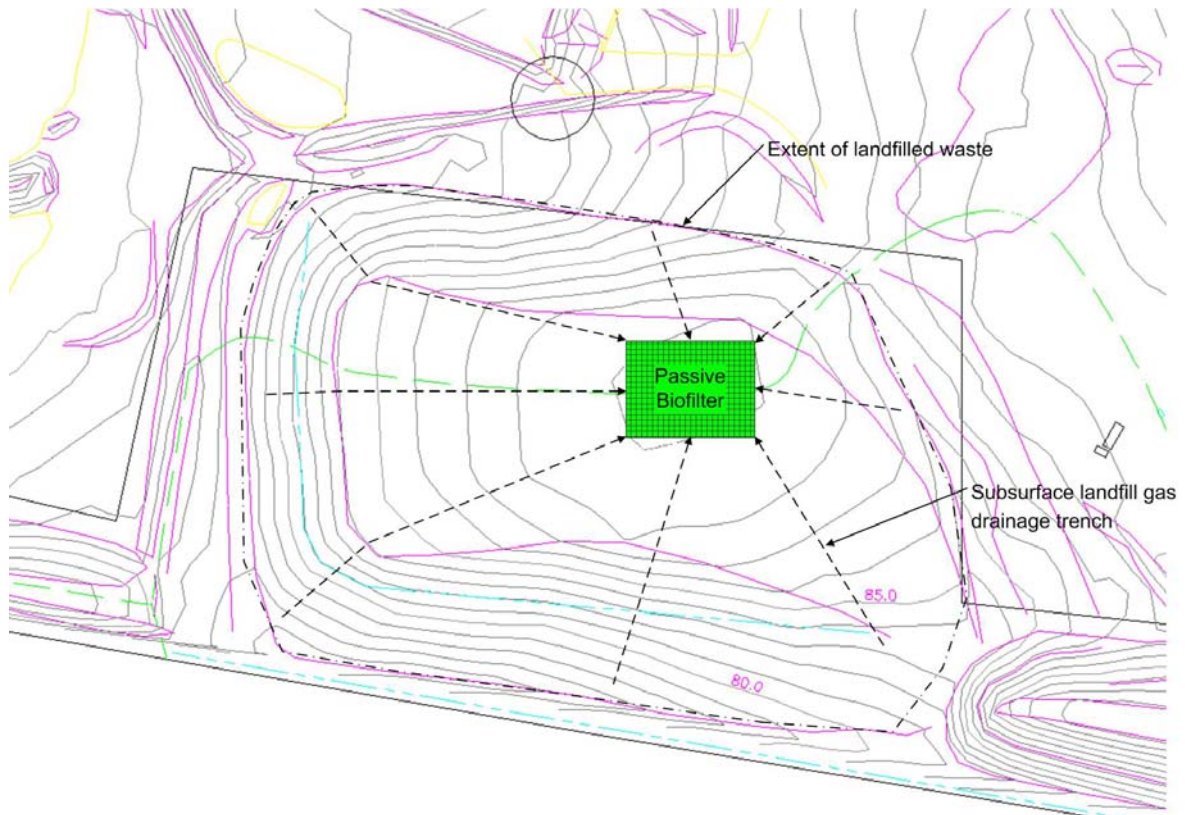
Figure 17: Typical layout of passive gas drainage and biofiltration system
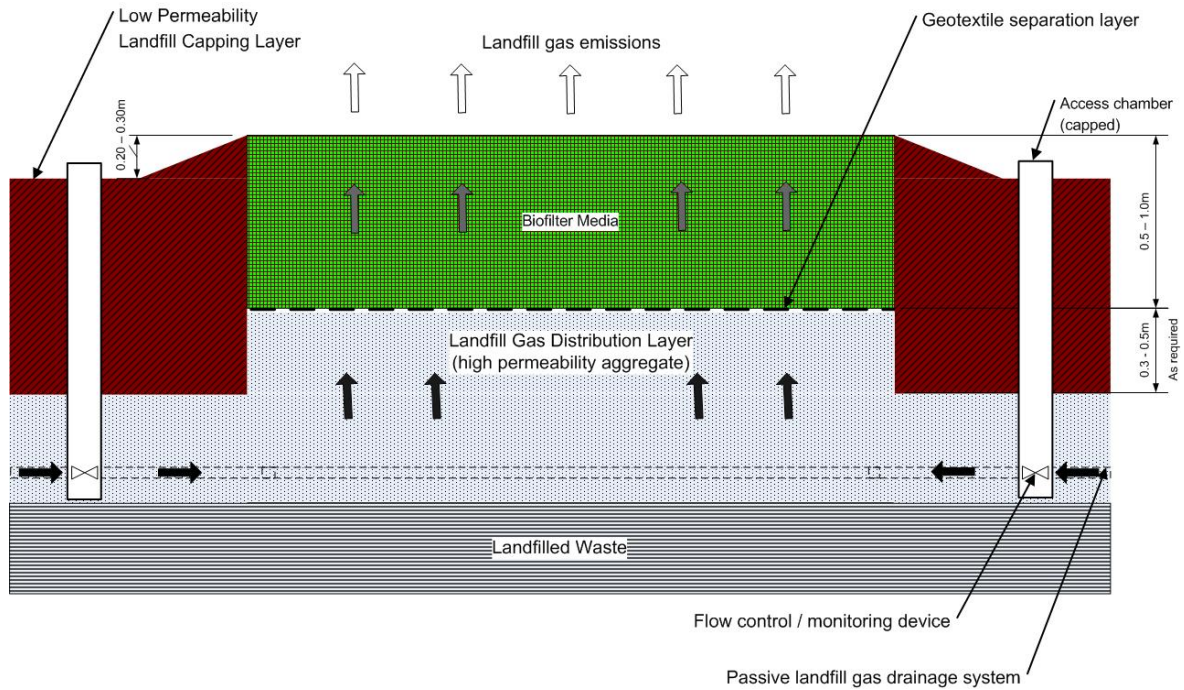
Figure 18: Typical section of passive biofilter installed in a landfill capping layer

3.5 Passive gas interception and biofiltration trench

Another possible approach is a passive gas interception and biofiltration trench as shown in Figure 19. Such a system may be appropriate at landfill sites where subsurface lateral migration of landfill gas is occurring. A typical section of the gas interception and biofiltration trench is shown in Figure 20. Note, the gas interception trench needs to be installed to a depth greater than the base of the landfill, or to the groundwater table, to ensure capture of all migrating landfill gas. Figure 21 shows a photograph of a gas interception and biofiltration trench installed at a landfill site in western Sydney, shortly after construction. Further details are available in CWWT (2006) and Dever (2008).
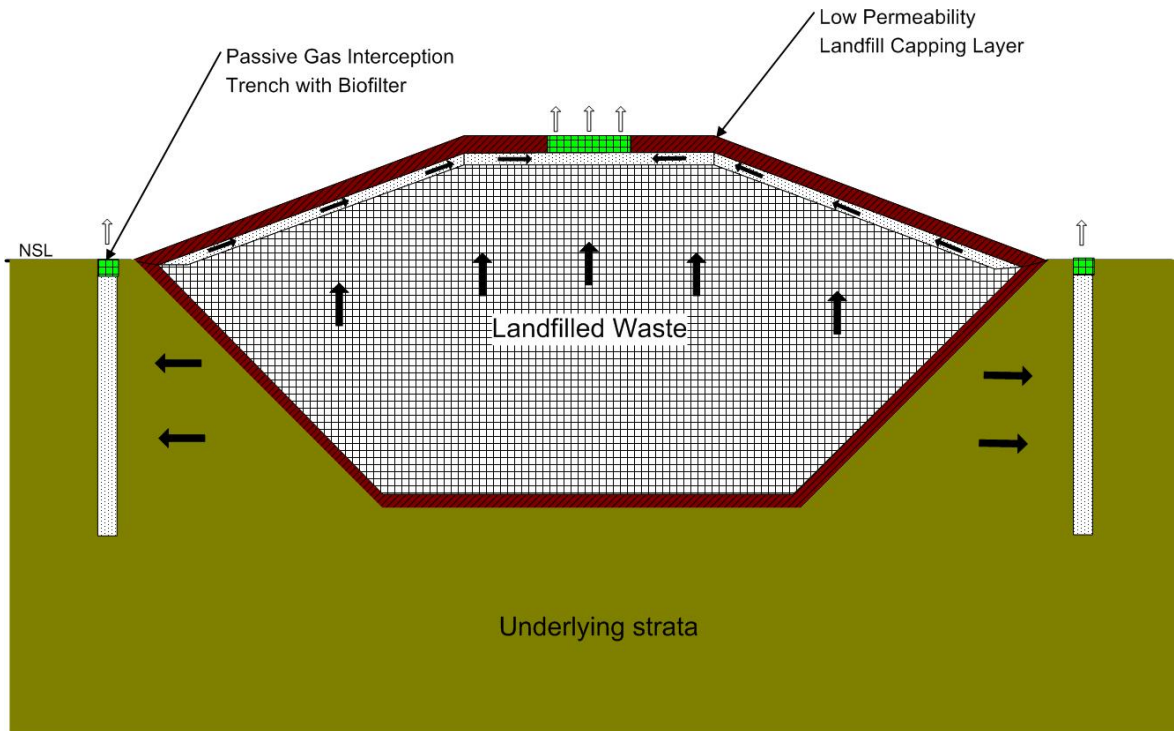
Figure 19: Passive gas interception and biofiltration trench
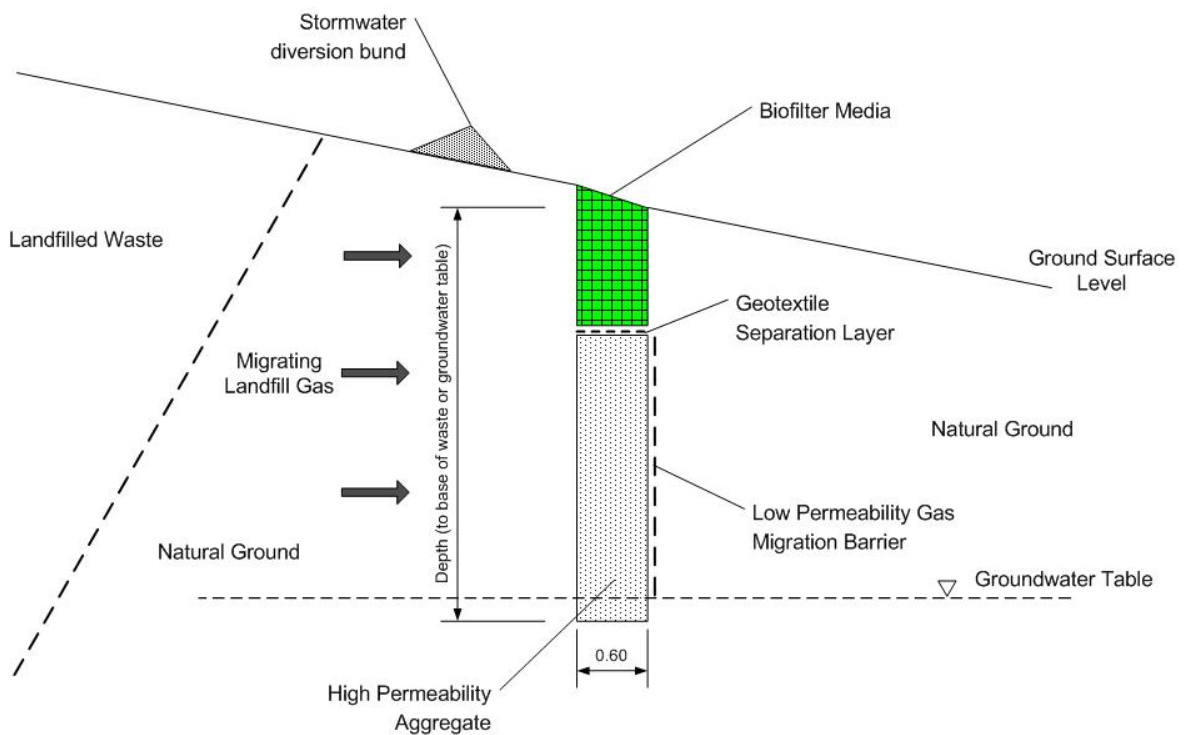
Figure 20: Typical section of gas interception and biofiltration trench

Figure 21: Photograph of passive gas interception and biofiltration trench

3.6   Passive biofilter to treat gas collected via from former active gas extraction system

Another potential application of a passive biofilter is treatment of landfill gas captured using a former active gas extraction system. As gas generation declines at a landfill site (as the waste degradation processes approach their end point) the flow of gas can decline to a point where it is technically difficult to flare the landfill gas i.e. for flow rates less than $30 - 50$ m^3.hr^{-1}. Biofiltration may be an appropriate alternative to the flaring in this situation, and can be undertaken as an active extraction and biofiltration operation or as a passive gas drainage and biofiltration operation. A description and discussion of active gas extraction and biofiltration was presented in Section 2.4.5 and is not discussed further.

When landfill gas flow from an active gas extraction system declines below 50 m^3.hr^{-1} it may be possible to convert the system to a passive drainage and biofiltration system, which would simply involve decommissioning the gas extraction system and connecting the system to a passive biofilter as shown in Figure 22. The passive biofilter(s) could be installed on or adjacent to the landfilled waste and be located above or below ground level (see Figure 11 and Figure 12). Issues that need to considered in addition to the gas flow include the effectiveness of the gas extraction system operating in a passive manner, the condition of the active gas extraction system, the characteristics and condition of the existing landfill capping layer (profile, soil types, barrier layer, permeability, cracking, erosion, vegetation), and the risk and consequences of surface methane emissions. Such a system has been evaluated in detail by Gebert et al (2001, 2003, 2004, 2005, and 2006).
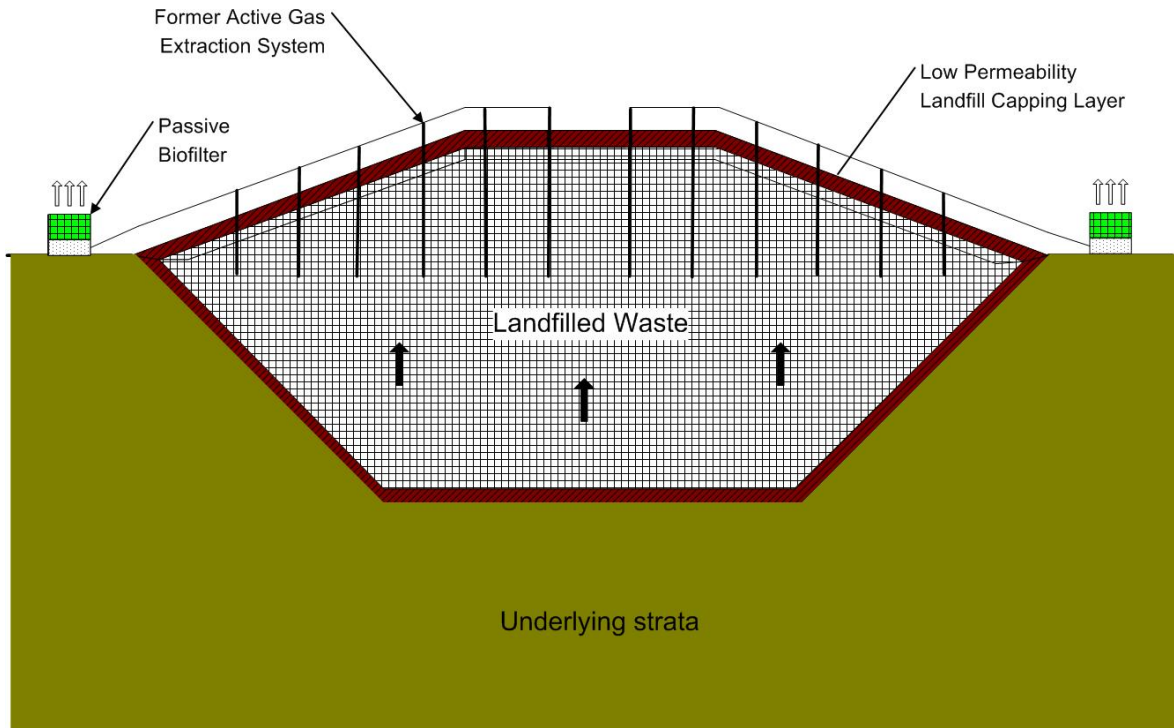
Figure 22: Passive biofilters for treating landfill gas flow from a former active gas extraction system

4 Factors that affect the behaviour and performance of a passive landfill gas drainage and biofiltration system

4.1 General

There are a number of factors that affect the behaviour and performance of a passive landfill gas drainage and biofiltration system, which need to be considered when designing the system. These include:

- the landfill gas / methane loading on the system and the fluctuations that may occur in such

- the local climate i.e. temperature, rainfall and evaporation, and its effect on the temperature and moisture content of the biofilter media

- the temperature of the biofilter media, which is affected by the temperature of the landfill gas to be treated, atmospheric temperature, rainfall, microbiological activity within the biofilter, and the location / exposure of the biofiltration system

- the moisture content of the biofilter media, and in particular the moisture content profile of the biofilter, which is affected by local rainfall, evaporation, properties of the biofilter media, and microbiological activity

- the characteristics of the biofilter media including media stability / degradability, grain size / particle distribution, porosity, water holding capacity, drainage / hydraulic conductivity, and gas conductivity.

These factors are discussed in the following sections.

4.2 Landfill gas / methane loading

The results of local research (UNSW and GHD 2006 and 2008, CWWT 2008, and Dever 2008) has shown that the performance of a passive biofilter is largely dependent on the landfill gas / methane loading: as the landfill gas / methane loading increases, diffusion of atmospheric oxygen into the biofilter declines until low oxygen levels within the biofilter begin to limit the methanotrophic methane oxidation process. Figure 23 and Figure 24 show the effect of landfill gas loading and methane loading on the performance of a passive biofilter (measured as % oxidation of the methane load) operating in western Sydney (temperate climate). Figure 25 and Figure 26 show the effect of landfill gas loading and methane loading on the absolute methane oxidation rate ($gCH_4.m^{-2}.hr^{-1}$). Note the performance of a passive biofilter fluctuates significantly and this is due to variations in the landfill gas loading as well as variation in the temperature and moisture conditions within the biofilter, which is discussed in following sections.
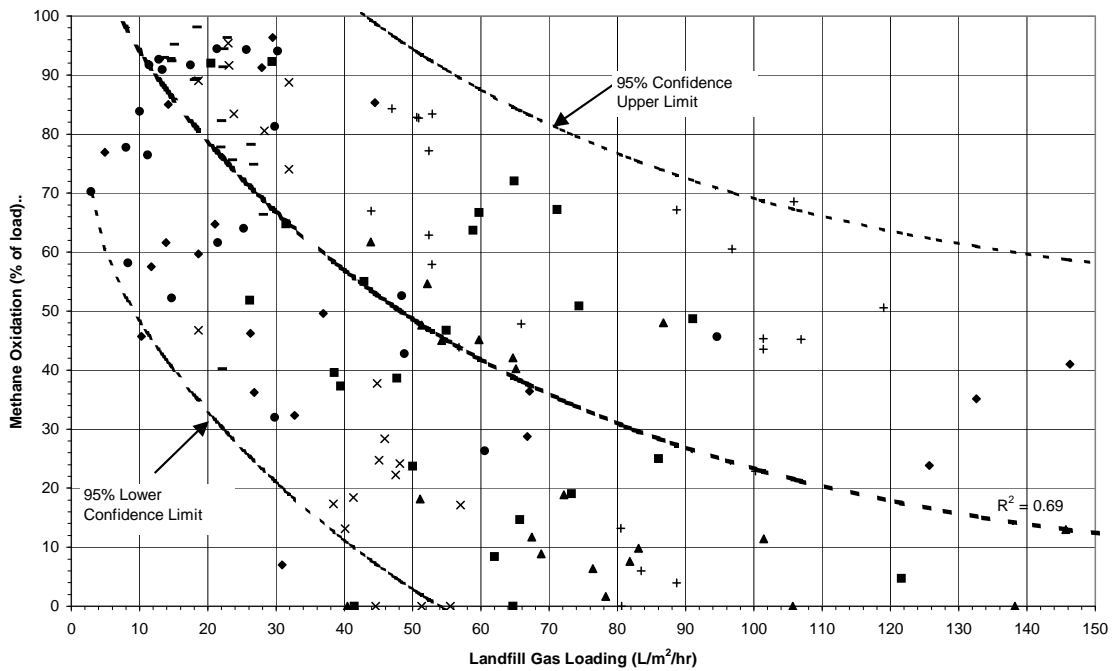
Figure 23: Effect of landfill gas loading on methane oxidation rate (% of load) of a passive biofilter operating in Sydney
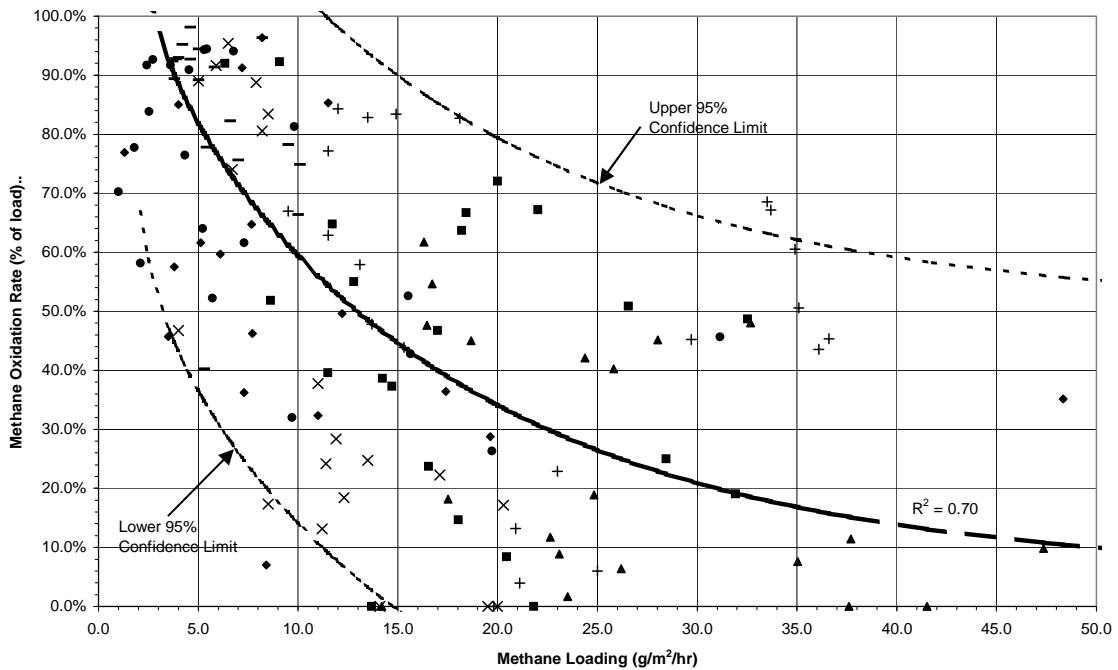
Figure 24: Effect of methane loading on methane oxidation rate (% of load) of a passive biofilter operating in Sydney
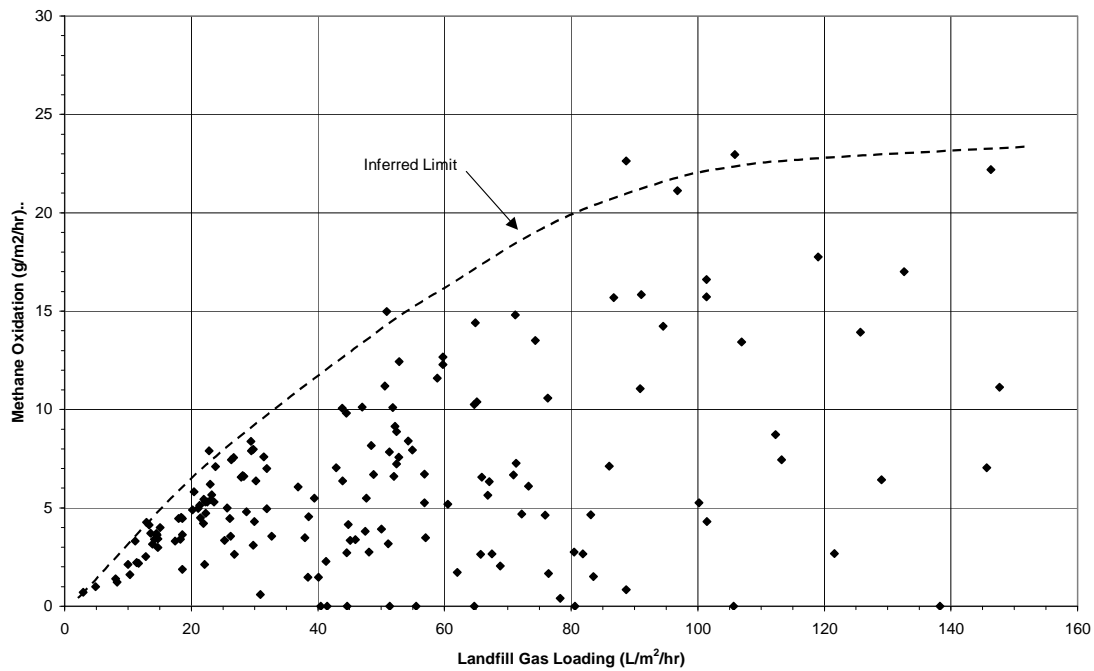
Figure 25: Effect of landfill gas loading on the absolute methane oxidation rate (g.m^{-2}.hr^{-1}) of a passive biofilter operating in Sydney
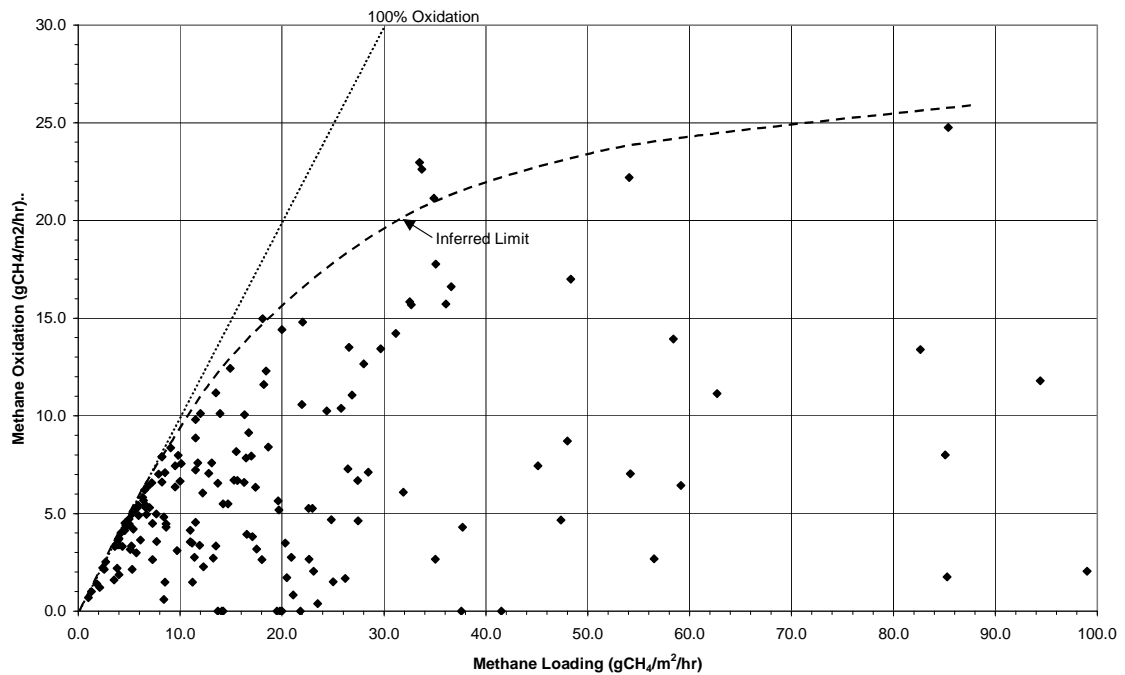
Figure 26: Effect of methane loading on the absolute methane oxidation rate (g.m^{-2}.hr^{-1}) of a passive biofilter operating in Sydney

From the data shown in Figure 23 to Figure 26 it can be seen that the performance of a passive biofilter can decline significantly once the landfill gas loading exceeds 20 L.m^{-2}.hr^{-1} and the methane loading exceeds 5 gCH$_4$/m^2/hr. Consequently, a passive biofilter needs to be sized considering the composition and flow of landfill gas and the fluctuations that may occur during operation of the biofilter. Factors that can affect landfill gas generation and flow of gas to a passive biofilter include:

Atmospheric pressure

- The condition / properties of the landfilling capping layer, which can be affected by climatic conditions e.g. saturated after heavy rainfall, which can reduce emissions through the capping layer and increase gas flows through a passive gas drainage system and / or cracks and faults in the landfill capping layer; and

- variations in the waste degradation process, which can be caused by changes in climatic conditions and activities such as recirculation of leachate within the landfilled waste.

Consequently it is beneficial for the design of a passive biofilter if the flow and composition of landfill gas generated at a landfill site has been monitored regularly over an extended period of time e.g. greater than 1 year. The field monitoring data may show possible variability in the gas composition and gas flow. However, often such data is limited at small to medium sized landfills and the field monitoring data should be compared to model estimates, particularly if the monitoring data set is limited.

Consideration also needs to be given to future landfill gas generation at a site and future loading on the passive gas drainage and biofiltration system. Generally landfill gas generation will peak shortly after landfilling ceases at a site, and then decline over time, reducing the loading on the biofilter, and this should be assessed by modelling landfill gas generation at the site (see Section 5).

4.3   Temperature of the biofilter media

As discussed in Section 2.3.4 the temperature within the passive biofilter affects the methanotrophic methane oxidation process, and research has shown that the optimum temperature range is 25 – 40°C. The temperature of the biofilter media is affected by a number of factors including the temperature of the landfill gas to be treated, atmospheric temperature, rainfall, and microbial activity. These effects are discussed in the following paragraphs along with discussion on the importance of the temperature profile within the biofilter media.

Effect of landfill gas temperature

The temperature of the landfill gas to be treated has a significant impact on the temperature within the biofilter, and can thus affect the performance of a passive biofilter. The effect of landfill gas temperature on the temperature of the media in a passive biofilter is shown in Figure 27, which shows the relationship between landfill gas temperature and the average temperature of the biofilter media in the Kelso Landfill trial biofilters (see UNSW and GHD 2008). The results show a strong relationship for these trial passive biofilters, which were located partially in-ground and received landfill gas direct from the landfilled waste via an underground gas drainage system.

Typically the temperature of landfill gas is in the range 30 – 40°C, but the temperature of the gas as it enters a biofilter for treatment can vary depending on the following:

- The temperature within the landfilled waste, which is a function of the microbial activity occurring within the landfilled waste.

- Atmospheric temperature.

- The location of the biofilter e.g. on the landfilled waste within the landfill capping layer, in a trench adjacent to the landfilled waste, or above ground adjacent to the landfilled waste. Data from the Kelso Landfill trial indicates that a biofilter installed partially in the landfill capping layer, on landfilled waste, generally receives warmer landfill gas (30 – 40°C) than a biofilter located above ground receiving gas via above ground pipework (10 – 25°C).

- The location of the gas drainage pipework feeding the biofilter. If this pipework is located above ground the gas will be subject to cooling during colder atmospheric conditions e.g. during nights and during winter, and warming during hot atmospheric conditions, which may adversely impact on the performance of the biofilter depending on the local climate. It may be necessary to install all pipework below ground level to minimise the impact of atmospheric temperature on the landfill gas, or to insulate the pipework.
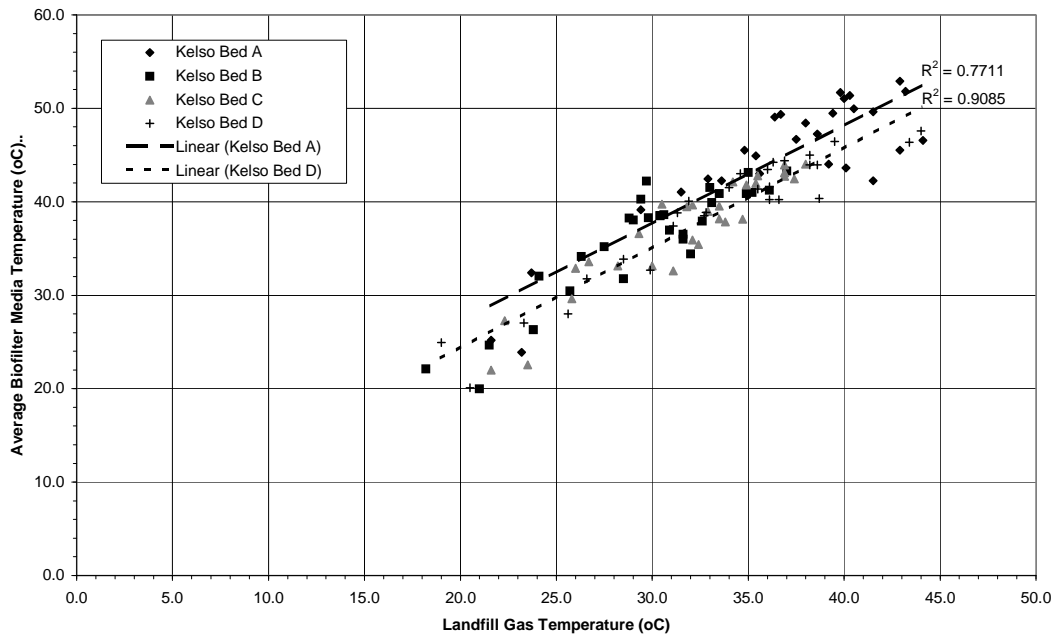
Figure 27: Effect of landfill gas temperature on the temperature of the media in the Kelso Landfill trial biofilters, which were located partially in-ground and on landfilled waste

Effect of atmospheric temperature

Atmospheric temperature changes during the day / night and seasonally, can also have a significant impact on the temperature of a passive biofilter, and consequently the performance of the biofilter. The effect of atmospheric temperature on the biofilter media temperature is dependent on the location / exposure of the biofilter media. A biofilter located below ground level will be less affected by atmospheric temperature than a biofilter located above ground level. Figure 28 shows the effect of atmospheric temperature on the Kelso Landfill trial biofilters, which were located partially in-ground biofilter on landfilled waste, in western Sydney. From the data it can be seen that the temperature of the biofilter media follows the seasonal trends in atmospheric temperature. Figure 29 shows the effect of atmospheric temperature on the average temperature of biofilter media in different types (arrangements) of passive biofilter. Note the difference between the biofilters in-ground (Kelso and Horsley Park biofilters) and those receiving landfill gas cooled by atmospheric conditions (Biofilters L, M1, M2 and H). The media in the trial biofilters L, M1, M2 and H was significantly colder than the biofilters that received warmer landfill gas.
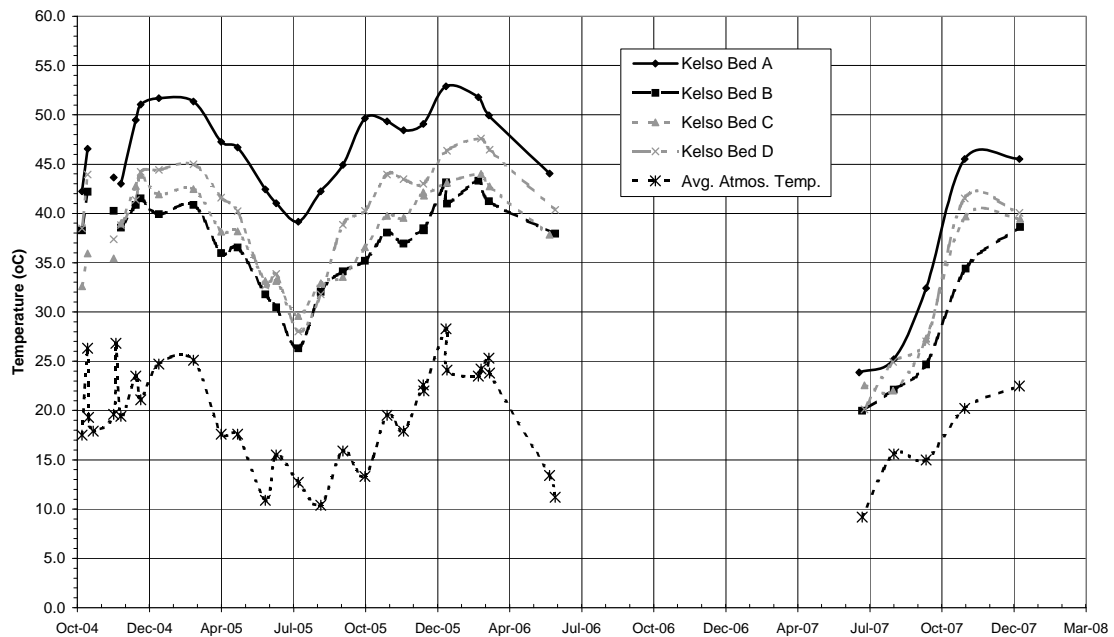
Figure 28: Effect of atmospheric temperature on the temperature of a biofilter located in ground on landfilled waste in Sydney
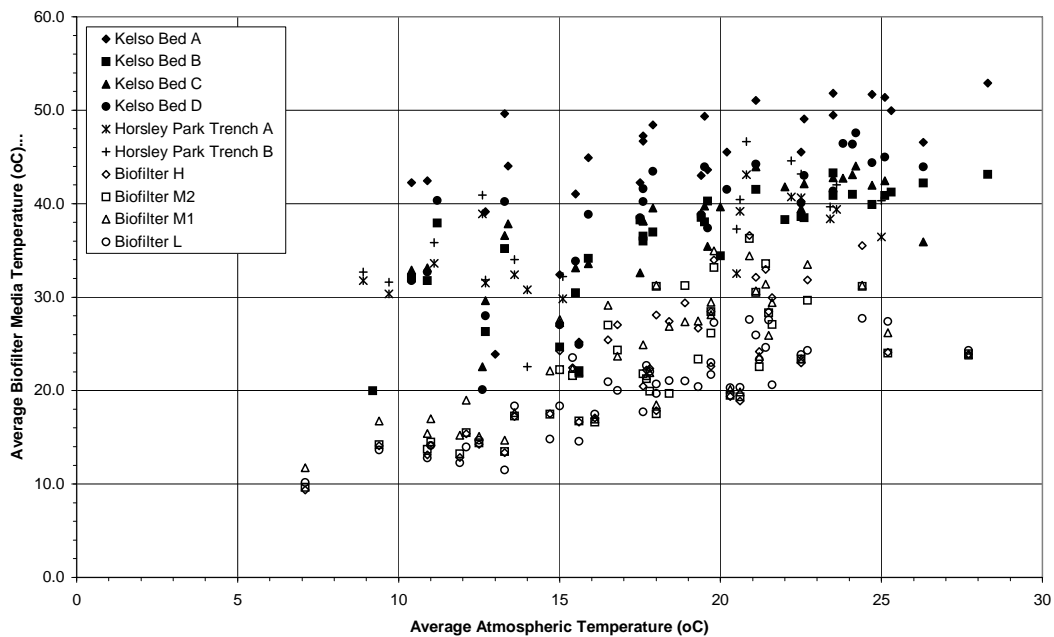
Figure 29: Effect of atmospheric temperature on the temperature of the biofilter media in different types of passive biofilters located in Sydney. Note, the Kelso trial biofilters were located partially in-ground on landfilled waste. The Horsley Park trench biofilter was located in-ground adjacent to landfilled waste. And Biofilter H, M2, M1 and L were located in 240L MGBs on a final capped landfill.

Effect of rainfall

Rainfall can rapidly reduce the temperature of the media in a passive biofilter, depending on the size of the rainfall event and consequent infiltration into the biofilter media, the atmospheric temperature at the time the rainfall event occurs, and the size / depth of the biofilter. A large rainfall event during winter will have a larger impact on the biofilter media temperature than a small event during summer. Figure 30 shows the effect of a number of significant rainfall events on the average temperature of the media in the Kelso Landfill trial biofilters, which were located partially in-ground and on landfilled waste.
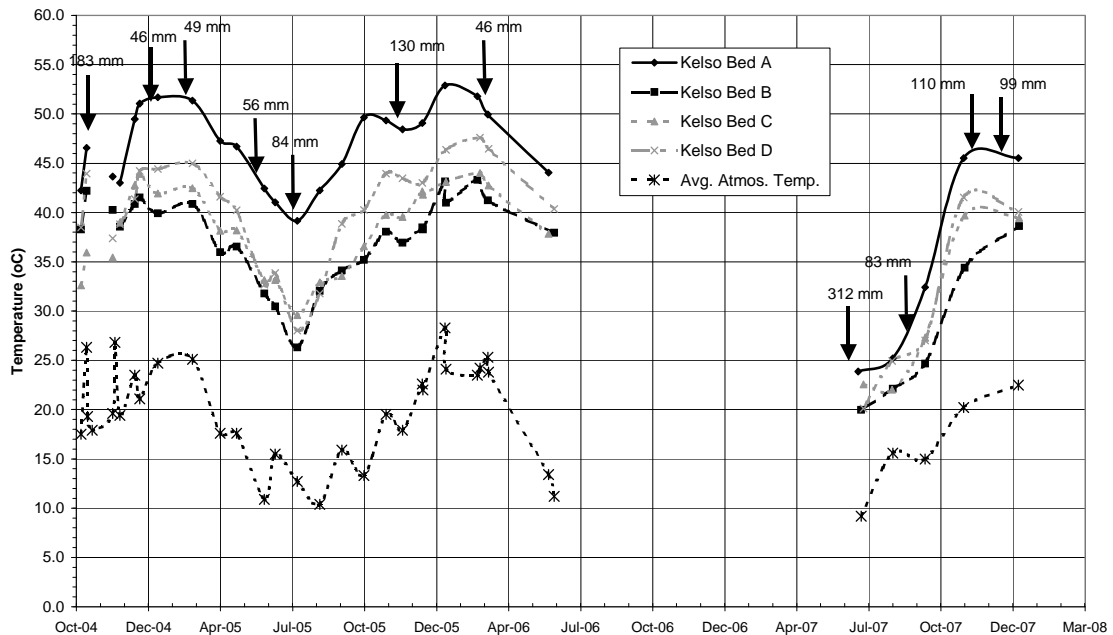
Figure 30: Effect of rainfall on biofilter media temperature

A very large rainfall occurred in June 2007, which significantly reduced the temperature of the biofilter media, and subsequently had an adverse impact on microbial activity in the trial biofilters and the performance of the biofilters.

Effect of microbial activity

Methanotrophic methane oxidation is an exothermic reaction i.e. it generates heats. The results of local research (Dever, 2008) have shown that microbial activity can increase the temperature within a passive biofilter media by more than 20°C (see Figure 31). This is significant in regard to the optimum temperature range for methane oxidation i.e. 25 – 40°C, and thus needs to be considered when evaluating the likely media temperature.
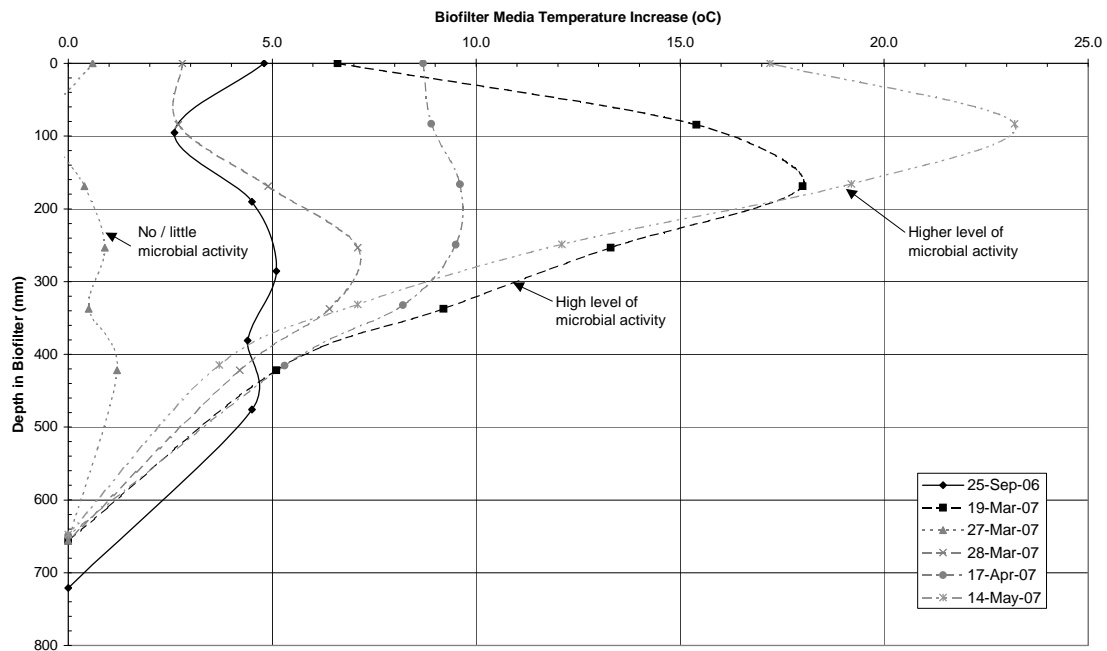
Figure 31: Effect of microbial activity on the increase in biofilter media temperature in trial biofilter M2

Temperature profile of the biofilter media

Consideration also needs to be given to the temperature profile of the biofilter media, which is also affected by the temperature of the landfill gas being treated, atmospheric temperature and the level of microbial methane oxidation occurring in the biofilter. The temperature profile of the biofilter is important in regard to where the microbial methane oxidation is occurring within the biofilter. Under a high landfill gas loading microbial activity at depth is limited due to the limited availability of oxygen deep in the biofilter, and thus the majority of microbial activity will occur near the surface of the biofilter. Therefore the microbial activity will be subject to increased influence of atmospheric temperature and rainfall / evaporation, which may adversely impact on the performance of the biofilter, depending on the local climate i.e. a warm climate will have less impact than a cold climate. However, a warm climate may result in increased evaporation, which dries out the upper layers of the biofilter, and consequently impacts on the performance of the biofilter.

Figure 32 shows the average temperature profiles of a number of different passive biofilters located in western Sydney. Note, the different temperature profiles of the biofilters located above ground and receiving gas affected (cooled) by atmospheric conditions (Biofilters L, M1, M2, and H). The Kelso trial biofilters were located partially in-ground on landfilled waste. The Horsley Park trench biofilter was located fully in-ground adjacent to landfilled waste. It should be noted that the temperature peak within the biofilters is due to methanotrophic microbial activity, which generates heat and can increase the temperature of the biofilter media by up to 20°C (but generally 5 – 15°C), depending on the level of microbial activity occurring in the media (see Figure 31).
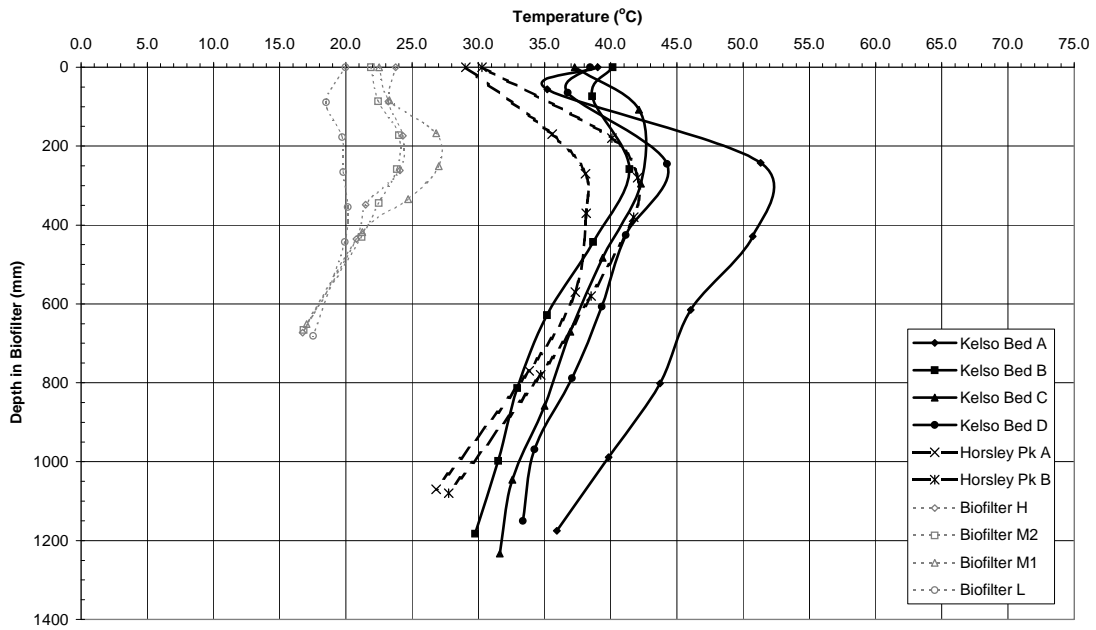
Figure 32: Average temperature profiles of trial biofilters located in Sydney

Figure 33 shows the seasonal fluctuations in the temperature profile of a partially in-ground passive biofilter located on landfilled waste, in western Sydney (Kelso Landfill trial biofilter bed A). The data shows that for this biofilter the temperature within the biofilter remained within or above the optimum range (25 – 40°C).
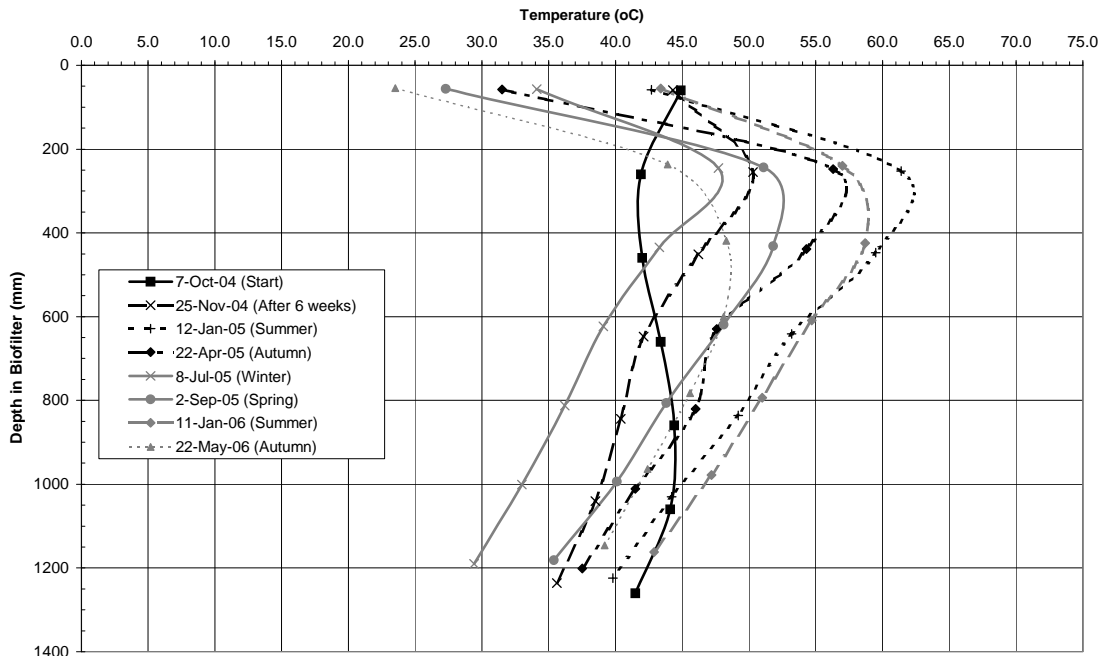
Figure 33: Seasonal fluctuation of the temperature profile of the Kelso bed A trial biofilter

Effect of biofilter media temperature on performance of a passive biofilter

The effect of biofilter media temperature on the performance of a passive biofilter (as measured by the methane oxidation rate) is shown in Figure 34. This data is from trials conducted in Sydney,

which has a temperate climate. The data has been sorted to separate the effects of landfill gas loading and the results show the following:

- maximum methane oxidation generally occurs at media temperatures between 20 – 40°C

- methane oxidation rates decline at temperature below 20°C and above 40°C

- the effect of media temperature is reduced at lower methane loading rates i.e. media temperature has less (or no) effect when the loading rate is < 10 $gCH_4.m^2.hr^{-1}$
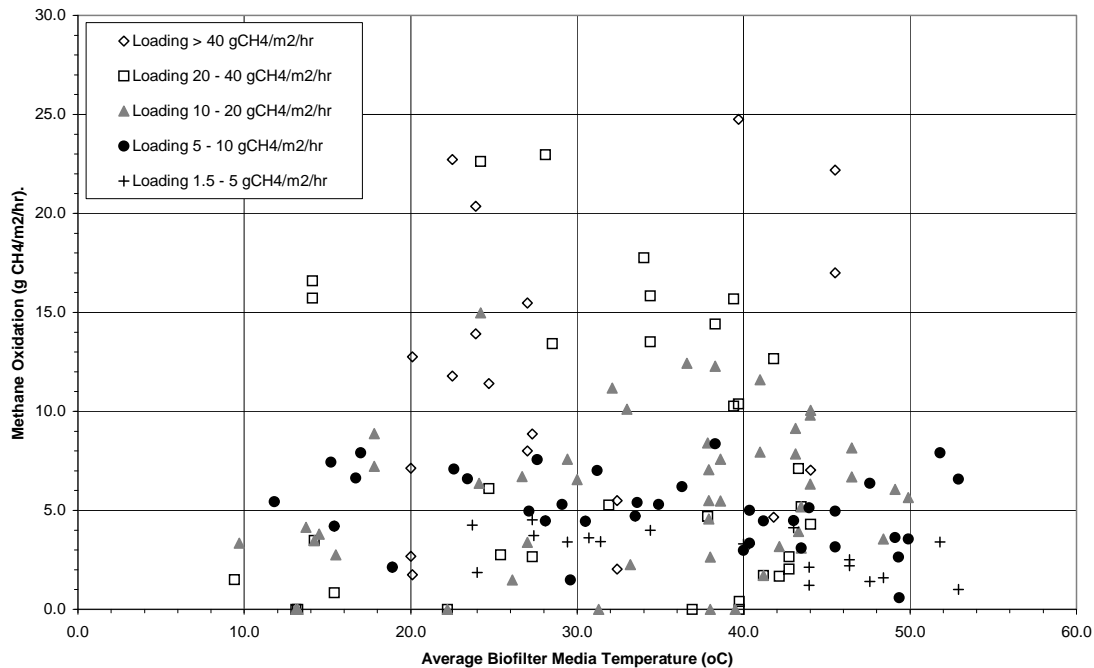
Figure 34: Effect of biofilter media temperature on methane oxidation in passive biofilter operating in a temperature climate

Consequently the temperature of the biofilter media is important and the likely temperature should be evaluated considering the temperature of the landfill gas, the effect of microbial activity, and the effects of climatic conditions (atmospheric temperature and rainfall).

4.4   Moisture content of the biofilter media

The moisture content of the media in a passive biofilter is important for microbial activity. Research indicates that the optimum moisture content for methanotrophic activity a compost-based biofilter media is in the range 30 – 100% of the water holding capacity of the media (Huber-Humer 2004). For soils the optimum moisture content typically ranges from 15 – 30% (wt/wt) (see Section 2.3.4). However, these optimum values are dependent on the characteristics of the media / soil.

At low moisture contents the methanotrophs experience water stress and consequently activity and methane oxidation rates are reduced. Bender and Conrad (1995) and Boeckx et al (1996) both found substantially reduced / no methane oxidation at low moisture content in soils (at 8% and 5% wt/wt respectively). Dever (2008) reports that the moisture content of a compost based biofilter media needs to be maintained above 15 – 20% (wt/wt) or 10 – 15% of the water holding capacity of the media to achieve high levels of methane oxidation.

At high moisture contents (greater than the water holding capacity) the movement of both methane and oxygen, and the transfer of such to the methanotrophs, is hindered and thus the performance of a biofilter is affected.

The moisture content of the media in a passive biofilter is affected by a number of factors including:

- Rainfall and evaporation at the site.

- The moisture content of the landfilled gas being treated, although this is not usually an issue as landfill gas is generally saturated.

- The initial moisture content of the biofilter media, as placed in the biofilter. This needs to be sufficient to initiate the microbial methane oxidation process.

- The design and construction of the biofilter, including the following,

  - The characteristics of the biofilter media (porosity, water holding capacity, drainage). A compost-based media can have a porosity of 65 – 75% (vol/vol) and a water holding capacity of 35 – 45% (vol/vol). This leaves 30% void space within the media for gas / water movement if the moisture content of media is at the water holding capacity.

  - Surface water management. All stormwater runoff generated on surfaces adjacent to the biofilter should be diverted away from the biofilter and

  - The incorporation of an aggregate gas distribution layer under the biofilter media to allow the media to drain and thus avoid saturation of the media. Saturation of the media prevents effective movement of methane and oxygen within the biofilter, thus preventing microbial methane oxidation.

Figure 35 and Figure 36 show the fluctuations in the moisture profiles of 2 of the Kelso Landfill trial biofilters (beds A and B). The trial biofilters were located in Western Sydney, which has a temperate climate, and the results show that the moisture content of the upper layers of trial biofilter Bed A (0 – 400 mm) fluctuated significantly and progressively dried out, whilst the upper layers of trial biofilter bed B were not as affected. Note, the media in the beds was different (composted garden waste + shredded wood in bed A compared to composted MSW plus shredded wood in bed B), and that climatic conditions were dry during the trial i.e. rainfall was significantly below average and less than evaporation at the site. The results demonstrate the effect of different media characteristics and the effect of below average rainfall conditions. In this case trial biofilter A should perhaps have been irrigated to maintain moisture levels in the upper layers of the biofilter.

The results also show that the moisture content of the upper layers can dry out substantially due to climatic conditions, and this may affect the performance of a passive biofilter depending on the landfill gas loading on the biofilter i.e. under a high landfill gas loading microbial activity at depth in the biofilter is limited by low oxygen diffusion into the biofilter, and thus the majority of microbial methane oxidation will occur in the upper layer, but only if the moisture (and temperature) conditions are favourable. Under a low landfill gas loading atmospheric oxygen can penetrate deep into the biofilter media and thus the moisture content of the upper layers may not be important.
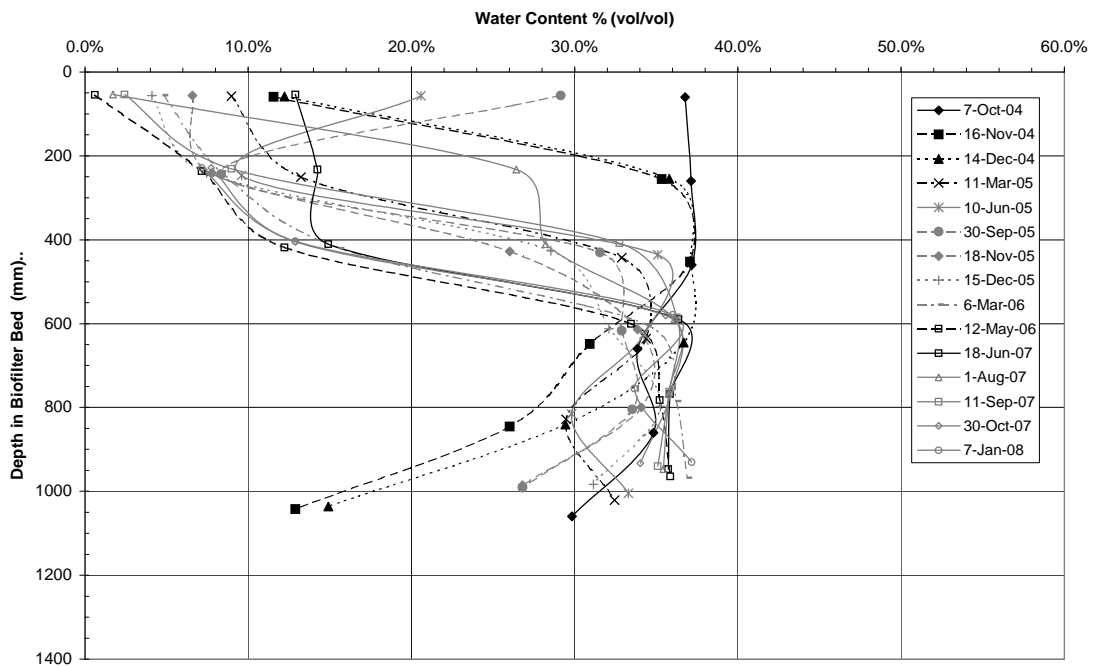
Figure 35: Moisture profiles of the Kelso Landfill trial biofilter bed A: composted garden organics + shredded wood biofilter media, located in Sydney
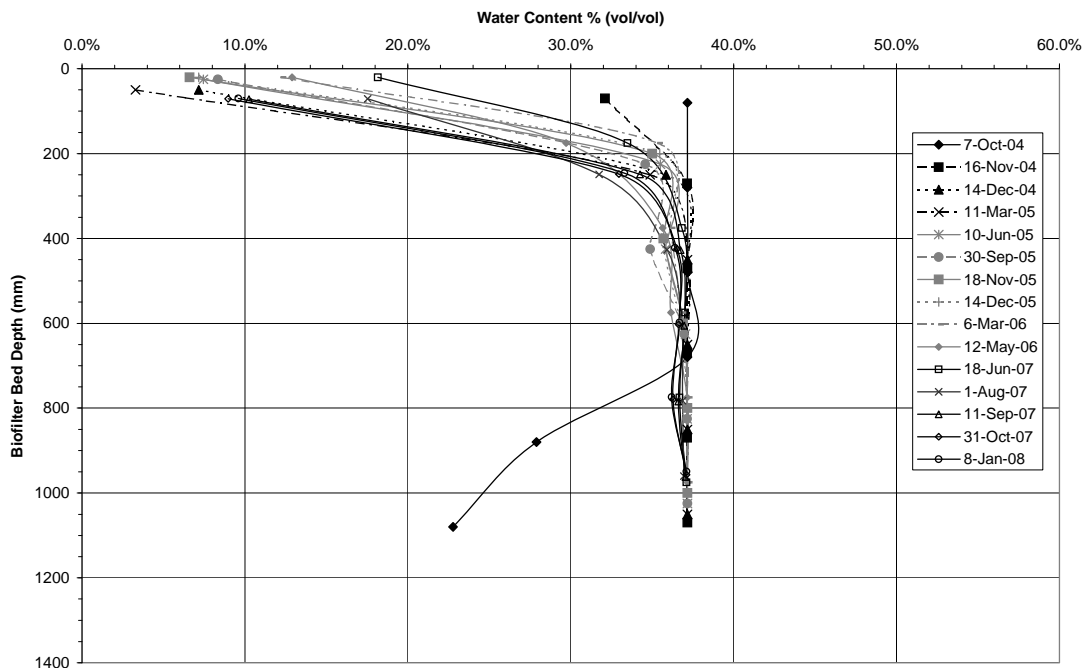
Figure 36: Moisture profiles of the Kelso Landfill trial biofilter bed B: a composted MSW + shredded wood biofilter media, located in Sydney

4.5   Characteristics of the biofilter media

The importance and effect of a number of biofilter media characteristics were discussed in previous sections i.e. water holding capacity and drainage characteristics. Other important characteristics include:

- Porosity and water holding capacity. The media must be sufficiently porous to allow the movement of landfill gas / methane, oxygen, and water through biofilter. An important value is the difference between the total porosity of the media and the water holding capacity. This value needs to be sufficiently large to allow the movement of landfill gas / methane, oxygen, and water through biofilter media, when the biofilter media is at water holding capacity, so as to not adversely impact on the methane oxidation process.

- Biological stability. It is important that a compost based biofilter media be biologically stable i.e. mature, so that other microbes do not compete against the methanotrophs for oxygen within the biofilter media. This could adversely impact on the performance of a passive biofilter until such time that the biofilter media becomes biologically stable.

- Well mixed and relatively homogeneous – to minimise potential short circuiting of landfill gas through the biofilter media layer.

- Physical / structural stability of the media. The media should contain material that provides a structural skeleton for the biofilter media, which provides interstices for biofilms and minimises settlement of the biofilter media – thus maintaining high porosity and high gas conductivity and

- A low level of compounds that may adversely impact on methanotrophic methane oxidation i.e. ammonia, nitrite, copper.

5 Feasibility assessment and design process

5.1 General

A 2 stage approach to the evaluation and design of a passive landfill gas drainage and biofiltration system is recommended, which involves:

i).   an assessment of the feasibility of utilising a passive gas drainage and biofiltration system at the site to reduce landfill methane emissions and

ii).   more detailed evaluation of the landfill site and design of a suitable passive gas drainage and biofiltration system.

This approach is described in the following sections.

5.2 Stage 1: Feasibility assessment

The recommended process for assessing the feasibility of using a passive gas drainage and biofiltration system at a particular landfill site encompasses the following:

i).   Assessment of landfill gas generation at the site:

- identify the characteristics of the waste landfilled at the site
  (types / composition, quantity landfilled for each year of operation) and

- model landfill gas generation at the site using a recognised landfill gas generation model e.g. US EPA LandGEM (US EPA, 2005), GasSIM2 (Golder Associates, 2006), IPCC multiphase model (IPCC, 2006).

ii).   Assessment of various combinations of biofilter size and performance, with the aim of maximising the performance of the system:

- size biofilter(s) (surface area) to achieve 90%, 75% and 50% methane oxidation

- need to consider landfill gas generation and performance over the life of the system i.e. over 20 years and

- are the biofilters of a practical size considering the topography and size of the landfill surface? Note: a biofilter that occupies 50% of the landfill surface may not be practical to construct, may be too costly, and may result in an unacceptable increase in landfill leachate generation. In this situation a biocover may be more appropriate.

iii).   Assessment of the likely effect of the local climate on the biofilter including:

- impact on media temperature and temperature profile within the biofilter media? This needs to include atmospheric temperature and rainfall, and needs to be considered in relation to the landfill gas loading rate on the biofilter and the likely location of methanotrophic activity? In cooler and hotter climates it may be necessary to reduce the loading on the biofilter to allow the diffusion of atmospheric oxygen deep into the biofilter and thus allow the methanotrophs to establish deep in the biofilter

- impact on media moisture content and the need for management measures e.g. roof / cover to reduce rainfall infiltration or need for media irrigation and

- impact of rainfall infiltration on landfill leachate generation. Note, in Sydney 10 – 15% of rainfall infiltrated and drained through the biofilter into the landfilled waste during a period of below average rainfall. In wetter and cooler climates this may

increase. In hotter, drier climates this may be less. Note the biofilter media used was compost. Other media types will behave differently.

iv). Assessment of the existing / proposed landfill capping layer (to facilitate passive gas drainage flow):

- Will it contain landfill gas generated by the landfilled waste and limit atmospheric emissions?

- Will it encourage flow of gas through the passive gas drainage system to the biofilter(s)? If the landfill capping layer is existing and highly permeable it may not effectively encourage the flow of landfill gas to a passive biofilter, and a biocover may be a more appropriate method for reducing landfill gas emissions and

- is a passive gas drainage system necessary? This depends on the characteristics and condition of the landfill capping layer, number and location / spacing of the passive biofilters, and the permeability of the upper layers of landfilled waste.

v). Assessment of the suitability of the final landform for a passive gas drainage and biofiltration system:

- ideally the final landform will be mounded or contain several high points, which allow effective drainage of landfill gas to a biofilter(s) located at the high points and

- can the landfilling be progressively staged and capped in a manner that allows a passive gas drainage and biofiltration system to be progressively installed?

vi). Assessment of the availability, suitability, and cost of materials for the system including:

- aggregate for the gas drainage system and gas distribution layer (under the biofilters). Note, recycled aggregate such as crushed concrete and crushed brick and tile are suitable and

- materials for the biofilter media e.g. composted garden organics, shredded wood, other suitable material. Note, organic materials should preferably be biologically stable / mature, so as to not undergo further aerobic degradation once placed in the biofilter, otherwise it can affect the methanotrophic methane process by competing for the oxygen within the biofilter.

vii). Assessment of the cost effectiveness (capital and operating costs) of using a passive gas drainage and biofiltration system at the site for reducing landfill methane emissions and

viii). Determination of the feasibility and suitability of using a passive gas drainage and biofiltration system at the site.

5.3   Stage 2: Design process

The recommended process for designing a passive gas drainage and biofiltration system for a landfill site encompasses the following:

i). Confirmation of landfill gas generation at the site by undertaking field measurements / monitoring, if able, encompassing:

- landfill gas composition and flow (if possible), including fluctuations in both and

- landfill gas temperature.

- Such monitoring should be undertaken for as long a period of time as possible to allow fluctuations in the gas composition and flow to be assessed. As a minimum 3 rounds of monitoring over a period of 3 months is recommended.

ii). Confirmation of the characteristics and suitability of potential biofilter media (by testing if necessary / able) i.e. stability, porosity, water holding capacity, gas conductivity, contamination, carbon / nitrogen ratio.

iii). Confirmation of the size and performance of the passive biofilter(s) required for the site, and selection of the biofilter profile considering:

- the landfill gas / methane loading and its likely impact on the performance of the biofilter and the likely location of methanotrophic activity and

- the likely effects of the local climate (atmospheric temperature, rainfall, and evaporation) on the biofilter media; and the ability to actively manage the moisture content of biofilter media or incorporate measures to control the temperature of the biofilter media. Ideally the effect of the local climate on the moisture content profile of the biofilter should be modelled to assess the likely impact of such on the biofilter media, assess the impact of landfill gas loading, and assess the need for irrigation of the biofilter media. This can be undertaken using a model such as the US EPA's HELP model (Schroeder et al 1994)

iv). Determination of the size and layout of the passive gas drainage system and location of the passive biofilter(s). Ideally this should be done using a suitable computer based model, which can model gas flow under the landfill capping layer, within the upper layers of the landfilled waste and the proposed gas drainage system e.g. STOMP (White et al, 1995), TOUGH2-LGM (Nastev et al, 2001), Important design factors include the following:

- landfill gas generation at the site, and in particular the quantity of landfill gas generated per square meter of the landfill surface (capping layer). Note, this will vary with the type and depth of waste landfilled at the site.

- gas pressure within the landfilled waste (due to the landfill gas generation)

- topography of the landfill surface

- the thickness, profile and permeability of the landfill capping layer

- the permeability of the upper layers of the landfilled waste

- the size, spacing, and permeability of the gas drainage trenches

- the distance between / spacing of the biofilters and

- the permeability of the biofilter media.

v). Preparation of documentation for the construction, operation, monitoring, and maintenance of the system including:

- layout plan, which shows the location of the gas drainage system and biofilter(s)

- details of the gas drainage system e.g. cross section of the drains, connection to the biofilter(s), monitoring / flow control wells

- details of the biofilter e.g. plan, profile / typical section, media / material characteristics, monitoring devices

- specification for the construction works and

- management and operations plan for system (for inclusion in the site LEMP).

6   Design factors

6.1   General

The following recommendations are provided to assist landfill owners, operators and designers with the design of a passive gas drainage and biofiltration system. It should be recognised that passive landfill gas drainage and biofiltration systems are a new method for treating landfill gas and the information provided in this handbook is based on research undertaken overseas and the results of a number of trials undertaken in Sydney. Consequently knowledge on the design, behaviour and performance of the systems is growing as the systems are implemented.

6.2   Gas drainage system layout and design

The layout of a landfill gas drainage system is dependent on a number of factors and should be designed to suit the site. There are a number of computer programs that may be used to assist with the design process including STOMP (White et al, 1995) and TOUGH2-LGM (Nastev et al, 2001). Consideration should be given to the following:

- landfill gas generation at the site, and in particular the quantity of landfill gas generated per square meter of the landfill surface (capping layer), which will vary with the type and depth of waste landfilled at the site.

- gas pressure within the landfilled waste (due to the landfill gas generation)

- topography of the landfill surface

- the thickness, profile and permeability of the landfill capping layer

- the permeability of the upper layers of the landfilled waste

- the size, spacing, and permeability of the gas drainage trenches

- the distance between / spacing of the biofilters

- the permeability of the biofilter media.

An example layout of a passive gas drainage was shown in Figure 17. Consideration should also be given to the need for a perimeter interception trench to prevent lateral subsurface migration of landfill gas, which can be connected to the site gas drainage system.

A typical section of a passive gas drainage trench is shown in Figure 37. However, the drainage trench should be designed considering the design landfill gas flow, which is a function of landfill gas generation, the area / volume of landfilled waste drained, and the gas pressure within the landfilled waste. A geotextile layer should be incorporated in the gas drainage trench to prevent the landfill capping layer soil mixing and clogging the gas drainage trench.
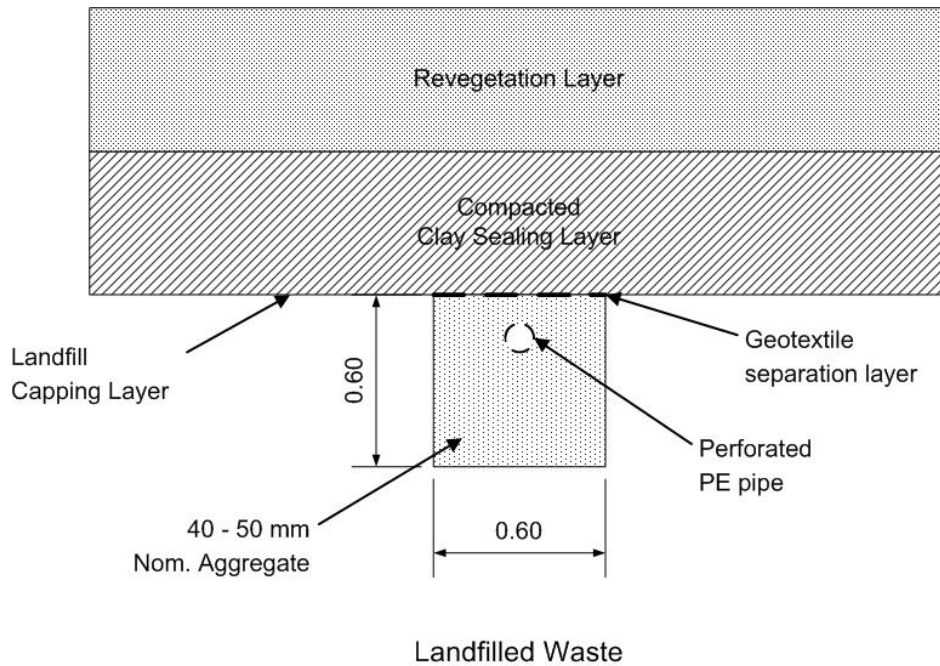
Figure 37: Typical cross section of passive landfill gas drainage trench

The gas drainage aggregate should have the following characteristics:

- large grain size / high porosity i.e. 40 – 50 mm nominal diameter and porosity 40 – 50% (vol/vol)

- less than 5% fines (< 1 mm)

- high permeability / gas conductivity (k > 10^{-3}m.s^{-1})

- physically stable / durable and

- recycled (crushed) concrete and brick and tile are suitable.

The gas drainage pipework should be a suitable class of polyethylene pipe or pipe made from other materials appropriate for the intended use.

The gas drainage pipework that connects the passive gas drainage system to the biofilter should be located below ground level to reduce the effects of atmospheric temperature, particularly in colder and warmer climates e.g. where atmospheric temperatures commonly fall below 10°C or rise above 30°C. For temporary above ground pipework it may be necessary to insulate the pipe work depending on the landfill gas temperature and climatic conditions at the site.

The gas drainage system should incorporate a landfill gas flow monitoring / control well, where able, to allow the composition and flow of landfill gas to the passive biofilter to be monitored. The well design should also allow the flow of landfill gas to the biofilter to be stopped if required e.g. for biofilter maintenance or media replacement.

A gas interception trench for collecting migrating landfill gas, located adjacent to landfilled waste or around the perimeter of the landfilled waste, should extend below the base of the landfilled waste or into the groundwater table (lowest recorded level) to ensure capture of landfill gas. See Figure 20 for a typical section of a passive gas interception and biofiltration trench.

6.3   Biofilter performance and loading

The passive biofilter(s) should be designed to maximise methane oxidation i.e. 90% oxidation, where able. Consideration should be given to the current and future performance of the system, which will be dependent on current and future landfill gas flow. Generally, gas generation peaks shortly after landfilling ceases, but this depends on the types and quantities of waste landfilled during the final years of landfilling. Consideration should also be given to landfill gas generation during the 20 to 30 year period after cessation of landfilling.

The landfill gas loading placed on a passive biofilter will have a significant effect on the performance of the biofilter (see Section 4.2) and consequently the design loading should be selected considering the desired / target performance. For a temperature climate (like Sydney) Figure 23 to Figure 26 may be used to assist selecting the biofilter performance / design loading. Table 4 provides a summary of selected performance targets / loading rates.

Table 4: Selected performance targets and landfill gas / methane loadings rates for a passive biofilter operating in a temperate climate (similar to Sydney)

Target Performance (Average) (% of load)	Landfill Gas Loading Rate (Average) ($L.m^{-2}.hr^{-1}$)	Methane Loading Rate (Average) ($g.m^{-2}.hr^{-1}$)
90%	12	3.8
75%	23	6.2
50%	48	13.0

For different climates the following guidance is provided:

- for <u>colder and wetter</u> climatic conditions a lower loading rate should be selected to achieve the targeted performance i.e. < 3.8 $gCH_4.m^{-2}.hr^{-1}$ to achieve 90% methane oxidation (to reduce temperature effects on biofilter performance)

- for <u>drier</u> climatic conditions a lower loading rate should be selected to achieve the targeted performance i.e. < 3.8 $gCH_4.m^{-2}.hr^{-1}$ to achieve 90% methane oxidation (to reduce moisture effects on biofilter performance). Unless the biofilter(s) can be regularly irrigated to maintain the moisture content of the upper layers of the biofilter media at an acceptable level and

- for <u>warmer and wetter</u> climatic conditions it may be possible to increase the landfill gas / methane loading rates to achieve the target performance e.g. up to 30 $L.m^{-2}.hr^{-1}$ and 8 $gCH_4.m^{-2}.hr^{-1}$ to achieve 90% methane oxidation.

If a biofilter has been sized based on the results of modelling and / or preliminary gas flow monitoring data, consideration should be given to a potential range of landfill gas flow / loading conditions. In addition, the biofilter(s) should be designed to allow easy / simple modification (increase in biofilter size), in the case monitoring shows the landfill gas / methane loading is greater than predicted.

Note, to avoid problems with production of exopolymeric substances (EPS) (see Section 2.3.4) the methane loading rate should be kept low.

6.4   Biofilter profile

A passive biofilter should comprise the following (as shown in Figure 11, Figure 12, Figure 14, Figure 18, and Figure 20):

- A layer of suitable biofilter media (see following paragraph). The thickness of the biofilter media depends on a number of factors including the landfill gas loading rate and the effect of the local climate on temperature and moisture conditions within the biofilter media, which are also affected by the characteristics of the media. In <u>cold and wet</u> climates the biofilter media layer may need to be 0.8 – 1.2m thick and a low landfill gas loading rate adopted to reduce the effect of atmospheric temperature on the performance of the biofilter. In <u>warmer</u> climates that receive an even spread of rainfall (throughout the year) the biofilter media layer may be able to be reduced to 0.6 – 0.8m thick. In warm dry climates the biofilter media layer may need to be thicker (0.8 – 1.0m) to reduce the effects of the media drying out, unless the moisture content of the media can be actively managed by irrigation.

- A geotextile separation layer located between the biofilter media and the aggregate gas distribution / drainage layer. This layer is recommended to prevent fines from the biofilter media washing into and clogging the aggregate layer.

- A layer of aggregate below the biofilter media to facilitate distribution of the landfill gas over the full surface of the biofilter and to ensure drainage of excess water from the biofilter media (and thus prevent saturation of the media). The thickness of the aggregate layer depends on a number of factors including the size (surface area) of the biofilter, whether gas distribution pipework is installed within the layer of aggregate, and the permeability of the biofilter media compared to the permeability of the aggregate. The thickness and performance of the gas distribution layer can be optimised by undertaking suitable computer modelling e.g. using STOMP (White et al, 1995). However, typically a 300 – 500 mm layer of aggregate should be used, although this may need to be increased if the biofilter is large.

6.5   Biofilter media characteristics

The biofilter media should have the following characteristics:

- High porosity (60 – 70% vol/vol) but with sufficient organic fines to hold moisture. The high porosity is required for movement of gas (methane and oxygen) and water within the biofilter media.

- Moderate gas permeability ($k > 10^{-5}m.s^{-1}$). Note the gas conductivity of the biofilter media should be less than that of the aggregate gas distribution layer to achieve effective distribution of the landfill gas across the base of the biofilter media.

- Biologically stable. If a compost based biofilter media is used the compost should be mature to avoid aerobic degradation of the organic matter in the media competing for oxygen required by the methanotrophic methane oxidation process. Humer and Lechner (2001) recommends a 7 day respiration rate <= 8 mg O_2/g of biofilter media (dry mass).

- A carbon / nitrogen of approximately 15 (Humer and Lechner 2001).

- Good water holding capacity (35 – 45% vol/vol).

- Significant difference between porosity and water holding content value i.e. 20 – 30% vol/vol, – to allow gas movement through the biofilter even when the biofilter is at water holding capacity.

- Good drainage / hydraulic conductivity i.e. permeability $k > 10^{-4}$ m.s^{-1}

- Structurally stable – to minimise settlement / consolidation and thus minimise adverse affects on the porosity and gas conductivity of the biofilter media.

- Well mixed and relatively homogeneous – to minimise short circuiting of landfill gas through the biofilter media layer.

- Acceptable concentrations of substances that may inhibit methanotrophic methane oxidation i.e. ammonia < 350 ppm and no nitrite (Humer and Lechner 2001), salinity < 6 mS.cm^{-1} (Gebert et al, 2003) and copper > 60 mg.kg^{-1} (Schuetz and Kjeldsen 2001).

The biofilter media may be derived from composted garden organics and shredded wood. A mix of 66% (vol/vol) composted garden organics and 34% (vol/vol) shredded wood has been shown to work well in a temperate climate. Composted MSW may be substituted for the composted garden organics if available.

6.6   Biofilter location / layout

The location of the biofilter(s) will be dependent on the proposed final land use, revegetation / landscaping and topography of the final landform of landfill site. Ideally, the biofilters will be located at the high points of the final landform, to facilitate effective landfill gas drainage.

To reduce the effects of atmospheric temperature, the biofilter should preferably be located in ground, on the landfilled waste, particularly in colder climates i.e. where atmospheric temperatures commonly fall below 10°C. However, the surface of the biofilter should be raised slightly above ground level to minimise the potential for surface water infiltration into the biofilter – see Figure 18.

Pipes connecting the gas drainage system to the biofilter(s) should preferably be located below ground to reduce the affects of climate, particularly in colder climates. Alternatively, the pipework could be insulated.

If a biofilter has been sized based on the results of modelling and / or preliminary gas flow monitoring data, the biofilter should be located to allow an increase in biofilter size, in case monitoring shows the gas / methane loading is greater than predicted and the biofilter needs to be enlarged.

6.7   Biofilter media moisture content

The moisture content of the biofilter media is important for the microbial methane oxidation process (see Section 4.4). Too little moisture affects microbial activity. Too much moisture interferes with gas movement in the media (both methane and oxygen), adversely affecting the microbial methane oxidation process. The optimum range for a compost based biofilter media is reported to be in the range 30 – 100% of the water holding capacity (Huber-Humer, 2004). And the moisture content of a compost based biofilter media should be maintained above 10 – 15 % of the water holding capacity to achieve high levels of the methane oxidation (Dever 2008).

The moisture content a passive biofilter will be affected by the local climate as well as the design of the biofilter. In designing the biofilter consideration should be given to the following:

- The effect of climate on the moisture profile of the biofilter media and the need for irrigation of the biofilter media to maintain acceptable moisture levels in the upper layer. This can be assessed using a suitable model e.g. US EPA's HELP Program (Schroeder et al 1994)

- Irrigating the biofilter media once in place, to raise the moisture content to an acceptable level, depending on the moisture content of the media as supplied.

- a layer a aggregate should be installed below the biofilter media to facilitate drainage of the biofilter media (see Section 6.4) and thus avoid saturation (flooding) of the biofilter media

- the biofilter media should have a water holding capacity that is 50 – 70% of the media porosity to allow free movement of gas (methane and oxygen) within the biofilter media even if the media is at water holding capacity, which is likely in the lower layers of the biofilter

- management of stormwater runoff from areas adjacent / upgradient of the biofilter – to prevent flooding / saturation and excessively high moisture contents in the biofilter

- vegetation may help to reduce water loss from the upper layers of the biofilter media in dry climates (by reducing surface temperatures of the biofilter surface). Note, it may be difficult to grow vegetation on a passive biofilter with high gas loading rate – due to low levels of oxygen in upper layers of biofilter media and

- the biofilter may be covered with a roof or a permeable cover layer e.g. shade cloth, geotextile or jute, to avoid excessive rainfall infiltration and reduce the effects of direct solar radiation on the temperature and moisture content of the biofilter media.

6.8   Biofilter media temperature

The optimum range for methanotrophic methane oxidation activity is 25 – 40°C (see Section 4.3). The temperature of the biofilter media is affected by the temperature of the landfill gas entering the biofilter, the local climate (atmospheric temperature and large rainfall events), and microbial activity. In designing the biofilter consideration should be given the following:

- the temperature of the landfill gas in the landfill (see Section 4.3)

- the effect of the local climate on the temperature of the biofilter media (see Section 4.3)

- the potential effect of microbial activity on the temperature of the biofilter media (see Section 4.3)

- the location of the pipework that feeds the biofilter(s). Locating the pipework below ground level will reduce effects of atmospheric temperature i.e. in both colder and hotter climates;

- the location of the biofilter(s), particularly in colder climates. Locating the biofilter(s) below ground level will reduce the effects of atmospheric temperature. Locating the biofilter(s) on the landfilled waste may also warm the biofilter, depending on the temperature of the landfilled waste

- vegetation may help to regulate the temperature of the biofilter media (reduce surface temperatures). Note, it may be difficult to grow vegetation on a passive biofilter that receives high gas loading rate – due to low levels of oxygen in upper layers of biofilter media and

- the biofilter may be covered with a roof or a permeable cover layer e.g. shade cloth, geotextile or jute, to reduce the effects of direct solar radiation on the temperature of the biofilter media.

6.9   Rainfall infiltration and leachate management

It should be recognised that incorporation of a passive biofilter(s) in the final capping layer of a landfill may lead to an increase in rainfall infiltration into the landfilled waste, and consequently

leachate generation at the site. This must be assessed and consideration should be given to the following:

- Infiltration through the biofilter(s). This can be assessed using a suitable model e.g. US EPA's HELP Program (Schroeder et al 1994). On average 10 – 15% of rainfall infiltrated through the Kelso Landfill trial biofilters, which were located in Sydney. However, rainfall during the trial was below average. Infiltration ranged from 5% to 100% of rainfall (during very heavy rainfall).

- The effect of infiltration through the biofilter(s) on leachate generation and management at the site. For a modern lined landfill with active collection and management of leachate a small increase in leachate generation may not cause a problem. At older, unlined landfills an increase in rainfall infiltration and leachate generation may not be acceptable.

- Rainfall infiltration could be reduced by constructing a roof over the biofilter, which also has other benefits (see Section 6.8), but then the media may require irrigation and the costs could high.

- Rainfall infiltration could be reduced by placing a layer of shade cloth, geotextile or jute on the surface of the media to encourage surface runoff and prevent excessive rainfall infiltration.

- The biofilter(s) could be lined and excess rainfall infiltration captured before entering the landfilled waste. A system for storing, draining and managing the excess rainfall infiltration would be required and the quantity of captured water (within the biofilter) would need to be regularly monitored to ensure the biofilter is not flooded.

- The aggregate gas distribution layer below the biofilter media should not be allowed to fill with water (saturate) as this may interfere with methane flow into the biofilter media and may cause flooding of the landfill gas drainage system.

6.10 Life of the biofilter media

The life of the biofilter media will depend on the landfill gas loading rate, level of microbial activity and growth within the media, clogging of the media due to settlement, microbial growth or formation of EPS, the characteristics of the media, and the effects of the local climate. Limited data is available on the effective life of the media in a passive biofilter treating landfill gas, however, the results of the Kelso Landfill trial (UNSW and GHD Pty Ltd, 2008) indicate that compost based biofilter media can achieve high methane oxidation rates for a period of more than 3 years. Effective monitoring of the biofilter(s) (see Section 8) will identify the need for biofilter media maintenance of replacement. Indicators include:

Reduced biofilter performance i.e. methane oxidation rate;

- Large / excessive settlement, which may adversely affect media porosity and subsequently gas and water movement through the biofilter media.

- Ponding of water on the surface of the biofilter, which indicates clogging (see following point).

- Clogging of the biofilter media, which may be due to settlement, microbial growth or EPS formation, and which may adversely affect media porosity and subsequently gas and water movement through the biofilter media.

- Drying / desiccation of the surface of the biofilter media, which may indicate that the media is no longer holding onto the water and has become hydrophobic. This may be remedied

by applying a wetting agent to the biofilter media, or replacing the upper layer of biofilter media.

- Increased rainfall infiltration into the biofilter media, which may indicate that the media is no longer holding onto the water and has become hydrophobic. This may be remedied by applying a wetting agent to the biofilter media.

- If an organic / compost media has been used, it may be possible to excavate the media and reprocess / compost the media. However, the media should be tested and managed in accordance with EPA requirements.

7 Construction factors

7.1 General

The following recommendations are provided to assist landfill owners and operators with the construction of a passive gas drainage and biofiltration system. It should be recognised that passive landfill gas drainage and biofiltration systems are a new method for treating landfill gas and the information provided in this handbook is based on research undertaken overseas and the results of a number of trials undertaken in Sydney. Consequently knowledge on the design and construction of the systems is growing as the systems are implemented.

The following sections address the following:

- potential construction issues

- construction staging and techniques

- environmental management and monitoring.

Note, before proceeding to construct a passive gas drainage and biofiltration system, approval for such should be obtained from the NSW EPA prior to the commencement of any work, in accordance with the requirements of the Environment Protection Licence for the site, and the POEO Act 1997 and regulations.

7.2 Potential issues

Construction of a passive gas drainage and biofiltration system presents a number of potential hazards and environmental issues that need to be considered and addressed, including the following:

- Exposure of landfilled waste, which will occur during the construction of the system i.e. when the cover layers are removed and the landfilled waste exposed. Such exposure can be hazardous to workers at the site.

- Landfill gas emissions, which will occur during the construction of the system i.e. when the cover layers are removed and the landfilled waste is exposed. Such emissions are odorous and potentially hazardous depending on the composition of the gas e.g. methane and hydrogen sulphide content.

- Stormwater management, which includes management of upgradient stormwater runoff, management of runoff from disturbed areas of the construction site, erosion and sediment control measures, and prevention / management of surface water contamination.

- Leachate generation, which will occur during the construction of the system i.e. when the cover layers are removed and the landfilled waste exposed. This could result in increased rainfall infiltration into the landfilled waste, and consequent leachate generation, and generation of contaminated stormwater runoff.

Occupational health and safety (OH&S). The hazards and risks presented by the proposed construction works should be evaluated and appropriate management measures implemented. In addition to common construction work hazards potential site specific issues may include:

- exposure of landfilled waste

- excavation and handling of landfilled waste

- landfill gas / methane emissions and potential explosion and

- trenches / excavated pits in landfilled waste and

- disposal of excavated waste, which needs to be disposed of at an EPA approved landfill site.

The following sections provide a description of the recommended approach to construction and recommended construction techniques, and recommended environmental management and monitoring measures, which reflect the above issues.

7.3 Staging and construction techniques

7.3.1 General

The following approach is recommended to successfully construct a passive gas drainage and biofiltration system:

- management and supervision of the works by a suitably qualified and experienced person

- effective planning and organisation (of the construction works)

- staging the work to minimise exposure of the landfilled waste and all the issues associated with such exposure i.e. landfill gas emissions / odours, surface water contamination, leachate generation, and exposure to the landfilled

- implementation of appropriate construction techniques and

- implementation of appropriate environmental management and monitoring measures.

- in addition it is recommended that a Health and Safety Plan be prepared and implemented for the construction works.

The following sections provide some guidance on staging, construction techniques, and environmental management and monitoring.

7.3.2 Staging

To minimise the potential hazards and environmental issues associated with the construction of a passive gas drainage and biofiltration system the works should be staged to minimise exposure of the landfilled waste and all the issues associated with such exposure i.e. landfill gas emissions / odours, surface water contamination, leachate generation, and exposure to the landfilled. The suggested sequence of construction is:

i).   construction of the passive biofilter (s) – so the passive gas drainage system can be connected immediately to the biofilter(s) and thus any gas released to the atmosphere is directed through the biofilter(s) and

ii).   progressive construction and connection of the passive gas drainage system(s) – moving away from the biofilter. The gas drainage trenches should be backfilled and covered / capped as soon as practical and ideally at the end of each day.

7.3.3 Construction techniques

General

Construction of a passive gas drainage and biofiltration system generally involves standard construction activities including:

- general earthworks i.e. excavation / filling / compaction

- installation of polyethylene and / or PVC pipework

- installation of geotextiles and

- material handling, including placement / filling with compost biofilter media.

- the following sections provide suggestions regarding the construction of an in-ground biofilter and a passive gas drainage system.

In-ground biofilter construction

- set out the works

- organise for all required materials to be delivered to the site

- prepare all materials / equipment for installation e.g. perforation / drilling of gas drainage pipework

- construct stormwater diversion drainage works as required

- construct down gradient stormwater drainage works, as required, including erosion and sediment controls

- excavate the required pit in the existing landfill cover layer. All excavated material will need to be disposed of appropriately on site or offsite. Any excavated waste will need to be disposed of at an approved landfill facility. If the excavation is deep and the pit will remain open for some time it may be necessary to erect temporary fencing around the pit to prevent access and potential accidents

- place and spread an initial lower layer of gas distribution aggregate over the base of the biofilter excavation. This provides a good working base

- install the leachate monitoring / drainage pipe (if required)

- install the gas distribution pipework and gas sampling / flow control well, if required. Perforate / drill all pipework as required prior to installation (to speed up installation and minimise exposure / landfill gas emissions)

- place and spread upper layer of gas distribution aggregate to required thickness

- install geotextile separation layer

- place premixed biofilter media to the required thickness. Minimise compaction of the media. Mound the media as required to allow for future settlement i.e. allow for 10 – 20% settlement.

- irrigate the biofilter media as required to increase the moisture content of the media to an acceptable level (dependent on the moisture content of the supplied media).

Passive gas drainage trench

Set out the works;

- Organise for all required materials to be delivered to the site

- Prepare all materials / equipment for installation e.g. perforation / drilling of gas drainage pipework

- Construct stormwater diversion drainage works as required

- Construct down gradient stormwater drainage works, as required, including erosion and sediment controls

- <u>Progressively</u> excavate the required trenches. Separate the upper / revegetation soil for later re-use (if installing in existing landfill capping layer). Separate capping barrier soil layer for later reuse (if installing in existing landfill capping layer). Special construction methods will be required if retrofitting the system at a landfill site that has a landfill capping layer that contains a geosynthetic barrier layer i.e. GCL or geomembrane. Separate intermediate cover soil for layer reuse. Dispose of excavated waste materials at an approved landfill site

- <u>Progressively</u> place and spread lower layer of gas drainage aggregate

- <u>Progressively</u> install the gas drainage pipework and connect to biofilter(s). Perforate / drill pipework as required prior to installation – to speed up installation and minimise exposure of landfilled waste / landfill gas emissions

- <u>Progressively</u> place and spread the upper layer of gas drainage aggregate to required thickness. It is recommended that a aggregate be lightly compacted to minimise future settlement

- <u>Progressively</u> install the geotextile separation layer

- <u>Progressively</u> reinstall the intermediate cover soil layer, if required

- <u>Progressively</u> construct / reconstruct final capping layer as per landfill design, / site LEMP and NSW EPA requirements, including CQA requirements. It may be beneficial to overfill the final layers to allow for potential future settlement.

7.3.4 Construction quality control and assurance

The following construction quality control and assurance measures are recommended:

- Biofilter media. Samples of the media should be collected and the media tested prior to installation, to ensure it meets the desired criteria – see Section 6.5

- Gas drainage aggregate. Samples of the aggregate should be collected and the aggregate tested prior to installation, to ensure it meets the desired criteria – see Section 6.2

- Gas drainage pipework. All pipework should meet relevant Australian or International Standards and the supplied pipework checked prior to installation

- Geotextile. All geotextile should meet relevant Australian or International Standards and the supplied geotextile checked prior to installation

- Reconstruction of landfill capping layer (existing / old site). Such works should be undertaken as per the approved landfill design / site LEMP / landfill closure plan and / or NSW EPA requirements

- Construction of new capping layer. Such works should be undertaken as per the approved landfill design / site LEMP and / or NSW EPA requirements

- Construction management and supervision. The construction works should be managed and supervised by a suitably qualified and experienced person

- As built drawings. Such drawings should be prepared to document any design changes and to define the system as constructed.

7.4   Environmental management and monitoring

The following measures should be implemented to manage and monitor landfill gas emissions, stormwater, and leachate during construction:

- Staged construction of the system, to minimise the area of exposed landfilled waste

- Good construction planning and management to minimise the time any landfilled waste is exposed. All materials should be pre-ordered, prepared and delivered to the site, ready for installation, prior to any excavation works

- Construction of upgradient stormwater diversion works, as required, prior to the commencement of any other construction works

- Construction of downgradient stormwater drainage works, as required, prior to the commencement of any other construction works

- Erection of silt fencing and other appropriate sedimentation controls downstream of the proposed works area and around any stockpiles of potentially erodible materials e.g. cover layer soil, biofilter media

- Regular inspection and maintenance of the stormwater drainage works, including the erosion and sediment control measures

- The biofilter media should be pre-mixed off site (at the source / producer of the materials) and delivered to site immediately prior to placement in the biofilter, to minimise construction time and storage on site, and consequently minimise potential odours or contamination of stormwater runoff

- Excavated waste should be disposed of immediately after excavation at an approved waste disposal site. Landfilled waste should not be stockpiled on the site;

- Landfilled waste should not be left exposed overnight. If necessary any uncovered areas should be covered with plastic sheeting and / or soil. This should include covering any incomplete drainage trenches

- Completion of the works as quickly as practical, to minimise the time any landfilled waste is exposed

- Regular monitoring of landfill gas emissions / concentrations in the trenches and pits a using suitable landfill gas analyser e.g. fitted with methane and hydrogen sulphide sensors and

- No construction work during heavy rainfall.

8 Operation, monitoring and maintenance

8.1 General

The following recommendations are provided to assist landfill owners and operators with the operation, monitoring and maintenance of a passive gas drainage and biofiltration system. It should be recognised that passive landfill gas drainage and biofiltration systems are a new method for treating landfill gas and the information provided in this handbook is based on research undertaken overseas and the results of a number of trials undertaken in Sydney. Consequently knowledge on the design, behaviour and performance of the systems is growing as the systems are implemented.

8.2 Operation and monitoring

Once installed, operation and monitoring of a passive gas drainage and biofiltration system is relatively simple and primarily involves regular monitoring and occasional / irregular monitoring that may be undertaken to further evaluate a potential problem. These are described in the following sections.

Regular monitoring:

Monitoring should initially occur more often e.g. weekly / monthly, then quarterly, then 6 monthly, plus after significant rainfall events e.g. > 20 mm of rainfall. Monitoring should also occur more regularly during drought to check the moisture levels of the biofilter media. Regular monitoring should include:

A regular inspection of the biofilter to assess the following:

- odours from the biofilter

- condition of the biofilter media including settlement, formation of a surface crust, scouring, and / or desiccation of the media

- moisture content of the upper layers of the biofilter media

- ponding of water on the surface of the biofilter media

- condition of vegetation growing on the biofilter surface, including weeds / unwanted vegetation and

- condition of surface water management measures.

Monitoring of the following:

- composition and flow of landfill gas from the passive drainage system(s) to the biofilter(s)

- emissions / flux from the surface of the biofilter (methane and carbon dioxide)

- moisture content of the upper layers of the biofilter media, particularly in a dry / hot climate / drought conditions and

- depth of drainage water in the gas distribution layer / biofilter media.

Occasional / as required monitoring

There may be a need to undertake additional monitoring of the system if regular monitoring identified a potential problem. This may include the following:

- full temperature profile of the biofilter media

- full moisture content profile of the biofilter media

- gas composition profile of the biofilter

- assessment of clogging, possibly involving excavation, sampling and visual inspection of the biofilter media

- quantification of settlement of the biofilter media surface and

- microbiological analysis of the biofilter media.

8.3 Maintenance

Maintenance of a passive gas drainage and biofiltration system is dependent on the results of monitoring and may involve the following:

- drainage of water from the aggregate gas distribution layer if the biofilter is in box / above ground or lined

- maintaining vegetation growth on the biofilter media e.g. mowing, trimming, weed removal and disposal

- topping up the media to overcome media settlement, if required

- turn / fork upper layer of media, as required, when / if a crust forms

- addition of a wetting agent to the biofilter media (upper layers), if found to not be holding water

- replacement of the upper layers of the biofilter media, if the crust too hard to break up and / or a wetting agent does not work.

Replacement of the biofilter media, if required, as determined by monitoring. Indicators may include:

- reduced biofilter performance i.e. methane oxidation rate

- large / excessive settlement, which may adversely affect media porosity and subsequently gas and water movement through the biofilter media

- ponding of water on the surface of the biofilter, which may indicate clogging and

- clogging of the biofilter media, which may be due to settlement, microbial growth or EPS formation, and which may adversely affect media porosity and subsequently gas and water movement through the biofilter media.

9   Estimated costs

The cost of constructing and operating a passive landfill gas drainage and biofiltration system is dependent on a number of factors, most of which are site specific and dependent on:

The design of the system including:

- the size of the biofilter(s), which is dependent on landfill gas generation at the site and the selected / desired performance

- the design / layout of the passive gas drainage system

- the local availability and cost of the required materials e.g. composted garden organics, shredded wood, and recycled aggregate

- the scope of the monitoring program.

Consequently, costs should be estimated based on a specific concept or design developed for a landfill site. However, the following information is provided to assist with estimating the costs of a passive biofilter and passive gas drainage system:

$25 – 35 / m^3 for composted garden organics (~$13.50 / m^2 for a 1.0m thick biofilter)

$10 – 20 / m^3 for shredded wood (~$8.25 / m^2 for a 1.0m thick biofilter)

$2 / m^2 for a geotextile separation layer

$5 / m^2 for gas distribution pipework (within the base of the biofilter)

$25 / m^3 for the recycled aggregate ($12.50 / m^2 for a 0.5m thick layer)

$2.50 / m for the perforated drainage pipe in the gas drainage trench.

Based on the above typical costs, the cost of a 1.0m thick passive biofilter (45% / 55% composted garden organics / shredded wood mix) constructed within a landfill capping layer, with a 0.5m thick gas distribution layer with gas distribution pipework, would be approximately $40 per square meter. It should be noted that this cost needs to be considered against the cost of the final landfill capping layer, as the biofilter will replace the final capping layer. The cost of a final landfill capping layer can vary significantly depending on its design and the materials used. Small to medium sized 'typical' landfills would generally utilise on site materials and the final landfill cover layer could comprise a 500 mm layer of compacted clay and a 500 mm layer of revegetation soil. The cost of such a final capping layer could be of the order of $10 – 20 / m^2. Thus a passive biofilter may cost an additional $20 – 30 per m^2 of biofilter (over the cost of the final capping layer over the biofilter footprint).

For a 'typical' small to medium landfill the additional capital cost of a passive biofilter (over the cost of the landfill capping layer) could be as shown in Table 5 (adapted from UNSW and GHD, 2008).

Table 5: Estimated additional capital cost of a passive biofilter for a 'typical' small to medium landfill (at \$20 / m^2) (adapted from UNSW and GHD, 2008)

Landfill size (t / yr)	90% Methane oxidation[1]	75% Methane oxidation[1]	50% Methane oxidation[1]
< 5000	\$38,000	\$20,000	\$10,000
5–10,000	\$105,000	\$60,000	\$30,000
10–20,000	\$220,000	\$130,000	\$60,000
20–40,000	\$400,000	\$240,000	\$115,000
40–60,000	\$700,000	\$410,000	\$200,000

Notes:

1. Average performance during the 30 years after closure of the landfill.

From Table 5 it can be seen that the additional capital cost of a passive biofiltration system can vary significantly depending on the size of the landfill and the desired biofilter performance.

It should be noted that one of the benefits of a passive landfill gas drainage and biofiltration system is the small / negligible ongoing operating costs, which are essentially associated with monitoring the system (see Section 8). The cost of such depends on the frequency of monitoring and how the monitoring is undertaken i.e. landfill staff or consultants. If consultants are used the cost could be of the order of \$5,000 – \$10,000 per monitoring event, depending on the size / complexity of the system and whether the monitoring event is incorporated with other monitoring undertaken at the site e.g. leachate monitoring. Alternatives such as an active gas extraction and flaring system can have significantly higher ongoing operation, monitoring and maintenance costs.

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