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Review and Investigation of deep-seated fires within landfill sites

Science Report: SC010066

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Executive Summary

Deep-seated fires are known to occur within landfills throughout the UK. To avoid confusion with surface fires, this report uses the term 'hot spot' when referring to exothermic reactions below the surface of a landfill. There has been a limited amount of published data and little sharing of industry experience on this subject both within the UK and internationally. This report is a review of practical solutions that have been employed in dealing with hot spots.

From both a financial and environmental perspective, avoiding the development of landfill hot spots is preferable to remediating and repairing their consequences. Accordingly, this report emphasises the role of proactive and informed landfill management to prevent the occurrence of landfill hot spots. Targeted gas and temperature monitoring, effective waste acceptance procedures and measures to minimise air ingress to the waste mass are key to achieving this outcome.

A hot spot may develop when a combustible material (waste), a supporter of combustion (typically oxygen) and a source of heat occur together. The oxidation of organic materials by oxygen is an exothermic process and so, once ignited, a hot spot may be self-sustaining. Sources of ignition are not fully understood but may include biological or local chemical processes, as well as operational practices such as burying hot material within the waste. A smouldering mass of hot material will pyrolise to give flammable gases, which are easily oxidised, and a porous carbon matrix. The main products of complete combustion are carbon dioxide and water, but, since oxygen will normally be a limiting factor, carbon monoxide and other products of incomplete oxidation are usually also generated.

A hot spot or conditions that indicate a risk of combustion may be detected by monitoring the composition of the landfill gas. The presence of oxygen or other indicators of air diluting the gas are an important risk factor, while elevated levels of hydrogen are often associated with hot spots. High concentrations of carbon monoxide in the gas are also generally regarded as a primary indicator of a hot spot. Nevertheless, monitoring this gas on site may be unreliable and trends in the concentration of carbon monoxide are difficult to interpret. Measuring changes in temperature at either the surface or within the waste has also been used to locate fires. However, the low thermal conductivity of waste and the insulation provided by confining layers limits the use of this method.

Four common scenarios for the development of a hot spot are presented and potential implications such as accelerated settlement, temperature effects on containment mechanisms (such as geomembranes) and potential environmental impacts are discussed.

Preventative measures are reviewed and the temperature and gas triggers used at case study sites across the UK are summarised. Operational procedures to minimise ingress of air into the waste mass are also presented.

Control measures that can be implemented after a hot spot has been detected are reviewed. Finally, various remediation techniques, including excavation, dousing, ponding, subsurface injection systems, grouting and perimeter cut-off trenches, are described, along with details on their application and implications for health and safety.

This report is not intended as guidance to best practice, although it may give an insight into how issues can be addressed.

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1. Introduction

1.1 Background

Deep-seated landfill fires affect the containment and emission of landfill gas. They therefore have implications for landfill management practices and should be considered in landfill risk assessments for licensed and permitted sites. It is therefore important to build up an understanding of landfill fires in the UK. This report is a review of practical solutions that have been employed in dealing with hot spots. It is not intended as guidance to best practice, although it may give an insight into how relevant issues can be addressed.

1.2 Aims and objectives

The objectives of this project are summarised as follows.

Review existing national and international literature on fires within landfills.
Review the occurrence of fires (both confirmed and suspected) and the current practice for dealing with them at UK landfill sites.
Examine in more detail the specific circumstances and characteristics of a selection of landfill fires.
Identify appropriate key indicators and monitoring regimes and methodologies for assessing landfill fires prior to their onset, during their early stages and when established.
Identify and review the potential remediation options.
Produce a report setting out the findings of the literature review and outlining recommendations on the best practices for preventing and combating landfill fires.

1.3 Methodology

The first stage of this project comprised a review of available literature on the subject of deep-seated landfill fires. This literature included published papers and case studies, governmental studies, local and international regulations and other publicly-available sources of information.

Following this literature review, the frequency of landfill fires and the circumstances of their occurrence, together with the general experiences of landfill operators and regulators in the UK, were assessed. A wide range of landfill operators, both large and small, were consulted to discuss their experiences in detail. Information sources such as the Environment Agency incident database were also consulted.

The discussions with landfill operators yielded information about a wide variety of deep-seated fire incidents at landfill sites across the country over the past decade. From this list of incidents, a number were chosen for more detailed review as ‘case studies’. These case studies included an equal spread of both shallow and deep-seated fires, with a range of suspected causes, characteristics, and control and remediation methodologies. The selection of suitable sites also depended on the type of monitoring undertaken and the availability of data. All incidents, from the initial discussions with the operators to the final case study sites, are confidential. Case study information is thus given in this report without reference to site name, location, general site characteristics or any other identifying feature.

1.4 Layout of this report

The report is laid out in six main chapters.

Chapter 2 introduces the terminology of deep-seated landfill fires and hot spots used throughout this report, together with a brief description of the main characteristics of deep and shallow hot spots. The frequency of occurrence of landfill fires and hot spots, both in the UK and internationally, is also discussed.

Chapter 3 provides an overview of the thermodynamic theory behind fire processes. The three elements of the fire triangle – heat, fuel and a supporter of combustion such as oxygen – are discussed, and the concepts of ignition, spontaneous ignition, pyrolysis and extinguishing are introduced. Waste specific influences on hot spot development, such as waste composition, moisture content and compaction, are also described.

Chapter 4 describes various methods of hot spot detection, including detection through site walkover surveys and detection through gas and temperature monitoring. The temperature and gas concentration indicator and trigger values commonly used by both UK operators and international regulators are presented. Recommended temperature and gas concentration trigger values for use in the UK are discussed.

Chapter 5 introduces four common hot spot development scenarios and reviews the various effects of hot spots, such as the potential for causing physical damage to geomembranes and tyre drainage layers within the landfills. The environmental impacts of landfill hot spots are also discussed, although a fuller discussion is outside the scope of this report. Finally, available techniques for prevention are reviewed.

Chapter 6 discusses the range of control and remediation strategies employed both in the UK and abroad.

2. Overview of current experience

2.1 Definition of a landfill fire

This report is concerned with deep-seated landfill fires that occur within the waste mass. It does not cover surface fires at landfill sites, although it does consider surface fires as possible initial causes of deep-seated fires.

The term *hot spot*, rather than landfill fire, is used throughout this report, as it more accurately defines the nature of the phenomena being investigated. The term *fire* is highly emotive and is not necessarily an appropriate description for areas of raised waste temperature or smouldering that do not produce flames and smoke.

For the purposes of this report, hot spots have been divided into two broad categories: *shallow* and *deep* hot spots. A broad definition of each of these hot spots is given below and illustrated in Figure 1.

2.1.1 Shallow hot spots

Hot spots that occur within 5m of the current waste surface are defined as shallow. This depth generally equates to one or two lifts of waste and is typically the maximum at which the waste mass can be practicably excavated from the surface using standard site equipment. The broad definition of a shallow hot spot used in this report and some of its generalised characteristics are detailed below.

- The waste is within 5m of the current landfill surface.
- The shallow hot spot is more likely to be associated with uncapped operational areas or waste flanks than deep hot spots.
- The waste is likely to be relatively young – typically less than two years old.
- The hot spot is likely to have been caused by a pilot ignition source, such as a spark from a vehicle or the delivery and burial of a hot load.
- The waste may still be within the aerobic phase of waste degradation and relatively high waste temperatures may persist.
- The waste may be exposed to heating from the sun during the summer months.
- Shallow hot spots are typically discovered when smoke is seen rising from the waste surface or rapid settlement occurs.
- Where there is a poor containment system, air ingress can occur as a result of active gas extraction.
- Prevailing winds can lead to air ingress at exposed waste flanks.

2.1.2 Deep hot spots

Hot spots that occur more than 5m below the current waste surface are defined as deep. These hot spots are deep enough to make cooling, extinguishing and excavation significantly more problematic and expensive than for shallow hot spots. The broad definition of a deep hot spot used in this report and some of its generalised characteristics are detailed below.

- The waste is more likely to be older and in an advanced state of biological and chemical degradation than in shallow hot spots.
- The hot spot's extent and exact location is more difficult to establish, due to its depth.

- The hot spot is more likely to be the result of processes occurring within the waste mass rather than caused by hot material placed at the time of landfilling, although in certain cases this may still play a significant role in deep-seated hot spots.
- Air ingress to the waste mass is likely to be a result of a badly-managed active gas extraction system or a poorly-designed leachate re-circulation system.

2.2 Frequency of incidents in the UK

The assessment of the frequency of the occurrence of landfill fires is based on consultations with landfill operators that were willing to participate in the study on a confidential basis, a literature review and the knowledge base within the Environment Agency.

2.2.1 Assessment of the frequency of deep-seated fires

Golder Associates conducted a survey of the frequency with which hot spots occurred. This was based on confidential consultations with medium to large landfill operators in the UK and discussions within the Environment Agency.

The Environment Agency confirmed the widespread occurrence of hot spots throughout the geographical regions of the UK. Combining the incidents recorded by the Environment Agency with the incidents known to Golder Associates, a total of 78 hot spots were identified as occurring in UK landfills over the past few years.

Of the 78 incidents, 46 per cent occurred at operational sites and 23 per cent at restored sites, with the remaining hot spots occurring at ‘uncharacterised sites’. Air ingress to the waste as a result of active gas extraction systems and the over-abstraction of landfill gas was suspected to be the principal contributing factor for the majority (62 per cent) of sites. An additional 10 per cent of sites identified air ingress at exposed waste flanks as a major contributing factor to the occurrence of the hot spot. Materials within the waste such as marine flares, chemical waste or hot loads were suspected of causing 20 per cent of the incidents, and tyres were considered to be a contributing factor in 8 per cent of the incidents (see Table 1). This survey confirmed the frequently quoted opinion that air ingress is the greatest single factor associated with the formation of hot spots.

Table 1 Suspected causes and contributing factors given in survey

Suspected cause of hot spot	Percentage occurrence from 78 assessed incidents
Air ingress related to gas extraction system	62%
Waste material, such as hot load, chemicals	20%
Air ingress to exposed waste flank	10%
Tyres	8%

2.2.2 Operator experience

Consultation with landfill operators revealed a range of estimates regarding the frequency of hot spot occurrence. Some operators believed that deep-seated fires were common and suggested that there was a significant risk of a fire occurring at all sites with an active gas extraction system. Other operators believed that hot spots were rare, occurring only after the unusual placement of a hot load or an extremely flammable material. Many operators pointed out that the true frequency of occurrence could never be known since there may be undetected hot spots at closed sites, where there is infrequent monitoring and no visible effects. Most operators agreed, however, that deep-seated hot spots are possibly becoming more common and that this may be related to an increased emphasis on landfill gas extraction, resulting in greater air ingress to the waste mass.

2.2.3 Environment Agency National Register

The Environment Agency National Register provides details of emergency incidents at national waste sites. At the time of writing, there were 10 months of data available for the year 2002. Approximately 57 individual fire incidents had been recorded, although the register covers all types of fire incidents. Of the deep-seated fires at landfill sites, 44 per cent occurred at non-inert landfills and a further 9 per cent occurred at inert landfills. The percentage occurring at each type of waste site (non-inert landfill, inert landfill, composting facility and household waste sites) is illustrated in Table 2.

Table 2 - Occurrence of fire incidents at UK waste sites during 2002

Occurrence of hot spot	Percentage occurrence from 57 incidents notified to Environment Agency
Non-inert landfill	44%
Composting facility	28%
Domestic waste site	19%
Inert landfill[1]	9%

Note: 1. This is based on Waste Management Licence terminology.

Of the non-inert landfill fire incidents, approximately 57 per cent occurred below the surface of the waste and 13 per cent occurred at the surface. A further 27 per cent were the result of bonfires, suspected arson or similar causes. Surface fires may subsequently cause deep-seated fires, if, for example, they are still smouldering when buried. However, analysis of surface fires is not within the scope of this report.

2.2.4 Previous assessments of incident frequency

A study of the occurrence of all types of subterranean fires in the UK was carried out by the Fire Research Station for the Building Research Establishment in 1989 (Beever 1989). Information was sought directly from the fire service authorities in the UK, with 62 out of the 67 fire authorities responding to the request for information. The author acknowledged, however, that the statistics presented in the paper were likely to underestimate the frequency of occurrence of subterranean fires in the UK, as not all subterranean fires are notified to or attended by the fire authorities.

The fire authorities reported 64 subterranean fires over a three-year period to June 1987. Of these, 42 per cent (27 incidents) involved domestic waste sites. As some responses grouped together attendance at ‘domestic waste tip fires’, these figures may be conservative. The report also did not make a distinction between active and disused or closed landfills. In addition, 25 per cent of fires (16 incidents) were recorded in the coal or colliery waste site material category, which includes tips and sites where colliery waste had been used in landfilling. One recorded fire incident at a landfill involved the placement of foundry sand.

2.3 Frequency of overseas incidents

Relatively little research has been carried out internationally on the frequency of occurrence and characteristics of deep-seated hot spots. Although there is much anecdotal experience of hot spots, research on other related topics often reveals the lack of quantitative and in-depth information. Recent studies into the emission of dioxins, for example, often identify hot spots as a contributing source yet are unable to quantify this due to a lack of data on the hot spots themselves.

Findings from overseas studies need be considered carefully in relation to the type of fire being discussed (surface, shallow, deep), and the type of waste (domestic, construction and demolition) and landfill characteristics involved. A wide range of incidents may be grouped under the term 'landfill fire', regardless of the type of fire incident or waste site. It is also important to take into account the wide variation in landfilling practices around the world; for example, in some countries the burning of waste is still carried out. In addition, variations in waste input and environmental conditions may have significant effects on the reasons for landfill fires around the world.

2.3.1 North America

The United States Fire Administration has recently completed a comprehensive report on landfill fires (USFA 2002a). It reports that, on average, 8,300 landfill fires are reported to fire services each year. The landfill fires data set uses a broad definition of the term 'landfill', which includes 'refuse disposal areas, trash receptacles and dumps in open ground' (USFA 2002a). In addition, the term 'landfill fire' is used to cover surface and deep-seated (underground) fires. It is estimated that spontaneous heating accounts for around 5 per cent of the landfill fires (USFA 2002a).

The study also found that hot spots caused by spontaneous combustion are more likely to occur in the late autumn, with 22 per cent of such fires occurring in October and November. A gradual increase in the number of spontaneous combustion events occurs as ambient temperatures rise over the summer months, followed by a decrease in September. It is suggested that the subsequent increase seen in October and November may be due to the stronger winds (leading to air ingress) in these months, as well as the land surface heating over the summer (USFA 2002a).

In Canada, Sperling Hansen Associates has published papers discussing its experience of landfill fires on a case-by-case basis. Sperling and Henderson (2001) report that spontaneous combustion is the cause of the majority of the problematic, difficult-to-extinguish deep-seated fires. For example, of the eight problematic landfill fires experienced by the District of British Columbia in a two-year period, half were 'very likely' caused by spontaneous combustion. These were the Delta Shake and Shingle landfill fire (Sperling 2002b), the Vancouver landfill fire (Henderson and Sperling 2002), the Kelowna landfill fire and the Cache Creek landfill fire. These landfills, however, contained predominately construction and demolition waste, with a high proportion of wood, and so the findings are not directly comparable to municipal waste landfill sites.

2.3.2 Europe

A study carried out by Ettala *et al.* (1996) in Finland revealed that between 1990 and 1992, out of 633 operational landfills, a total of 380 were reported to have landfill fires annually. Of these fires, a quarter (approximately 95 sites) were deep-seated, which was defined for the purposes of the report as greater than 2m in depth.

This information was collected from questionnaires sent to technical departments responsible for landfilling and to fire brigades in 100 communities. Responses were received from 78 technical departments and 71 fire brigades. This study correlates well with an earlier estimate of 360 landfill fires per year in Finland (Viatek Tapiola Oy 1993 cited Ettala *et al.* 1996).

The frequency of occurrence of fires at landfill sites in Sweden is similar to that in Finland. A 1994 study by Naturvardverket (1994 cited Ettala *et al.* 1996) found that, out of 400 sanitary landfills, between 200 and 250 fires had been reported, a quarter of which were deep fires.

A study to better understand the release of dioxins in Denmark (Hansen 2000) concluded that dioxins may be formed within landfill fires. However, it asserted that landfill fires are rare in Denmark, stating that ‘the frequency and extent of such events in Denmark is small, as it is standard procedure in Danish landfills to cover the waste with soil’.

2.3.3 Asia and Australasia

It is quite common for poorly managed landfills in south-east Asia to be on fire. At one deep-seated hot spot in Manila, Philippines, flames were visible at the surface across the site (Golder Associates internal correspondence 2003).

Landfill fires are known to occur in Australia, although there is little regulatory guidance or involvement. Environmental management in Australia is on a state basis and each state’s Environmental Protection Agency (EPA) issues its own guidance.

The state of Victoria, for example, has included a two-page discussion of landfill fires in its Best Practice Guidance document for landfills (EPA Victoria 2001), which suggests that they have some experience of the topic.

A national review of all landfills in New Zealand was undertaken in 1995 by the Ministry for the Environment. This revealed that more than half of the landfill operators who responded had experienced fires at their landfills in the previous year. Almost a third of these fires were intentional, but the majority were accidental. Burning occurred more commonly at small landfills, although a significant proportion of large landfills also experienced fires.

A deep-seated landfill fire at a construction and demolition (C&D) landfill in Ma'alaea, Hawaii, led to widespread debate regarding landfill fires. According to the state Department of Health, almost every Hawaiian island has at least one landfill on fire, and all but one of the landfills in Hawaii has been on fire within the last six years (Environment Hawaii 1998).

2.3.4 Summary

Although there are reports of deep-seated hot spots occurring in a number of countries, there appears to be little published data on the frequency of occurrence or on methods for dealing with hot spots. Where case studies have been published, they tend to concentrate on the methods of containment or excavation and dousing to control the hot spot. There is anecdotal evidence of other techniques being employed, but little in the way of published case studies detailing the success or otherwise of these techniques.

3. Theory of hot spot development

3.1 Introduction

The development of hot spots in landfills is a complex process. There are many possible causes, with each hot spot having its own unique characteristics, conditions and contributing factors. A discussion of the possible causes of hot spots, many of them interrelated, is given in this section.

A fire is a chemical oxidation reaction, releasing energy in the form of heat radiation (elevated temperatures) and optical radiation (visible and invisible light). There are various manifestations of this chemical reaction, depending on the particular circumstances. Oxidation can occur with merely the liberation of small quantities of heat or can develop into self-propagating flaming combustion.

Similarly, oxidation within a landfill can occur slowly, with an area of the waste mass generating excess heat but not necessarily producing smoke and flames. These incidents are commonly called ‘hot spots’, ‘heating incidents’ or ROSEs (Rapid Oxidation Subsurface Events). The term ROSE is used by some US authors as an alternative to landfill fire, as it describes the heating of waste rather than waste that is actually on fire. The term hot spot is preferred to ROSE and is therefore used throughout this report.

Given the right conditions (ongoing presence of oxygen, insulation of heat), elevated temperatures can lead to slow smouldering combustion within the waste and flaming combustion on increased exposure to oxygen.

A brief introduction to fire theory and the key elements required, including overviews of the concepts of heating, smouldering and combustion and the interrelationship between them, are considered below.

3.2 The fire triangle

A fire is a chemical reaction involving heat, fuel and a supporter. All three – heat, the supporter of combustion (typically oxygen) and a combustible material (fuel) – must be present at the same time for a fire to occur. These three components can be illustrated by the ‘fire triangle’ (see Figure 2) and are discussed in more detail below.

The *supporter of combustion* is usually oxygen. However, there are some other supporters of combustion; for example, chlorine gas may oxidise reactive materials such as hydrogen, turpentine or finely divided metals, causing them to burn.

The amount of *heat* required to start a fire depends on many factors, including the combustion substance in question, the physical state of that substance and the size of the substance particles.

The *combustible material* is usually in the form of a vapour that has been released from the source material. Although it is this vapour that burns in reality, we will use the terms solid fuel when describing waste within the landfill and gaseous fuel when considering the burning of landfill gas.

A development of the fire triangle is the fire tetrahedron, which includes a fourth component – an uninhibited chemical chain reaction. This reflects the need for self-sustained combustion and therefore propagation, which is an essential feature of a fire. Self-sustained combustion occurs when sufficient excess heat is generated by the combustion reaction to produce ignitable vapours from the fuel source. This may be an important effect in the confined, low conductivity environment of a deep-seated landfill hot spot.

3.3 Fuel

Typical landfill waste materials such as domestic and commercial waste are potential fuel materials in a hot spot. Small quantities of highly flammable materials with low ignition points may also be present within the waste. Gases produced naturally in a landfill due to waste degradation, such as methane and hydrogen, are also potential fuel sources.

Materials that undergo smouldering combustion must be porous, in order to allow air to permeate within them, and must form a solid carbonaceous char when undergoing thermal decomposition. This charring process usually occurs at the point where the effects of self-heating are greatest, such as deep inside a landfill where insulation prevents loss of heat to the surroundings. The smouldering wave will then move outwards from the smouldering origin.

3.4 Heat

Heat can be generated within a landfill by both biological (microbial activity within the waste) and chemical (oxidation) processes. Heat can also be introduced into the landfill by hot waste loads.

Heat within a landfill cannot dissipate easily, due to the insulating properties of the waste mass. Self-heating of waste material occurs if the rate at which heat is generated is greater than the rate at which the heat can be lost to the surroundings. The rate of self-heating is critical to hot spot development within the waste.

If heat persists after the flames of a fire are extinguished and no opportunities for heat dissipation exist, slow smouldering of the waste may continue for a long period of time.

3.4.1 Biological degradation of waste

Biological degradation of the organic fraction of the waste generates heat. The typical temperature ranges for both aerobic and anaerobic waste degradation are given in Table 3. As this table shows, the temperature of a landfill greatly depends on whether the micro-organisms involved in the bacterial decomposition of the waste are in aerobic or anaerobic conditions.

Table 3 Heat generated by microbial activity in landfills

Stage		Temperature range (°C)
Phase 1 (aerobic)	Aerobic	80–90
Phase 2 (acidogenic)	Anaerobic	30–50
Phase 3 (acetogenic)	Anaerobic	
Phase 4 (methangenic)	Anaerobic	
Phase 5 (aerobic re-establishment)	Aerobic	80–90

Refs: Department of the Environment (1995); Environment Agency (2002a)

Background temperatures for non-hazardous landfills are typically in the range of 40–45°C for the first five years, stabilising in the majority of landfills to an optimum of 35–45°C (Environment Agency 2002a). These observations tend to confirm that the microbial population is dominated by mesophyllic bacteria (which prefer temperatures of 20–45°C), although it is possible for thermophilic bacteria (which prefer high temperatures) to perform the same roles of degradation at higher temperatures (50–80°C, given suitable conditions). As Table 3 shows, the ingress of air and resulting re-establishment of aerobic conditions may cause the temperature to increase to 80–90°C.

Various studies of landfill temperatures have been carried out internationally. A study on the old City of Hanover landfill, which was filled between 1936 and 1980 (Rowe 1998 cited Environment Agency 2003), showed that the temperature increased with depth to 30m below the surface and then decreased towards the base of the landfill. The base temperatures 10 years after closure (1990) ranged from 30°C to 60°C, with leachate levels at 4–6m above the base.

Similarly, leachate temperature monitoring data from six landfill sites in the UK was reviewed as part of an Environment Agency study (2003) into the generation of defects in geomembrane liners. The temperatures of extracted leachate samples ranged from 8°C to 46°C at five out of the six sites, with temperatures at each of the sites fluctuating by 16–30°C over the monitoring period. The sixth site, which had the greatest number of monitoring points, showed the greatest fluctuation over the monitoring period, with a minimum of 6°C and a maximum of 65°C. A more detailed discussion of typical leachate temperatures is given in the Environment Agency study (2003). Discussion of the actual temperatures measured in known hot spots is given in Section 7.

3.4.2 Other heat sources

Solar heating of a landfill surface is capable of increasing the temperature of landfilled waste and, in particular, of exposed waste on operational areas and waste batters. Shallow landfill waste is more sensitive to climatic conditions than deeper landfill waste, with variations in the waste temperature following seasonal variation in atmospheric temperatures. During the summer months, for example, the temperature of shallow waste can be seen to increase in direct proportion to increases in atmospheric temperatures.

Heat can also be generated by the waste itself. A number of hot spots have been attributed to the burial of hot loads or by smouldering waste from a partially-extinguished surface fire. In addition, some operators suspect that discarded cigarettes may provide an initial source of heat, resulting in the smouldering of buried waste.

3.5 Oxygen

The presence of oxygen within a degrading waste mass is believed to be major contributing factor in the development of hot spots. When oxygen is present within the waste mass, temperatures may increase as a result of aerobic microbial activity.

Evidence from the study of aerobic bioreactor landfills illustrates the role of oxygen in both waste degradation and fire ignition. Promoting rapid aerobic degradation of the organic fraction of waste leads to a faster initial rate of waste decomposition and settlement. The key to achieving 'stabilisation' of the landfill is the careful control of the oxygen concentration and keeping the waste mass temperatures and moisture content within optimal ranges.

Studies of aerobic landfills show the effects of increased oxygen within the waste mass, as also occurs in normal landfills due to uncontrolled air ingress to the waste. It was shown by Merz (1970 cited Hudgins and Harper 1999) that the introduction of air into a landfill caused temperatures in the waste mass to rise above 80ºC and led to ignition of the waste. However, it was proposed by Murphy (1992 cited Hudgins and Harper 1999) that adding moisture could control these temperatures.

A study by Reinhart *et al.* (2002) highlighted fires as a potential disadvantage of aerobic bioreactor landfills. 'The addition of air to landfills has long been associated with the potential for landfill fires. If uncontrolled, aerobic respiration can increase waste temperatures to levels where waste combustion may be a concern. Uncontrolled air addition could also result in creating gas mixtures with explosive characteristics. Proper control of the process remains a major issue.'

3.6 Combustion theory

3.6.1 Combustion of a simplified 'biomass' system

Upon burning, the organic fraction of landfill waste oxidises and decomposes into a complex mixture of gases (mostly comprising hydrocarbons) known as 'volatile matter' and a solid residue known as 'charcoal' (comprising mostly carbon.) During normal flaming combustion, the volatile matter burns above the surface of the biomass bed whilst the charcoal burns within it according to the following reaction.

Carbon combustion: $\text{C (solid)} + O_2 \text{ (gas)} = CO_2 \text{ (gas)}$
$[\Delta H^0 = -394 \text{ kJ/mol}]$

The above reaction is typically the biggest liberator of heat energy per mole of oxygen during the burning of organic material and biomass. The products of the combustion of the charcoal and volatile matter mix above the burning bed to produce a luminous flame.

One mole of pure carbon (graphite) has a mass of approximately 12 grams and will release 394kJ of heat energy upon complete reaction ($\Delta H = -394$kJ/mol). In practice, in charcoal beds where secondary heat consuming (endothermic) reactions normally occur (reaction of carbon dioxide (CO_2) and oxygen (O_2) to form carbon monoxide (CO)), it has been found that 1 kilogram of carbon will release 10.4MJ of heat energy when fully burned, which requires 4.85m^3 of air (Rehder 2000).

Once burning, the rate of heat energy release will depend on the rate of air supply. The typical carbon content of organic material is somewhere in the range 40 to 50 weight per cent. Upon burning, some of this will partition to the charcoal and some to the volatiles, typically in the form of hydrocarbons.

3.6.2 Enthalpy: heat of combustion

The term Adiabatic Flame Temperature (AFT) is used to describe the maximum attainable temperature from a combustion reaction. The AFT of a typical biomass mixture is approximately 1600°C. This can only be achieved if the heat is generated more rapidly than it is taken away. The rate at which the heat is generated is a function of the oxygen supply rate, while the rate of heat loss is influenced by any containment or insulating materials that surround the burning bed. The foremost factors that affect the AFT are described below.

An increase in the moisture content of the biomass fuel causes a reduction in the temperature of combustion. This is principally due to the fact that energy is absorbed in heating water and converting it to steam. It takes 0.075kJ/mol[1] to increase the temperatures of water by one degree Celsius and then a further 40.66kJ/mol to change its state from water to gas and allow it to escape from the system. It is not uncommon for biomass to contain up to 60 weight per cent moisture. Other combustible organic fractions such as plastics and paper will generally have lower moisture contents, but may hold leachate in their pores.

An increase in the air supply rate above that required for perfect (stoichiometric) combustion will cause a decrease in the AFT due to the presence of excess air in the system. The excess air does not react to liberate any heat energy, but acts as a heat sink as it passes through the system, exiting at a much higher temperature (hence energy level) than it entered.

A decrease in the air supply rate below the amount required for stoichiometric combustion will also decrease the maximum attainable combustion temperature, because the reduced heat energy liberation rate will create a lower equilibrium temperature in balance with the dissipation rate. If the air supply is reduced below a certain critical rate, the temperature will fall beneath that required to sustain the combustion reaction.

3.6.3 Exothermic and endothermic reactions

The carbon burning reaction detailed earlier produces a large quantity of energy as heat (394kJ/mol) and hence it is termed an ‘exothermic’ reaction. There will also be ‘endothermic’ processes that absorb heat energy. Two endothermic processes involving water are detailed below.

Energy absorbed (ΔH) in heating water from 25°C to 100°C = 28.0-22.4 = 5.6kJ/mol
Enthalpy change (ΔH) of water boiling (liquid to gas) at 100°C = 40.66kJ/mol

This demonstrates that when water is present in the system, a significant amount of heat energy is required to remove it (as gas).

3.6.4 Thermodynamics of combustion reactions

If a reaction results in a decrease of Gibb’s free energy (ΔG is negative) for that system, then it can happen spontaneously without interference from another system.

$\Delta G = \Delta H - T\Delta S$

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[1] One mole of water is approximately 18 grams

Where ΔG is the change in Gibb's free energy, ΔH is the change in enthalpy, T is the temperature in K and ΔS is the change in entropy (degree of disorder) caused by the reaction.

Carbon Combustion: $C \text{ (solid)} + O_2 \text{ (gas)} = CO_2 \text{ (gas)}$
$\Delta H^0 = -394\text{kJ/mol}$
$\Delta S^0 = 289\text{J/K}$
$T = 298\text{K}$
Hence, $\Delta G^0 = -480\text{kJ/mol}$

The principal combustion reaction of carbon has a ΔG of -480 kJ/mol at standard conditions (298K, 1atm), as calculated above. Hence it can occur spontaneously provided the activation energy is overcome (activation energy and ignition are discussed later.)

Combustion of other organic materials also takes place in landfill sites. Consider the combustion reactions for the following three substances, which are considered to be 'high-risk' waste fractions (Section 3.8).

Phenol combustion: $C_6H_6O + 7O_2 = 3H_2O + 6CO_2$
[ΔH = -2948 kJ/mol of Phenol]

Alcohol combustion (ethanol): $CH_3CH_2OH + 3O_2 = 2CO_2 + 3H_2O$
[ΔH = -1367 kJ/mol]

Benzene combustion: $2C_6H_6 + 15O_2 = 6H_2O + 12CO_2$
[ΔH = -3108 kJ/mol]

When compared to the carbon combustion reaction, it can be seen that these fuels will release a greater heat energy per mole of reactant (though marginally less per mole of O_2). In all three cases above, the combustion reaction involves the breakdown of a large, structured molecule into smaller products. Hence, there will be a corresponding increase in entropy (ΔS) and the reactions will be thermodynamically favourable at all temperatures. Such reactions will begin when the activation energy is achieved and will generate heat energy at a rate determined by the supply of oxygen.

3.6.5 Combustion in low oxygen atmospheres

When biomass materials are heated for a long period of time out of contact with air, pyrolysis occurs. Pyrolysis is the destructive distillation of carbonaceous material (Rehder 2000). It results in the formation of four types of product:

(i) gas of mixed organic composition;
(ii) pyroligneous liquid (water formed from the reaction of hydrogen and oxygen in the organic compounds);
(iii) tar; and
(iv) charcoal or pyrophoric carbon.

All the products except charcoal are gases at the temperature of their formation.

During pyrolysis, any moisture is first evaporated and then, at approximately 225–250°C (depending on the exact mix of fuels), pyrolysis (or thermal decomposition) begins to occur. A common example is the conversion of wood to charcoal, as described in Table 4.

Table 4 Effect of prolonged exposure to a heat source on timber

Temperature (ºC)	Effect of heating	Comments
150	Change of state starts	-
230	External browning	Self ignition possible
270	Pyrophoric carbon formed	Self ignition possible
300	Wood becomes charcoal	-

Ref: Dennet (1980)

The main products of pyrolysis have a lower ignition temperature than the material from which they were derived (Dennet 1980). In theory, pyrolysis can continue to char waste within a landfill for long periods. Or it can merely be the first step in the fire process, whereby the resultant char material, with a lower ignition temperature than the original material, undergoes spontaneous combustion. The pyrolysis of wood is believed to be a significant factor in producing hot spots in the US.

3.6.6 Smouldering

If a material begins to generate heat (for example by biochemical reaction) at a rate that is more rapid than the heat can be dissipated by surrounding material, then that material will continue to increase in temperature. Such a material may then begin smouldering. Only materials that form solid carbonaceous residue when heated (such as biomass) may undergo smouldering. A smouldering material is described as having three zones, which are given here in order (moving towards the smouldering front):

1. the virgin material;
2. zone of pyrolysis of the material to form carbonaceous residue; and
3. zone of oxidation of the carbonaceous material.

The highest temperature that is typically attained is in zone three and is in the order of 600–750°C. This is normally a localised temperature maximum.

3.6.7 Surface oxidation

Surface oxidation is a chemical reaction that occurs when a substance is exposed to oxygen. Its rate is far slower than that of combustion. Surface oxidation occurs more readily if the fuel is already at a raised temperature and so landfilled waste undergoing biodegradation could be more susceptible to surface oxidation than pre-landfilled waste. The surface of any free metal within the waste will oxidise, particularly if the local pH prevents the formation of a protective film on aluminium items. Surface oxidation is exothermic, releasing heat energy. However, since this reaction proceeds slowly it could have induction periods (delays) of days, weeks or months. Surface oxidation can potentially accelerate into a fire.

3.6.8 Oxygen and combustion processes

The type of combustion that may occur within a landfill is dependent on the amount of oxygen present (see Table 5). As previously described, waste can experience pyrolysis/thermal degradation in an oxygen-free environment. However, as the amount of oxygen is increased, the waste undergoes oxidation processes followed by smouldering combustion and, finally, with sufficient oxygen flaming occurs. The completeness of burning and heat generation increases with increasing oxygen, as illustrated in Table 5. Likewise, if oxygen is taken away from a flaming environment, smouldering may be re-established. This highlights an important factor when considering remediation of a landfill fire. By sealing off air ingress, the landfill fire may reduce to a smouldering hot spot. However, this does not mean that the fire has gone out and if oxygen is re-introduced within a suitable time period the fire can be re-established.

Table 5 Oxygen, heat and degrees of combustion

Term	Oxygen required	Heat liberation	Characteristics
Pyrolysis/ thermal degradation	No	No	Changes to waste occur on application of heat; Endothermic reaction (absorbs heat).
Surface oxidation	Yes	Yes	Chemical reaction that occurs when a substance is exposed to oxygen; occurs more readily when material is heated; exothermic (generates heat).
Smouldering combustion	Yes	Yes	Accelerated surface oxidation; insufficient oxygen results in incomplete/ inefficient burning and no flames; energy released as heat
Glowing combustion	Yes	Yes	Increased oxygen but again insufficient oxygen to produce flames; energy released as heat and in visible glowing
Flaming combustion	Yes	Yes	Sufficient oxygen for complete burning to occur; energy released as heat and in visible flames

3.7 Ignition

Ignition is a process by which a rapid exothermic combustion reaction is initiated and propagates, causing the material involved to undergo change (such as when a landfill hot spot becomes a fire). As described earlier, large amounts of heat energy are generated and temperatures greatly in excess of ambient temperatures are produced. Flammable volatiles are released from the surface of the burning material, which in turn ignite and contribute to heat generation.

There are two types of ignition: spontaneous ignition and piloted ignition; these will be discussed later.

3.7.1 Arrhenius equation (activation energy)

Although a given reaction is thermodynamically favourable at a given temperature, the activation energy must be achieved before ignition will occur and combustion reactions can proceed. The Arrhenius equation gives the activation energy (E_A) for a reaction. It is related to the rate constant (k) for a reaction by:

$$k = A.e^{E_A/RT}$$

Where R is the universal gas constant, T is Temperature and A is the Arrhenius constant for the reaction. Different reactions have different activation energies.

The ease with which the activation energy for a given reaction can be attained at a local reaction site will depend on the temperature of the substance. A higher temperature gives a greater probability that the required activation energy will be attained locally (Atkins 1994).

This is reflected in the Maxwell-Boltzmann distribution for the kinetic energy of particles in samples at different temperatures and is the reason that high temperatures can result in spontaneous combustion in materials (discussed later). A spark or a pilot flame can help overcome the activation energy and initiate the combustion reaction.

3.7.2 Flashpoint and spontaneous combustion

The flashpoint of a liquid is taken as the lowest temperature at which a flammable vapour/air mixture exists above its surface. The same phenomena can be observed with solids under conditions of surface heating. The generation of flammable volatiles involves chemical decomposition at the surface of the solid – as is seen during the pyrolysis process (previously described).

Spontaneous ignition (also referred to as spontaneous combustion or auto ignition) is the ignition of a fire without the application of a pilot flame. The volatiles arising from the surface of a heated combustible solid may ignite spontaneously if the volatile/oxygen mixture is within the correct ratio range and at a sufficiently high temperature. The process of spontaneous ignition requires a higher temperature than pilot ignition.

The induction period for spontaneous ignition of bulk solids is much greater than for gases. This is because oxygen must diffuse into the (porous) solid material to maintain oxidation reactions on the surface of individual particles, or microbiological activity within the waste must heat up surrounding waste to the temperature of ignition. Typical temperatures for the spontaneous ignition of timber are given in Table 6.

Table 6 Spontaneous ignition of timber

Type	Temperature (˚C)
Various	180–350
Wood-fibre board	215
Cane-fibre board	240
All timbers	430 (30 seconds exposure)

Ref: Dennet (1980)

3.7.3 Piloted ignition

Piloted ignition refers to the lighting of a material from an external source, such as an electrical spark or flame. This causes flaming to occur in the flammable vapour/oxygen mixture. This type of ignition again requires the presence of oxygen and high temperatures, in order to produce vapours before application of the pilot.

3.7.4 Flammability diagrams

Flammability diagrams (such as Figure 3) show the upper and lower limits of flammability for a vapour/air mixture plotted against temperature. If a vapour/air mixture is in the flammable region, the supply of the required activation energy (by a spark or ignition source) will cause combustion to start. This combustion then typically proceeds autogenously, with the energy released by the reaction supplying the activation energy required for it to perpetuate. If a critical temperature is reached, auto-ignition (spontaneous combustion) will occur without the requirement of a spark.

There are equations that can be used to calculate the critical temperature for auto-ignition. For example, the Frank-Kamenetskii model can give the critical ignition temperature for solids (Drysdale 1980) as long as the material has certain physical and chemical properties. In this model, the critical temperature is related to the activation energy for the reaction.

The Arrhenius equation demonstrates the principle of the activation energy required to begin the combustion reaction. At higher temperatures, the required activation energy is more likely to exist in local areas. Flammability diagrams (Figure 3) show the vapour/air mix and temperature limits that allow combustion and auto-ignition to occur. The exact locations of the boundaries of the flammable region are dependent on the chemistry and vapour pressures of the system reactants. Two main principles are demonstrated by the flammability diagram. Firstly, a reduction of oxygen supply can remove the system from the flammable region (A to B in Figure 3). Secondly, the higher the temperature, the more likely ignition is to occur. If the temperature is low enough, then the system is removed from the flammable region of the flammability diagram (C to D in Figure 3). Both of these principles are also reflected in the fire triangle discussed earlier (Figure 2).

3.7.5 Ignition of landfill gas

Gases such as methane and hydrogen are only flammable when they are mixed in certain proportions with other gases. These concentrations are referred to as the flammability or explosive range. The concentration limits are commonly known as the Lower Explosive Limit (LEL) and the Upper Explosive Limit (UEL), as shown in Figure 3. Both carbon monoxide and hydrogen sulphide are flammable gases, as are many of the volatile organic compounds (VOCs) present in landfill gas. These occur in such small concentrations that they are unlikely to affect the LEL but will add to the combustion of the gas. This contrasts with hydrogen, which may reach a concentration of several per cent by volume in some landfill gas. In circumstances where insufficient water has been used to cool hot carbonaceous material, concentrations of hydrogen may reach over 20 per cent. Furthermore, hydrogen is a very small molecule and will diffuse through barriers more rapidly than other gases, potentially enriching confined atmospheres.

The presence of percentage levels of hydrogen in the landfill gas mixture will significantly affect the overall explosive limit. The flammability limits for a selection of individual flammable agents within landfill gas (at 20ºC and 1 atmospheric pressure) are given in Table 7. Within these limits, where oxygen is present a small source of ignition is capable of generating an explosive ignition.

Table 7 Flammability limits for selected gases

Gas	Lower Explosive Limit (% vol)	Upper Explosive Limit (% vol)
Methane	5.4	15
Hydrogen	4.0	74.2
Hydrogen sulphide	4.0 (EA 200a)	44 (EA 200a)
carbon monoxide	12.5	74.2

Ref: CEC Handbook of Chemistry and Physics, taken from Lewis, B. and Elbe von, G., 1951. *Combustion flame and explosions of gases*.
Note: Values given in air at room temperature and pressure.

Above a particular threshold temperature, some gases will ignite and explode spontaneously. Table 8 gives typical spontaneous ignition temperatures for a range of gases. The common landfill gases – methane, hydrogen and carbon monoxide – all have high ignition temperatures compared to the typical temperature of a degrading waste mass. Therefore, spontaneous ignition is unlikely to be the main cause for the initiation of hot spots. However, there is still a significant health and safety issue with regard to the presence of a hot spot in a gas-rich landfill environment.

Table 8 Typical values of minimum spontaneous ignition temperature

Gases and vapours	Minimum spontaneous ignition temperatures (ºC)
Methane	601[1], 536[2]
Hydrogen	400[1]
carbon monoxide	609[1]
Carbon Disulphide	901
Ethane	514[2]
Propane	468[2]
Butane	406[2]

Refs: 1. Drysdale (1998)*; 2. Dennet (1980)*

**Note that other sources give similar but slightly different temperatures depending on circumstances.*

3.8 Waste specific influences

3.8.1 Composition

Landfill permits and licences provide controls on the waste types that may be deposited in non-inert landfills, thereby minimising the risk of unsuitable chemicals or highly flammable materials being placed in landfill. However, some materials that are commonly found within municipal waste streams are potential triggers for the development of hot spots. For example, Table 9 lists typical flash points of alcoholic drinks, which may be present in small quantities within household waste streams. The flash point is the theoretical temperature at which vapour released from the liquid will 'flash' momentarily when a flame is placed near it, but will not continue to burn. Similarly, Table 10 lists the flammability properties of some household cleaning products that may be present in the waste accepted at non-inert landfill sites.

Table 9 Typical flash points of alcoholic drinks

Alcoholic drinks	Flash point temperature (ºC)
Whisky	28
Brandy	29
Gin	32
Sherry	54
Port	54

Ref: Dennet (1980)

Table 10 Typical flammable materials within municipal waste

Product type	Possible ingredients	Flammability
Disinfectants	Phenols	Flammable
Floor cleaner/wax	Petroleum solvents	Highly flammable
Furniture polish	Petroleum distillates or mineral	Highly flammable

	spirits	
Paint thinner	Alcohols	Volatile and flammable
	Chlorinated aromatic hydrocarbons	Flammable
	Ketones	Flammable
Paints	Aromatic hydrocarbon thinners	Flammable
	Mineral spirits	Highly flammable
Motor oil/gasoline	Petroleum hydrocarbons (benzene)	Highly flammable
Toilet bowl cleaner	Chlorinated phenols	Flammable
Wood stain/varnish	Mineral spirits, gasoline	Highly flammable
	Benzene	Flammable

Ref: University of Arkansas (2003)

A wide range of other waste materials that may be flammable or ignite spontaneously are given in Table 11.

Table 11 Characteristics of various waste materials

Possible materials within waste mass	Characteristics
Clothing materials[1]	
Polyester	Moderately flammable, melts, drips
Rayon	Flammable (as cotton)
Polyamide *(nylon)*	Slow burning, melts, drips
Tendency to spontaneous heating	
Other[2]	
Sawdust	Possible
Manure	Moderate
Oiled rags	High
Charcoal	High
Linseed oil	High

Refs: 1. Dennet (1980); 2. Drysdale (1998)

It is considered likely that some hot spots are triggered by the presence of the materials listed in Tables 9–11. Certain waste streams may contain these materials, which are sometimes dispersed within finely divided materials. For instance, some fragmentiser wastes will contain oils, plastics and metal fragments in an open, porous matrix. A combination of biological and chemical reactions can heat this mixture soon after deposition.

Metals with a high electrochemical potential will undergo exothermic oxidation. Normally, a stable surface oxide protects aluminium, but if this is removed, for instance under conditions of high or low pH in the waste mass, then oxidation will proceed rapidly where air is present.

3.8.2 Waste moisture content

The presence of moisture is necessary for microbiological activity to occur within the waste (therby raising temperatures). But a high moisture content will affect the thermal conductivity of the waste, increasing the heat losses and thereby restricting the extent of self-heating, which is essential for sustained combustion to occur.

A moisture content of approximately 25 per cent is reported as being the optimum for spontaneous combustion. Drier conditions are likely to reduce the potential for microbial activity, whereas wetter conditions will reduce the mass porosity and restrict potential increases in temperature. (House 1998 cited Henderson and Sperling 2002).

3.8.3 Waste compaction

The effect of waste compaction on the occurrence of hot spots is not clear from existing literature or operator experience. Sperling and Henderson (2001) argue that continuous cover layers, such as intermediate capping, ‘may actually promote the spread of deep-seated landfill fires’ by ‘driving hot gases laterally and inducing horizontal convection currents’. Wilhelm (1995) suggests limiting the height of fill layers to 0.3m, compacting the waste in layers using compactors, creating embankments and limiting fill areas to 2000m^2 in order to reduce the potential for air to enter the waste body.

Although greater compaction can minimise the potential for air ingress to the waste mass, a major disadvantage is that the waste becomes denser, limiting the dissipation of heat and promoting increases in temperature.

Given the variability of the waste mass and the clear impact of air ingress, it seems unlikely that waste compaction will be considered a major contributing factor to the development of hot spots.

3.9 Extinguishing Fires

There are three basic methods for extinguishing fires, each of which involve removing one or more of the essential components of a fire – heat, fuel and oxygen.

1. Cooling – reducing the temperature of the combustible material so that it falls below the ignition point.
2. Smothering – excluding all or part of the oxygen.
3. Starving – removing the fuel or combustible material.

The overall aim of any intervention is to extinguish the hot spot and then reduce the temperature (and thereby the supply of flammable vapours) to below the critical limit. It is important to note that if the flame is extinguished without an accompanying reduction in the supply of vapours, a risk of re-ignition remains.

Materials that can be used in the extinguishing process include:

- inert diluents (such as nitrogen and carbon dioxide), which cool the reaction zone by increasing the effective thermal capacity of the surroundings;
- chemical suppressants that inhibit flame reactions; and
- water, which is commonly used for extinguishing and is particularly effective as it has a high latent heat of evaporation (2.4kJ/g at 25ºC) (Drysdale 1998).

Fires may extinguish themselves if one or more of the factors sustaining the oxidation process fails. For instance, if the hot spot is confined by incombustible wastes or the porosity of the matrix is reduced, the hot spot may be naturally smothered or staved. Competing processes such as microbial action may also remove the oxygen. Thus, it may not always be clear whether the successful extinguishing of a hot spot has been caused by a positive action or by exhaustion of a key factor.

3.10 Summary

There are a number of possible mechanisms for the development of hot spots within a landfill. The waste mass is highly variable between sites and even across a single site, and in many cases it will contain materials with relatively low ignition points. Therefore, each individual hot spot may be caused by a combination of the mechanisms described above or simply by burying a smouldering bag of waste.

The conditions for the development of a hot spot do not appear to be related to the waste type or age, the life stage of the landfill or the general landfill characteristics. Therefore, it seems likely that a specific trigger is required to generate a hot spot. The most likely trigger appears to be the ingress of air to the waste body, resulting in various exothermic oxidation processes. A hot spot may be extinguished by removing one of the sustaining factors, which may be achieved by positive action or by exhaustion of a factor.

4. Detection

4.1 Introduction

Hot spots can smoulder for many months or even years without detection. Although routine environmental monitoring data can be used to detect the presence or development of a hot spot, they are often not used.

Where sites do not utilise existing monitoring data, the methods for hot spot detection are generally unsophisticated, with a reliance on visual signs such as unusual settlement, smoke or even flames, and excessive heat at leachate or gas wells.

Typical methods of detection together with examples of monitoring installations are detailed below.

4.1.1 Detection surveys

Regular site walkovers can lead to the early detection of hot spots. Observation of the landfill surface and any unusual changes over time can provide invaluable information. The following is a list of some of the signs of potential hot spot activity.

- *Unusual/localised settlement leading to the possible emergence of cracks in the cap and restoration soils.* However, distinguishing between settlement caused by normal waste degradation processes and rapid waste breakdown due to a hot spot is difficult. In addition, not all hot spots will produce a distinct surface impression, particularly if the hot spot is deep or if it occurs in an operational area, where surface irregularities are more difficult to discern.

- *Rising smoke or steam.* Some hot spots produce rising smoke or steam from breaks in the cap or from installations within the waste mass, such as gas or leachate wells. This is often the first sign of a shallow hot spot, particularly in operational or temporary cap areas. At some sites, the smoke or steam indicates that a hot spot is located close to or immediately beneath the area of emission. However, it is equally likely that the steam or smoke is not directly above the location of the hot spot. Hot gases and smoke can be drawn away from the hot spot by the gas extraction system or air currents within the waste mass. The steam or smoke only becomes visible where there is a pathway to the surface.

- *Nutty or barbeque odour from in-waste installations*.

- *Hot-to-touch leachate or gas wells*. These are usually in close proximity to the hot spot, although the temperature of installations may be affected by the migration of hot gases.

- *Changes in vegetation on restored areas*. This may be lush growth due to warming from below. In contrast, where the hot spot is close to the roots of existing plants, there will be die back.

- *Presence of tar-like residues in gas collection system, such as valves*.

- *Increased requirement to change engine oils in gas-to-power plants*. This may be due to the landfill gas containing a more aggressive chemistry as a result of a partial or complete combustion process.

4.1.2 Detection through monitoring

Monitoring can be carried out to identify the risk of a hot spot developing and, once identified, to monitor its development, control and decline following remediation works. All monitoring should be carried out according to the monitoring protocols set out in guidance documents, such as those produced by the Environment Agency (2002a).

Primary aims of the monitoring scheme should be to:

- provide a warning of the potential development or occurrence of a hot spot;
- identify the lateral and vertical location of the hot spot;
- determine the possible causes of the hot spot;
- determine the actual and potential effects on the site engineering and environmental management system; and
- to verify the effectiveness of the control and remediation strategies.

4.2 Gas concentration monitoring

In-waste landfill gas monitoring is typically undertaken for methane, carbon dioxide and oxygen. In addition, some sites will record some or all of the following: hydrogen, hydrogen sulphide, carbon monoxide and nitrogen. In the majority of cases, the measurement of carbon monoxide and hydrogen is in response to a known hot spot or simply carried out because the portable gas monitoring equipment supposedly has the capability to do so. Monitoring of other gases is undertaken at selected sites, although usually as a result of ongoing research or in response to a known gas problem.

In-waste gas monitoring is typically undertaken with industry standard portable instruments and for the majority of sites this has proved suitable for the operators' requirements. At some sites, field gas monitoring results are periodically calibrated with laboratory analysis. However, in most of the case studies investigated, laboratory analysis of in-waste gas samples was not undertaken on a regular basis. Where laboratory analysis was undertaken, it was generally in response to concerns over the validity of results obtained with the portable instruments when measuring carbon monoxide, hydrogen and hydrogen sulphide.

In many cases, the monitoring of carbon monoxide is not undertaken as part of routine site monitoring but is undertaken once a hot spot is suspected or known to be present. Therefore, not all sites have a reliable indication of the background carbon monoxide concentration prior to the onset of the hot spot.

The data detailed in this section has been taken from a number of operators, using different monitoring equipment, monitoring strategies, record keeping and frequency of monitoring. The datasets are generally insufficient to stand up to rigorous examination and can only be used to provide general trends and indications of the effects of hot spot development on gas concentrations. The range of concentrations given for the various gases and the trends they show are site-specific. However, the results do show that sufficient data can be obtained from monitoring the typical suite of landfill gases using industry standard equipment to provide clear indications of the risk of a hot spot developing, the presence or otherwise of a hot spot and the measurement of the hot spot decline. The exception is carbon monoxide, as discussed in Section 4.2.3, for which erroneous results have been recorded as a result of interference within the monitoring equipment.

The typical range of landfill gases monitored and the changes in gas concentrations identified prior to and on discovery of a hot spot are summarised in Table 12. Typical trends from sites with known hot spots are described in the following sections and indicative trigger values – taken from literature and operator experience – are given where appropriate. A suggested range of trigger values, based on the data gathered, is given in Section 4.2.6.

The monitoring of oxygen, methane and carbon dioxide can be used to provide an indication of the potential increase in the risk of a hot spot occurring. It can also be used to monitor the effectiveness of some control and remediation techniques, but it cannot measure the hot spot.

Table 12 Summary of gas monitoring

Gas	Indication of potential development/presence of hot spot	Comments
Methane	Decrease	Indicates ingress of air. Concentration may recover even though hot spot still active.
Carbon dioxide	Decrease	Indicates ingress of air. Concentration may recover even though hot spot still active.
Oxygen	Increase	Indicates ingress of air. A precursor to hot spot development and continued feed to hot spot development.
Carbon monoxide	Increase	Used to indicate the presence of a smouldering waste.
Nitrogen	Increase	Indicates ingress of air. Remains stable, illustrating ingress of air to the waste mass.
Hydrogen	Increase	May indicate disruption of microbial action or water gas generation in a hot spot. Monitoring may be required to assess the impact on carbon monoxide. Can be used to monitor remediation works.
Hydrogen sulphide	Variable	Monitoring required to assess impact on carbon monoxide. If hydrogen sulphide is high (>10ppm), then scrubbers should be fitted in line between the analyser and measuring points.

4.2.1 Oxygen concentration

Elevated oxygen concentrations, or an unexpected increase in oxygen concentration, generally indicates the ingress of air to the waste mass. Although the presence of oxygen does not mean that a hot spot exists, the presence of oxygen makes exothermic reactions more likely. Hence, it is closely associated with an increase in waste temperature, thereby increasing the risk of a hot spot occurring. Also, the addition of oxygen to a waste mass with an existing hot spot is likely to increase the magnitude of the problem. Therefore, oxygen is commonly used as an indicator for the potential development of a hot spot.

The majority of operators have established trigger values for the concentration of oxygen within the waste mass. These trigger values tend to be site-specific and related to the layout of the gas extraction system and the method of in-waste monitoring. The trigger value for oxygen should not be taken in isolation, but should be used in conjunction with the concentrations of bulk landfill gas. From discussions with operators, the typical range of oxygen concentrations that are used as indicators of concern range from 1 per cent to 10 per cent oxygen by volume. The consensus is a trigger towards the lower end of this range.

Table 13 Typical oxygen trigger values

Oxygen concentration	Comments
Lewicki (1999)	>1 per cent oxygen indicates significant air ingress and over-pumping
United States Landfill Guidance (EPA 1999)	>5 per cent oxygen indicates air infiltration into the landfill and likelihood of hot spot development

When establishing trigger concentrations for oxygen in the waste mass, the following points should be taken into consideration.

- The concentration of oxygen monitored will depend on the proximity of the monitoring point to the source of the oxygen. Oxygen concentrations are likely to become depleted as oxygen passes through an anaerobic waste mass or is used for combustion in hot spot areas. This means that the concentration of oxygen at the monitoring point may be less than within the waste mass. Therefore, it is advisable to take a conservative approach when considering the trigger levels for oxygen.
- In-waste gas monitoring is not always undertaken at individual installations. In some cases, the monitoring may be undertaken by testing a mixture of gases at collection manifolds, in collection pipe monitoring points or from the flare/engine compound. As a result, the recorded concentration of oxygen may be significantly less than at the hot spot location.
- Reduction of oxygen concentrations following control and remediation work indicates that a hot spot has been controlled by reducing the level of air ingress. It does not mean that the hot spot has been extinguished, as experience from a number of sites suggests that a hot spot may smoulder in an oxygen-deficient environment for many months or even years.

Due to the importance of oxygen to the development of hot spots, it is recommended that measured oxygen concentrations exceeding 1 per cent by volume in the waste or gas extraction system should be used to trigger action on site.

4.2.2 Methane and carbon dioxide

The monitoring of in-waste methane and carbon dioxide concentrations can provide a good indicator for the potential development of a hot spot and also for the success of any remediation strategies.

Regular monitoring of bulk landfill gas should allow the operator to determine the stage of waste degradation and therefore the expected gas concentration when compared with the established gas generation curve (see Figure 4). Regular monitoring will also allow the operator to determine the typical background bulk gas concentrations for the site. Significant variations from background gas concentrations or from the expected gas generation curve should be investigated, as this may indicate conditions suitable for the development of a hot spot.

As an example, a landfill cell with aged waste in the Phase 4 (anaerobic) stage of degradation (see Figure 4) and reaching peak landfill gas production will typically produce gas containing in the region of 60 per cent methane, 40 per cent carbon dioxide and no oxygen. In contrast, hot spots where significant air ingress has occurred have gas with depleted methane and carbon dioxide concentrations and an increased oxygen concentration. They also show a corresponding increase in the proportion of nitrogen, which will be higher than in the normal composition of air due to the depletion of oxygen by reactions in the waste. In addition, when air has been pulled into the waste, the ratio of the concentration of methane to carbon dioxide will fall, due to chemical and microbial oxidation processes generating carbon dioxide. An example of this is given in Table 14 and Figures 5 and 6.

Table 14 Example gas concentrations at hot spot

The gas concentrations given below are taken from a site with a hot spot suspected at a depth of approximately 15m below the top of the waste. The hot spot was identified through routine inspections, which indicated an unusually hot gas well. At this stage, gas and temperature monitoring was undertaken. There are no significant data for gas concentrations prior to the known occurrence of the hot spot. However, the case study shows typically depleted carbon dioxide and methane concentrations compared to the background concentrations for the site, which are approximately 55 per cent methane and 45 per cent carbon dioxide.

Date	Methane (%)	Carbon dioxide (%)	Oxygen (%)	Carbon monoxide (ppm)	Hydrogen (%)
Pre action	**10**	**16**	**8**	**52**	**1.6**
Post action	**55–56**	**43–44**	**0.05**	**6–19**	**0.06–0.07**

Notes: 1. Pre action refers to a monitoring round prior to hot spot control actions; 2. Post action refers to four monitoring rounds over a two month period following the hot spot control actions.

The effects of sealing off the potential pathways for air ingress, turning down the gas extraction system and dousing the hot spot can be clearly seen in Figure 4, with a recovery of the gas concentrations to background levels.
(Case Study)

From the reviewed case studies, the time period for recovery of gas concentrations is expected to be rapid. Figure 5 shows a recovery of gas concentrations within three weeks of implementing control measures. It should be noted that the hot spot in this case study may be under control but has not necessarily been extinguished.

The monitoring of bulk landfill gas can be used, in conjunction with other monitoring, to provide a general indication of the potential location of the hot spot. Table 15 shows the correlation of gas concentration with distance from a known hot spot, as measured from in-waste gas extraction wells. It records landfill gas at expected background concentrations within at least 70m of the hot spot. The actual distance to recovered gas concentrations will be site-specific and a function of the source of air ingress and the effect of the gas extraction system in the waste environment.

Given the clear correlation between the drawing in of air and the bulk landfill gas

Table 15 Comparison of hot spot with background gas concentration data

The data below shows depleted methane and carbon dioxide concentrations and elevated oxygen concentrations in the closest well to the hot spot. The recovery to typical background bulk gas concentrations for the site occurs over a maximum distance of 70m. The location of the hot spot is an estimate, since monitoring is only undertaken from existing gas wells within the waste mass. Similarly, the recovery of bulk gas concentrations to background concentrations may occur much closer to the hot spot than indicated below.

Monitoring point	Methane (%)		Carbon dioxide (%)		Oxygen (%)	
	Pre action	Post action	Pre action	Post action	Pre action	Post action
Close to hot spot	10	55–56	16	43–44	8	0.05
70m away	56	56	43	43–44	0.05	0.05
110m away	51	52–55	40	41–42	0.2	0.05–0.15

Notes: 1. Pre action refers to the period immediately before remediation action was undertaken but after the hot spot was identified; 2. Post action refers to four monitoring rounds over a two month period following the hot spot control actions; 3. Actions included sealing of air ingress, turning down the gas extraction system and dousing.

(Case Study)

concentrations, regular monitoring of in-waste installations should be used to provide an early warning of the development of conditions that are related to the development of a hot spot. Suggested trigger values are given in Section 4.2.6.

4.2.3 Carbon monoxide concentration

Carbon monoxide is potentially a vital gas for the monitoring of all stages of hot spot development and decline, as it is a direct product of the heating/combustion process. However, the data reviewed during this research was insufficient for clearly identifying the concentrations of carbon monoxide at various stages of hot spot development. Therefore, at present, the use of carbon monoxide is restricted to monitoring the effectiveness of control and remediation strategies, unless site-specific background data are available.

Carbon monoxide is not usually present in significant quantities within landfill gas but is produced by fires involving carbon-based fuels. The yield of carbon monoxide depends on the conditions at the hot spot and the availability of oxygen. Within a landfill, the combustion of carbon is likely to be sub-stoichiometric with respect to oxygen (oxygen will be limited) and so carbon monoxide will be a component of the gases produced in deep-seated hot spots. However, when a hot spot is smothered, oxygen is severely limited and so a high proportion of the gas produced may be carbon monoxide. It is widely reported that an increase and subsequent decrease in carbon monoxide concentrations can indicate the presence and subsequent successful extinguishing of a hot spot (see the following case study).

Monitoring at an experimental waste bank,

An experiment was undertaken in Finland (Ettala *et al*. 1996) to determine the characteristic gases and temperatures generated by a landfill fire. This was carried out by establishing an artificial municipal landfill and setting it alight. Thermocouples shielded by steel tubes measured the waste temperature at 1.5m and 5m from the edge of the ignition well and at depths of 7m and 3m respectively. The temperatures measured rose to 350ºC after which the temperatures decreased slowly. Temperatures within waste unaffected by the fire were within the range 25–37ºC at 3m depth and 25–46ºC at 7m depth.

Steel gas sampling tubes placed on a wide 3mx3m network of monitoring points were used to measure the carbon monoxide, carbon dioxide (using an infra-red analyser) and oxygen (paramagnetic analyser) concentrations. Table A below reproduces the concentrations of the carbon monoxide and oxygen detected in the experiment.

Table A Oxygen and carbon monoxide sampling

	Oxygen (%)		carbon monoxide (ppm)	
	Median	Range	Median	Range
Setting alight	1.1	0.7–11	280	190–1300
Smouldering fire	2.5	0.7–3.3	280	94–1200
Extinguishing	5.1	5.1–6.0	1600	1500–1600

This experimental study showed that carbon monoxide concentrations peaked during the fire-extinguishing phase. The median concentrations during the setting alight and smouldering phases were both 280ppm, increasing to 1600ppm during the extinguishing phase. The range of carbon monoxide concentrations is similar to those recorded from sites in the UK.
(Case Study)

Typically reported ranges for background concentrations of carbon monoxide vary, resulting in a wide range of trigger values for those using carbon monoxide as an indicator gas. Research work by Sperling (2002a) reports that carbon monoxide concentrations of up to 1,000ppm have been monitored at landfill sites where there is no suspicion of combustion, although the nature of the waste streams involved is unclear. Sperling (2002a) also argues that elevated carbon monoxide concentrations may be due to pyrolytic processes within the waste, as pyrolysis of cellulose produces by-products such as tar, char, carbon dioxide, water and carbon monoxide. As such, Sperling (2002a) argues that carbon monoxide levels above 500ppm are of concern, as pyrolysis is the precursor to spontaneous combustion. However, such high background levels of carbon monoxide are not accepted elsewhere; a summary of the broad range of carbon monoxide concentrations and the relationship with hot spots is given in Table 16.

Table 16: Carbon monoxide indicator concentrations

Carbon monoxide concentration	New Zealand[1]	Canada[2]	California[3]
> 1ppm or 2ppm	Indication of underground combustion	No underground combustion	No underground combustion
10ppm to 100ppm			May indicate a fire but active combustion not present
25ppm to 100ppm		Possible fire in area	
100ppm to 500ppm		Potential smouldering nearby Fire likely	Suspicious and require further monitoring

500ppm to 1,000ppm			Fire likely
>1,000ppm		Active underground fire	Indication of active underground fire

Notes: 1.New Zealand Ministry for Environment (1997); 2. Canada Practice (Henderson and Sperling 2002; Sperling 2002a); 3. Regulators in California (USFA 2002, p.14); USFA 2002a.

The wide range of trigger concentrations associated with carbon monoxide and hot spots may in part be due to inaccuracies in the monitoring of this gas. Monitoring of carbon monoxide using some industry standard portable instruments is subject to interference from other trace gases, resulting in erroneous readings. Older equipment particularly suffered from interference and so a review of historical data does not accurately reveal the role of carbon monoxide before, during or after a hot spot.

Carbon monoxide is often considered to be a ‘sticky’ gas, and is thought to affect subsequent readings by the carbon monoxide cell in standard monitoring equipment. It is often stated that residual carbon monoxide can remain within the analyser following measurement of elevated carbon monoxide concentrations. This may result in subsequent readings being erroneously high. However, this issue may be avoided if monitoring is undertaken correctly and if the equipment is purged between each monitoring location.

Various VOCs, hydrogen and hydrogen sulphide can interfere with the measurement carbon monoxide using hand-held instruments. Hydrogen and hydrogen sulphide may be present in landfill gas at concentrations where the electrochemical cell used to measure carbon monoxide can suffer from cross-gas effects.

Recently a new gas analyser has been developed in the UK, with the aim of avoiding these cross-gas effects. However, carbon monoxide concentrations recorded on some portable equipment are likely to give erroneous readings, typically greater than the actual concentrations present. Concentrations are also often reported that are outside the accuracy

Table 17: Examples of Carbon monoxide trigger values from UK operators

Carbon monoxide concentration	Comments from a variety of operators
1–50ppm	**Typical range of carbon monoxide concentrations regarded as background.**
50ppm	**Indicates the possible presence of a hot spot and the gas extraction system may be reduced until concentrations return to below 20ppm.**
100ppm	**Background carbon monoxide concentrations measured at sites with no known hot spot.**
250ppm	**Some operators use this value as an indicator to undertake further investigation.**
500–1000 ppm	**Generally considered to indicate the presence of a hot spot.**

The values given above are generally taken from sites where carbon monoxide has been determined using industry-standard, portable monitoring instruments. These are subject to interference and in the absence of supporting laboratory analysis the field values will correspond to much lower actual concentrations of carbon monoxide.

(Case Study)

range of the portable equipment. As a result, comparing carbon monoxide monitoring data obtained using typical portable instruments is fraught with difficulties. Until a sufficient dataset is available, either from existing laboratory data or obtained in the future by more reliable portable monitoring equipment, carbon monoxide can not be regarded as a reliable indicator of the potential development of a hot spot.

Data from laboratory analysis of carbon monoxide confirms the variability in the data collected using portable instruments. Insufficient laboratory data are available to provide a clear understanding of the concentrations of carbon monoxide before, during or after a hot spot. However, the data provided does show a change in carbon monoxide concentrations during the remediation and decline of a hot spot.

The monitoring of carbon monoxide is commonly undertaken by operators once the presence of a hot spot has been identified and is then often continued throughout the remediation process. As a result, most operators with experience of hot spots will have established general trigger concentrations. Operators generally use an increase and subsequent decrease in carbon monoxide concentrations as an indicator of the presence and control of a hot spot. These are typically relative variations in concentration, used to indicate changes in hot spot activity within the waste. Examples of trigger values used by some operators are given in Table 17.

A wide range of trigger values for carbon monoxide are in common use. This may be due, in part, to carbon monoxide:

- not normally being measured as a background gas for each landfill and so there is little data on site-specific background concentrations; and
- concentrations may peak during the smouldering stage, after control measures have been carried out.

Carbon monoxide concentrations generally show a good correlation with temperature, even if actual values of carbon monoxide may be erroneous. As a result, carbon monoxide is often monitored in conjunction with temperature as an indicator of the success of control and remediation works.

Carbon monoxide is a good indicator for the presence of ongoing combustion processes. However, it may also be generated by processes such as the pyrolysis of waste (which may not lead to combustion). Therefore, using low concentrations of this gas as a key indicator for the potential development of a hot spot is fraught with difficulty. Unless a site has an established background concentration, or until accurate monitoring is undertaken over a wide range of sites, it is difficult to apply a general trigger value for carbon monoxide.

- The background concentration of carbon monoxide should be determined by routine monitoring throughout the site, using reliable portable instruments or laboratory analysis.
- Cross-gas interference on some portable monitoring equipment may give an overestimate of the carbon monoxide concentration. Portable instruments should not be used above their accuracy ranges (for example, 0–500ppm – see individual manuals). Concentrations should also be confirmed with laboratory gas chromatograph (GC) analysis.
- An increase in carbon monoxide concentration above background, or a significant change in the trend of carbon monoxide concentration, should initiate actions to investigate the cause.

- From the small data set reviewed, background carbon monoxide values ranged from zero to approximately 30ppm. At least one case study undertook regular laboratory analysis at a known hot spot, giving maximum carbon monoxide concentrations of 52ppm. Some sites have monitored background carbon monoxide at 100ppm with no known hot spot. Therefore, until a larger data set is established, a likely conservative concentration of 25ppm carbon monoxide may be used to indicate the presence or development of a hot spot.
- Trends in carbon monoxide concentration can be used as a measure of the development and effectiveness of control measures.

4.2.4 Nitrogen concentration

Nitrogen is not typically directly monitored at landfill sites, but it is a potentially good indicator of the ingress of air to the waste mass. Although the nitrogen gas concentration is often reported, it is a calculated value rather than a measured one. It is normally the residual after accounting for the measured concentration of methane, carbon dioxide and oxygen. Nitrogen exists within landfilled waste during the aerobic and early stages (I, II, III and V) of waste degradation. However, nitrogen is not expected in the anaerobic, methane-producing phase of waste degradation (stage IV). Therefore, where nitrogen is present at this stage of landfilling, it indicates that air is being drawn into the waste mass.

Nitrogen concentrations can be used in conjunction with oxygen content as a measure of air ingress into the waste mass. Whereas oxygen can be consumed within the waste, either by aerobic degradation of the waste or by oxidation/fire processes, nitrogen is inert and will be conserved within the landfill environment. Lewicki (1999) suggests that a concentration of nitrogen above 10 per cent by volume may indicate considerable air ingress into the waste mass.

Landfill guidance in the US (EPA 1999) recommends that nitrogen concentrations are monitored and used as an indication of air infiltration into the landfill. The guidance states: '[An] excessive gas extraction rate may cause air infiltration into the landfill through its surface and sides. Under the rule, nitrogen gas concentration in the collected landfill gas must be maintained below 20 per cent (or the oxygen concentration below 5 per cent)…'.

Work undertaken by Lewicki (1999) suggests that the ratio of nitrogen to oxygen can be used to estimate the likely source of air ingress in relation to the monitoring point. In brief, as distance from the source of air ingress increases, the oxygen component is lost whereas the nitrogen component remains. A ratio of oxygen to nitrogen in the region of 1:4 indicates air ingress close to the monitoring point (little change in oxygen concentration from atmospheric) whereas a lower ratio indicates air ingress at a greater distance from the monitoring point.

Riquier *et al.* (2003) found that when the monitored concentrations of methane, carbon dioxide and oxygen, together with a calculated nitrogen concentration (3.8 x monitored oxygen), are added together, a sum of 100 per cent is never obtained in a hot spot area. Riquier *et al.* (2003) concluded that this was as a result of oxygen and methane being consumed by the combustion. However, it should also be noted that if the nitrogen content was measured rather than calculated, the measured value could be significantly higher than the calculated value and a sum close to 100 per cent results.

In practice, nitrogen is not commonly monitored from in-waste gas monitoring points and none of the case studies had sufficient data to add to the literature studies. However, the potential benefit of monitoring nitrogen can be seen from the measurements of bulk gases.

A waste mass in the anaerobic stage of degradation (Stage IV) and reaching peak landfill gas production would be expected to produce approximately 60 per cent methane, 40 per cent carbon dioxide and zero oxygen. The total percentage of gas would be approximately 100 per cent. As shown in Table 18, the concentration of bulk gases reduces dramatically with the ingress of air. The case study example given in Table 18 shows a total percentage of bulk gases (methane, carbon dioxide, oxygen) of 34 per cent. It is generally assumed that the majority of gas making up the remaining 66 per cent is nitrogen, indicating a significant ingress of air (there are four parts air to one part landfill gas in this example).

Table 18 Comparison of nitrogen and bulk gas concentrations from case study data

Gas	Background concentrations (%)	Hot spot area (%)	Air (%)
Methane (%)	**56**	**16**	**-**
Carbon dioxide (%)	**43**	**10**	**-**
Oxygen (%)	**0.05**	**8**	**~20**
Nitrogen (%)	**Not analysed**	**Not analysed**	**~80**
Total (%)	**~ 100**	**34**	**~ 100**

Note: 1. Landfill gas and hot spot gas concentrations taken from a case study.

(Case Study)

Therefore, if monitored or calculated from other bulk gases, nitrogen can be used as an indicator of air ingress and potential hot spot development. However, elevated nitrogen concentrations do not indicate that a hot spot is present and do not provide an indication of the success or otherwise of remediation techniques other than sealing off the air ingress.

4.2.5 Hydrogen

Hydrogen is produced during the early (acidogenic and acetogenic) stages of waste decomposition (see Figure 3). Under fully anaerobic conditions, hydrogen is rapidly scavenged and used in the reduction of carbon dioxide to methane (CH_4). Young waste in its early stages of decomposition would normally exhibit a net production of hydrogen, whereas older waste undergoing anaerobic degradation would not. Therefore, if measurable amounts of hydrogen occur in landfill gas during the anaerobic stage of degradation, then processes other than typical landfill gas generation are occurring.

The majority of sites investigated did not undertake regular monitoring for hydrogen. However, at one case study site the operator monitored for hydrogen, because it showed a close correlation with hot spot activity during remediation work (see Figure 6). On discovery of the hot spot, the hydrogen concentration at the well closest to the hot spot gave a maximum concentration of 1.5 per cent, compared with a typical background concentration of less than 0.2 per cent

Following control activities, including sealing points of air ingress, reducing suction to the gas wells and dousing, the hydrogen concentration reduced to background concentrations. This reduction showed a close correlation with the reduction in temperature.

Equimolar amounts of hydrogen and carbon monoxide are also generated through the water gas reaction, which occurs when steam comes into contact with hot carbonaceous material. Hydrogen concentrations in excess of 20 per cent v/v have been reported in the landfill gas emitted from regions where water has been slowly introduced into an area with a suspected hot spot. Such concentrations are well within the explosive range and demonstrate the importance of monitoring hydrogen concentrations during all stages of detecting and treating hot spots.

4.2.6 Summary of gas monitoring

Monitoring the bulk landfill gases provides sufficient data to warn of conditions that could result in the development of a hot spot. The monitoring of bulk landfill gas, in conjunction with monitoring of carbon monoxide, nitrogen, hydrogen and temperature, should be sufficient to determine the effectiveness of control and remediation works.

A summary table of the key indicators for gas monitoring is given in Table 19.

Table 19 Typically-reported gas concentration trigger values

Gas	Trigger Gas Concentration	Comments
Oxygen[1]	>1 per cent	A key precursor indicator for the potential development of a hot spot.
Methane and carbon dioxide[2]	Rapid drop of 10 per cent against background concentration.	Change in typical gas concentration could indicate air ingress. Therefore, a key precursor indicator.
Nitrogen[2]	>5 per cent	Potential indicator of air ingress to an anaerobic waste mass. Therefore, a key precursor indicator.
Carbon monoxide	Increase above background	Quantity and rate of increase will be dependent on background data. Can only be used as a precursor indicator of a hot spot if sufficient background data.
	1ppm to 100ppm	Potential background concentration. Without site-specific background concentration, 25ppm can be taken as a conservative trigger value.
	25ppm to 100ppm	Increasing likelihood of hot spot development. If concentration is significantly above background levels then further investigation should be carried out.
	>100ppm	Possibility of hot spot in the area. Carbon monoxide concentrations from portable instruments should be checked with reliable monitoring equipment or laboratory GC analysis.
Hydrogen[2]	Rapid change from background	Limited data available to set actual trigger value, although an increase in hydrogen with the occurrence of a hot spot may be expected.

Notes: 1. Based on waste in the anaerobic (Phase II, III and IV) stages of waste degradation (see Figure 3); 2. Based on waste in the anaerobic (Phase IV) stage of waste degradation (see Figure 3); 3. All gas concentrations refer to concentrations monitored at individual wells rather than at manifolds or the flare/engine compound.

There are many factors affecting the gas concentrations within a landfill, not least the stage of decomposition and the location of the monitoring point. Therefore, trigger concentrations should not be considered in isolation but should be assessed with the aim of determining whether any changes in their relative values indicate the onset or development of a hot spot.

4.3 Temperature monitoring

Temperature is one of the most commonly used parameters by operators during hot spot investigations. Temperature monitoring can be used to locate the extent of a hot spot both horizontally and vertically, as well as to monitor the migration of a hot spot and its development and decline over time.

Most operators with experience of hot spots are familiar with the use of temperature monitoring probes to establish in-waste temperatures and will have developed in-house trigger values for temperature monitoring.

Temperature monitoring can be carried out in two distinct ways: as an indicator of hot spot temperature or as an actual measure of temperature. Indicator temperatures are usually recorded at shallow probes or at locations known to be a distance away from the core of the hot spot and can then be used to establish relative increases or decreases in temperature over time. Temperature monitoring carried out within the hot spot core is more useful for establishing hot spot development and decline, but is more difficult and hazardous to obtain.

4.3.1 Surface temperature monitoring

4.3.1.1 Technique

Thermal imaging (aerial thermography) is the infrared mapping of temperature and detects changes in the subsurface temperatures within a landfill. This technique may be useful in providing an early warning of increased surface temperatures and in identifying areas for further investigation during remediation work. Thermal imaging can also be used for detection purposes, with repeat surveys identifying any changes in subsurface temperature over time.

The technique usually involves imaging from a position high above the site, such as from a plane, helicopter, crane or balloon. There are a number of interferences to thermal imaging, most notably the effects of solar heating. This is generally overcome by surveying early in the morning or at night. Other potential interferences include: hot gas extraction pipework or leachate re-circulation pipework crossing the site; areas covered by thick vegetation; or materials with particular reflecting properties. Success in using this technique and further discussion is reported by Titman (1995), Lewicki (1999), Feliubadalo and Relea (1995) and Neusinger *et al.* (1995).

Thermal imaging can also be undertaken using hand-held thermal cameras to detect areas of increased temperature. This has been used with some success at sites with known problems.

4.3.1.2 Practical application

Thermal imaging has been undertaken at a number of sites to determine the extent and location of hot spots. From discussions with operators, it is clear that the results obtained with this technique have been variable, with most success for shallow hot spots. Some operators have lost confidence in the technique, as known hot spots were not detected by the surveys. In some cases, this may be a result of the inappropriate application of the technique and interpretation of the results rather than a failure of the technique itself.

In two of the reports detailed above, which involved shallow hot spots, Fire Brigade thermal cameras were used to locate hot areas on the surface of the site. In both instances, the location of the hot spot was already known and the technique successfully determined the lateral extent of surface heating and identified areas for further investigation. Both hot spots were located within 5m of the landfill surface. This technique is also likely to be successful in determining areas of surface heating from deeper hot spots. However, it is unlikely to provide additional data on the location of the core of a deep hot spot.

4.3.2 In-waste temperature monitoring

Determining temperature within the waste body can be achieved using thermocouples. These are used to measure temperature in a variety of materials and are robust and relatively simple to use. As a result, they are relatively inexpensive and there are a variety of devices available on the market. Temperature monitoring is typically undertaken at existing in-waste environmental monitoring points such as gas wells, leachate wells or at monitoring points installed for the purpose. Typical temperatures from the case studies reviewed found temperatures ranging from 10ºC to 550ºC.

The higher temperature value is similar to that recorded by Ettala *et al.* (1996) at an experimental municipal landfill fire (see Section 6.3.1). Ettala *et al.* undertook temperature monitoring at the core of the hot spot, at a distance of 5m away and at various depths below ground level (bgl). A temperature of 690ºC was recorded close to the hot spot. However, no increase above background levels was detected vertically above the hot spot (at 1.5m bgl) and vertically below the hot spot (at 5m bgl). They concluded that this was a result of the good insulating characteristics of the waste mass.

The low thermal conductivity of emplaced waste is a significant factor to take into account when considering the effects of a hot spot on containment engineering. In addition, it is an important factor when assessing the potential for hot spot migration, control and remediation techniques.

4.3.2.1 Technique for monitoring shallow hot spots

In-waste temperature monitoring using shallow installations has proved successful in locating areas for further investigation and in identifying the likely location of the centre of a shallow hot spot.

Installation of shallow temperature monitoring probes has also been used for initial surveys on the lateral extent of deeper hot spots. This method can be successful in determining areas for further investigation, but is unlikely to provide sufficient data to identify the hot spot location or to monitor the effect of remediation work.

The range of temperatures monitored from shallow wells (less than 5m) is dependent on a number of factors, including:

- proximity of the well to the hot spot;
- proximity to the landfill surface;
- whether the landfill is capped;
- changes in atmospheric temperature; and
- a consistent monitoring technique between probes, as results may vary considerably with a small change in monitoring technique.

Typical temperature ranges for two shallow hot spots from two of the case studies are given in Table 20.

Table 20 Temperature ranges at two shallow hot spots from case study data

Depth	Temperature close to hot spot	Background waste temperature	Atmospheric temperature	Temperature change with distance from hot spot
3–4 m	**40–60 ºC**	**7–22 ºC**	**7–22 ºC**	**20ºC over 15m**
5 m	**40–60 ºC**	**27–35 ºC**	**10–22 ºC**	**10ºC over 15m**

The highest recorded temperature given in Table 20 is 60ºC. It can be assumed that at both sites the actual temperatures of the smouldering waste masses were significantly higher, as both flamed during excavation and remediation works.

An example of the installation of shallow wells for identifying the location and general characteristics of a shallow hot spot is given in the case study below. The advantage of monitoring points of this type is that they are relatively quick and cheap to install, and provide a way of comparing and contouring relative temperatures. This information is then used to delineate the centre of the hot spot and to target future monitoring or remediation strategies.

Shallow gas and temperature monitoring probes

A series of 24 semi-permanent monitoring points were installed over an area approximately 25m by 50m at the location of a suspected hot spot. The monitoring points were designed to allow monitoring of both temperature and gas concentrations. The installation process involved using the bucket of a tracked excavator to push a 1.5m long steel rod into the waste surface, producing a 100mm-diameter hole. A 1.5m length of 50mm slotted HDPE (high density polyethylene) pipe was then installed to 1.0m below surface level and the waste was allowed to close around the pipe. The top of the pipe was then sealed against the waste surface.

The spikes were monitored for temperature and gas concentrations on a twice-weekly basis over a two-month period. The waste in the investigation area was not capped and some interference from air ingress was encountered. However, areas of elevated temperature could be clearly distinguished and the location of the hot spot could be broadly identified. The lower (background) temperatures monitored (7–22ºC) were similar to or only slightly above ambient temperatures at that time. Temperatures ranging between 41ºC and 60ºC were detected at three monitoring points, which coincided with three hot-spot centres, indicating that the hot spots were typically 30–40ºC higher than the background area.

The temperature contour plan produced from these results revealed a linear feature of higher temperature. On excavation, this was shown to be an operational waste bund of car fragmentiser waste (car frag). The car frag had a relatively high permeability and although it was not on fire or smouldering it did allow the transfer of heat over a greater distance than typical domestic waste mass.

(Case Study)

The temperature monitoring results from the above case study are shown in Figure 7 and the elevated temperatures clearly show the location of the shallow hot spot. This data was used to produce a contour of the near-surface temperature, based on which intrusive investigations were undertaken as the remediation strategy.

In this example, there was no significant change in waste temperature with a change in atmospheric temperature, although it can have a significant impact. Waste temperatures recorded near the surface of a landfill are susceptible to changes in atmospheric temperature and this should be considered when assessing shallow hot spot temperature monitoring data.

Temperature monitoring

Figure 8 shows the relationship between in-waste temperatures and atmospheric air temperatures at a case study site. Temperature monitoring was conducted at approximately 70 shallow wells installed to a typical depth of 5m to locate the hot spot and to monitor the effect of the remediation strategy. The elevated temperature of 60ºC was used to indicate the location of the hot spot, as typical background waste temperatures tend to be within approximately 10ºC of atmospheric temperature.
(Case Study)

The falls in-waste temperatures show a close correlation with the fall in atmospheric temperature and care is required when interpreting the results. Waste temperatures should not be interpreted without considering atmospheric temperature readings.

4.3.2.3 Technique for monitoring deep hot spots

In-waste temperature monitoring is usually undertaken using temperature probes lowered into existing installations, such as gas extraction and leachate wells. In addition, some sites have installed strings of thermistors, which record temperatures simultaneously for a range of depths at each monitoring point. The probe will normally be used to measure the gas temperature, but where probes are inserted into the waste mass they may be in direct contact with solid waste. Leachate has a high thermal capacity and so is a less sensitive indicator of a hot spot.

Temperatures of deep hot spots will vary considerably due to the nature of the waste and the availability of free oxygen and combustible fuels. From the monitoring data reviewed as part of this study and discussions with operators, the range of temperatures recorded on site are generally believed to be lower than the expected hottest part of the hot spot. The main reasons for the lower temperature readings are detailed below.

- Locating the core, and therefore the hottest part of the hot spot, is difficult and not often achieved. Many of the temperatures recorded are at some distance from the hot spot. As the waste mass is generally a good insulator of heat, the temperature may decrease rapidly at increasing distances from the hot spot core.
- Incorrect positioning of the temperature probe. Once the gas extraction system is turned off, temperature migration through waste via the convection of hot gases is significantly reduced. Temperature probes installed whilst the gas extraction system is operating may be incorrectly located once the gas extraction system is turned off.
- The temperature monitoring probe is not always installed at the same depth as the hot spot. There is a significant variation in the recorded temperature with depth for most monitoring points.
- Some monitoring instruments are not robust enough to withstand high temperatures or do not have sufficient temperature ranges and so cannot be used at the hottest part of the monitoring well.

As a result of the above issues, actual temperature monitoring results are highly variable. A range of temperature results from three of the case studies is given in Table 21.

Table 21 Temperature ranges at deep hot spots

Depth of hot spot	Temperature in hot spot area	Background waste temperature	Temperature change with lateral distance from hot spot	Temperature change with depth
15m	Maximum 105ºC	45–55ºC	10ºC over 20m	Maximum 15ºC over 1m
25–30m	70ºC	30–40ºC	20ºC over 15m	Not measured
10m	550ºC	39–65ºC	35ºC over 1m (1)	1–2ºC over 1m (2)

Notes: 1. Temperature gradient steeper as close to flaming hot spot core; 2. Temperature gradient measured at a distance of approximately 30m from the hot spot; 3. Closer to the hot spot, the temperature gradient may be steeper.

(Case Study)

Temperature monitoring is typically undertaken by lowering a temperature probe down the in-waste monitoring point and recording the temperature as the probe is lowered. Changes in the recorded temperatures with increasing depth can then be used to determine the likely depth of the hot spot and to target future remediation works. The frequency of readings is site specific and dependant on the range of temperatures encountered, although typically readings are taken at 1m to 5m spacings.

Figure 9 illustrates downhole temperature monitoring at a site with a known deep hot spot. The plot clearly shows increases in temperature with depth, followed by a decrease in temperature beneath the hot spot.

Changes in temperature with depth are expected to vary considerably from site to site. Figure 9 shows a typical change in temperature of 1–2ºC for each vertical metre. However, other sites have recorded more pronounced changes in temperature of up to 15ºC per metre. Temperature monitoring close to the hot spot will typically show a much steeper temperature gradient than further away.

When interpreting temperature data to determine the approximate depth of a hot spot, a number of factors should be taken into account. These include:

- hot gases can be expected to rise within the monitoring point and this may affect interpretation of the results; and
- the effect of gas extraction systems on the direction of hot gas flow.

The transfer of heat through a waste mass will be through conduction or convection. Conduction is the transfer of heat by direct contact, whilst convection is the transfer of heat through a circulating medium such as a hot gas or liquid. Hot gases may migrate due to gas being drawn from extraction systems or due to the rising of hot gas through convection currents. When migrating hot gas comes into contact with cooler waste, heat is transferred by conduction.

Changes in temperature along a horizontal plane are commonly used to identify the location and extent of a hot spot. They can also be used to estimate the extent and direction of possible hot spot migration and assist in predicting the impact on containment engineering.

Analysis of temperature monitoring data indicates that there is a relatively rapid drop in temperature away from the core of the hot spot, as shown in Table 21.

An example of the lateral change in temperature as the distance from the hot spot increases is provided by the following case study.

Decrease in temperature with lateral distance from hot spot

Background waste temperatures at this landfill were typically 50ºC. Following the installation of investigative boreholes around the deep hot spot, a maximum temperature of 550ºC was recorded at the hot spot centre.

Temperature decreased laterally from the hot spot at a maximum gradient of 35ºC per metre. Typically, elevated temperatures were not detected beyond 60m from the hot spot. Contouring of the hot spot temperatures showed that temperatures above 300ºC were only recorded within an area of approximately 15m^2 around the hot spot. Temperatures above 200ºC were only recorded within an area of 200m^2 and temperatures above 100ºC were only recorded within 900 m^2 of the hot spot. Following further investigation, it was concluded that the actual hot spot core was limited to an area no more than 8m^3. These results show that the waste mass at this site is a good insulator of heat. It also shows that high temperatures (above 100ºC) were not generally detected beyond 30m from the core of the hot spot, which had a temperature of 550ºC.

The experience of this case study is corroborated by evidence from other sites, in particular a site where landfill excavation and remediation of a deep hot spot confirmed that at a depth of approximately 10m the hot spot was restricted to an area no greater than 2m^2 with a vertical thickness of approximately 300mm. This layer was revealed as charcoal/ash material whilst waste in close proximity showed no signs of burning or charring. Both case studies suggest that the waste mass is a relatively good insulator of heat.

(Case Study)

At many sites it is not known whether the highest temperature reading is representative of the hot spot. As many sites undertake temperature monitoring from existing gas and leachate wells, which are typically 25–50m apart, the accuracy of temperature monitoring for determining the maximum temperature is limited. Therefore, without further investigation at the site, a conservative recommendation would be to assume that a significantly higher temperature might exist between the monitoring points. This has an impact on the remediation strategies adopted for the hot spot (see Section 6).

Anecdotal evidence from operators that have exposed hot spot cores indicates that waste close to the hot spot does not show evidence of burning. This suggests that the migration of heat occurs via convection (the migration of hot gases), rather than conduction (heat passing from waste mass to waste mass).

The data set for determining the temperature gradient away from the hot spot is limited and additional work is recommended to determine whether the reported gradients are representative of other sites. However, it is clear that temperature monitoring should be undertaken at existing in-waste points to determine the extent of the hot spot and the potential temperature gradient. This will allow site-specific assessments to be made on the likely impact of the hot spot on site engineering.

Several sites recorded a reduction in temperature in response to turning the gas extraction system in the affected area down or off. These drops in temperature may be the result of removing the oxygen source or of the gas extraction systems no longer pulling hot air away from the hot spot towards the monitoring point.

Temperature monitoring

One of the case studies monitored temperatures from in-waste monitoring points before and after the gas extraction system was turned off. The results showed a significant change in temperature, with variations in excess of 250ºC (from 375ºC to 108ºC).

(Case Study)

4.3.3 Migration of hot spots

Hot spots are usually relatively localised and do not necessarily migrate unless there is a driving force, such as is created by a gas control system. From discussions with operators, the extent to which hot spots migrate through the waste mass is variable.

Studies at two sites in particular show the hot spot migrating laterally. In the first example, the hot spot was clearly migrating laterally towards the operational gas extraction system. This produced a trough shape within the surface of the restored cap. In the second example, the hot spot migrated laterally in three directions. This hot spot caused significant differential settlement at the surface and increased in size from approximately 100m^2 to 350m^2 in two to three years.

The reason for the migration is suspected to be the gas extraction system drawing hot gases away from the hot spot area.

4.3.4 Trigger values for temperature monitoring

Most operators that have experienced hot spots and undertaken temperature monitoring have established ‘in house’ trigger values. A range of these trigger values, including some examples from regulators in the US, are given in Table 22.

Table 22 Reported trigger values for gas temperature

Trigger temperature	Comments from a variety of operators
Increasing temperature	
Outside typical anaerobic range 30ºC to 50ºC	Investigation work to be undertaken if temperature falls outside this range.
>55ºC	Landfill guidance in the US (EPA 1999) considers elevated temperatures of collected landfill gas as an indicator of subsurface fires.
>60ºC	Above typical background for the site and should result in further investigation.
>60ºC	The USFA (2002) cites a temperature increase above 60°C as confirmation of an underground fire.
>100ºC	Used as an indicator that the site is unusually hot and investigation should be undertaken.
Decreasing temperature	
Cooling to <150ºC	Used to confirm whether sufficient cooling has occurred.
Cooling to 40–60ºC	Used to confirm that the waste is within normal background temperature ranges.
>20ºC above background	Used where temperature monitoring is undertaken on a regular basis (typically sites with a history of shallow hot spots).

Note: 1. Unless specifically referenced, comments are as reported to Golder from operators with experience of landfill fires.

Table 22 highlights the wide variation in rules of thumb used by the industry. The majority of these trigger values are established from two benchmarks: the typical background temperature of the waste mass and the typical anaerobic temperature for biodegradable waste.

4.3.5 Temperature of leachate

An unexpected increase in the temperature of the landfill leachate can indicate the presence of a hot spot. Lewicki (1999) suggests that leachate temperatures above 60ºC or sudden peaks require further investigation. Some UK operators have a rule of thumb that leachate temperatures exceeding 50ºC are suspicious and that additional monitoring should be undertaken in the area.

Leachate temperature

The distance over which elevated leachate temperatures may be encountered is unclear. However, it is known that at one site leachate temperatures increased by 13ºC in the cell adjacent to the cell containing the hot spot (measured approximately 60m from the hot spot area).
(Case Study)

4.3.6 Summary of temperature monitoring

Temperature should be used as an indicator for the potential development of a hot spot, for the monitoring of control and remediation works and for identifying the most likely location of the hot spot.

Based on the information from the case studies and available literature, a summary of recommended trigger values for temperature is given below.

Table 23 Recommended temperature trigger values

Trigger temperature (in-waste)	Remarks
>10ºC above normal operating temperature	Where the site has a good record of background temperature monitoring, further investigation should be carried out.
>60ºC	Temperatures above 60ºC are higher than typical anaerobic waste temperatures and so further investigations should be undertaken.
>80ºC	A hot spot may be present or may develop at the site.
Trigger temperature (leachate)	Remarks
>50ºC	Suspicious – additional monitoring should be undertaken.

4.4 Other forms of monitoring

There are a number of other monitoring techniques that can potentially lead to the early identification of a hot spot.

- *Aerial photographs*. Many sites conduct regular aerial photos of the site. These can be used to spot areas of significant differential settlement or changes in vegetation, which may indicate the presence of a hot spot.
- *Infra-red surveys*. Some sites routinely conduct infra-red surveys, as these can indicate a range of issues, such as off-site gas or leachate migration. As discussed in Section 4.3.1, these can also be used, to varying degrees of success, to locate unusually hot areas within the landfill.

5. Hot spot scenarios, implications and prevention

5.1 Hot spot scenarios

Hot spots typically develop according to one of four main scenarios: horizontal development; vertical development; confined fires; and unconfined fires. Each of these scenarios is described in detail in the following sub-sections.

5.1.1 Horizontal development

As detailed in Section 3.8.3, Sperling and Henderson (2001) argue that continuous cover layers, such as intermediate capping, ‘may actually promote the spread of deep-seated landfill fires’ by ‘driving hot gases laterally and inducing horizontal convection currents’. Figure 10 depicts such a scenario, where air is drawn through a leachate well or other inlet pathway and over the hot spot following a horizontal convection current. Connection with the atmosphere is provided by a gas abstraction or gas venting well.

Horizontal development pathway hot spots are typically characterised by a depression in the landfill surface immediately above the hot spot epicentre and through detection of partial oxidation products, such as carbon dioxide, carbon monoxide and hydrogen cyanide, at elevated temperatures in the gas abstraction well.

5.1.2 Vertical development

Vertical development pathway hot spots describe the scenario where hot spots form around an area with a discrete vertical air flow pathway, such as around a gas or leachate well. Figure 11 depicts a typical vertical development pathway scenario. As the hot spot develops, a localised depression is formed around the well, damaging the cap seal in this location. Air is drawn through this damaged cap and this assists the development of the hot spot.

Vertical development pathway hot spots are characterised by a depression in the cap immediately surrounding the gas or leachate well and by the emission of steam from the well.

5.1.3 Confined hot spot

Figure 12 illustrates a confined and deep-seated hot spot. These hot spots are typically difficult to detect as there are no obvious indications of their existence. The lack of a connection pathway to the atmosphere limits the volume of oxygen available to these hot spots and as such the combustion reaction is limited to smouldering. Existence of confined hot spots presents a risk to the installation of new gas or leachate abstraction wells, which may introduce a connection to atmosphere and thus quickly escalate the combustion reaction.

5.1.4 Unconfined hot spot

An unconfined hot spot is illustrated in Figure 13 and describes the scenario where expansion of the hot spot is not confined to the vertical plane. High permeability and low compaction waste allows the free flow of air through the waste mass, fuelling the hot spot. In addition, the high permeability waste permits hot combustion gases to migrate away from the hot spot epicentre, allowing the hot spot to expand. Unconfined hot spots have the potential to alter the surface profile of the landfill and combustion products are likely to be detected within gas or leachate wells and across the landfill surface.

5.2 Implications of hot spots in landfill

There is little published data on the known impact of hot spots on landfill engineering structures. This is due in part to the difficulty of examining structures that are buried under significant quantities of waste. There is therefore little conclusive data on the effects of hot spots on engineering materials. However, this section does list some of the key factors that need to be considered and also the potential environmental impacts. A range of known and suspected impacts on landfill engineering occur as a result of hot spots, with settlement and heat the two main contributing causes.

5.2.1 Settlement

One of the most common signs of a hot spot in a restored area is localised differential settlement. The degree of settlement varies considerably and will depend on the size and depth of the hot spot.

Settlement characterisation

The type of settlements encountered during this research varied considerably: shallow depressions typically were in the order of 300mm over an area of approximately 10m radius, whereas larger depressions were irregular in size and covered areas approaching 1ha, with pronounced vertical settlement that was up to 2m greater than the surrounding cap.

(Case Study)

At several sites, settlement occurred in a roughly circular area and is assumed to be directly above the hot spot. This is more likely for hot spots where the air ingress is associated with one particular gas well. However, there are examples of hot spots migrating laterally and producing a trough shape, or even an irregular moonscape, on the surface of the landfill.

There are a number of general effects of differential settlement on a site.

- Damage to the low permeability cap. Few clays are self-sealing and so significant movement and cracking of a clay cap can greatly increase its overall permeability. Welded geomembrane caps may be affected by excessive elongation, leading to tearing, whilst lap and lay caps may be pulled apart.
- Once damaged, the cap will provide a less effective seal against gas migration. This could potentially result in increased emissions to atmosphere and an increase in the development of the hot spot if air and/or moisture are allowed to enter the site.
- Damage to the gas extraction system by differential settlement, which may result in a break in the gas extraction collector pipework. Most gas extraction pipework consists of butt-welded polyethylene, which is strong in both tension and compression. Therefore, although breakage of the pipe may occur, it is more common for the pipe to become blocked by a build-up of condensate at a low point.
- Damage to vertical gas wells and leachate monitoring or abstraction points, where they are close to areas of differential settlement. In addition, several sites have reported melting of vertical polyethylene pipework where it is close to hot spot areas.
- Ponding of surface water above the cap and the development of a low point, leading to a reduction in surface water drainage capacity through the area of settlement.

5.2.2 Elevated temperatures

5.2.2.1 Geomembranes

The physical and mechanical performance properties of geomembranes are strongly temperature dependent. Exposing geomembranes to elevated temperatures can lead to long-term weakening, in particular for areas under stress, such as sidewall liners or caps suffering from differential settlement.

Temperature monitoring data from the Environment Agency (2003) suggests that typical landfill temperature values range between 6ºC and 65ºC, with a range between 16ºC and 30ºC across a single site. A reasonable long-term average for active bioreactors practising leachate recirculation and/or with high leachate levels is estimated to be 30–35ºC.

Studies have shown that the performance of HDPE is acceptable over a long period of time under conditions involving repetitive fluctuations within the range -20ºC to 60ºC (Budiman 1994). However, the performance of geomembranes at temperatures above 60ºC is less well understood. It is clear that heat generated from a hot spot is sufficient to cause damage to a range of geomembrane materials – from HDPE to LDPE (low density polyethylene). Some typical thermal properties for a variety of polyethylenes are given in Table 24.

Table 24 Thermal properties of polyethylenes

Plastic	Thermal properties						
	Coefficient of linear thermal expansion ($\times 10^{-6}$ K^{-1})	Heat distortion temperature (at 0.45Mpa) (ºC)	Heat distortion temperature (at 1.8Mpa) (ºC)	Specific heat (J K^{-1} kg^{-1})	Thermal conductivity (at 23ºC) (W m^{-1} K^{-1})	Upper working temperature (ºC)	Melting point (ºC)
HDPE	100–200	75	46	1900	0.45–0.52	55–120	130
LDPE	100–200	50	35	1900	0.33	50–90	-

Refs: Goodfellow Cambridge Limited (www.goodfellow.com); Material information: Polyethylene – High Density and Polyethylene – Low Density; and Material Property Data (www.matweb.com).

Considering the data presented by the Environment Agency (2003), Table 24 shows that typical landfill temperatures, particularly in the anaerobic phase, are lower than the melting point for typical polyethylene engineering materials. However, Table 24 also shows that typical temperatures measured at hot spots are capable of melting polyethylene.

Although no examples of melting sidewall liners or basal liners were uncovered during this research work, examples of geomembrane caps melting due to increased temperatures from hot spots were encountered, as described in the following case study.

Melting of a geomembrane

A welded 1mm LDPE geomembrane was used to cap a landfill site. Following installation of the geomembrane, it was left exposed for a few months. During this period, small holes and pin pricks with a maximum size of approx 1–2mm appeared in the geomembrane, which became hot to touch. The holes were believed to have resulted from melting/deterioration of the geomembrane due to a known underlying hot spot. Further investigation and remediation at the site confirmed that the damage to the geomembrane was caused by a hot spot. The depth of the hot spot was not known, but the maximum waste depth in the area is believed to be less than 10m.

(Case Study)

French *et al.* (1998) describe the effects of a fire on the tyre chips used as a protective layer over a sand drainage layer on a geotextile and a geomembrane liner. The fire occurred on the exposed chips, prior to waste placement. Although the tyre chips burned and melted, the sand layer, which had become moist following rainfall, provided an effective thermal barrier over most of the liner, even under severe tyre chip fire conditions. The maximum temperature recorded at a depth of 25cm below the surface of the chips was 53ºC, whereas the maximum temperature recorded 5cm into the 30cm thick sand drainage layer was 35ºC. The typical temperature below a depth of 5cm in the sand drainage layer was found to be 18ºC. The drainage stones over the perforated HDPE leachate pipes also proved to be an effective thermal barrier. However, the pipe did melt and collapse under the weight of the overlying stones in the area that burned the longest (the last area to be extinguished).

Elevated landfill temperatures have also been shown to influence the rate of oxidisation of polyethylene liners (Environment Agency 2003). The results of a series of tests carried out by Hsuan and Koerner (1995 and 1998) and Sangam (2001) indicated that the oxidisation induction time (OIT) and hence the predicted lifespan of the geomembrane liner reduced rapidly with increasing temperature.

Correlating the suggested average field temperature range of 30–35ºC with the geomembrane lifetime predictions made by Koerner and Hsuan (2003) indicates that the effect of a 5ºC temperature rise is a decrease in the lifespan prediction for a HDPE geomembrane liner to 170 years (from 270).

Hence, even where the elevated temperatures caused by landfill hotspots are not capable of melting polyethylene, the effects of thermal oxidative degradation on the polyethylene should still be taken into consideration in assessing the long term durability of the liner.

5.2.2.2 Containment engineering

The impact of a hot spot on the containment engineering should be determined on a site-specific basis. A number of key factors need to be considered.

- The maximum measured temperature of the hot spot.
- The temperature gradient in the area surrounding the hot spot, and therefore the insulating capacity of the waste. The case studies suggest that waste is a relatively good heat insulator, with elevated temperatures reducing rapidly away from the centre of the hot spot. To predict the effect of the hot spot on engineering materials, measurements of temperature should be undertaken at various distances away from the hot spot. These measurements can be used to provide an estimate of the temperature likely to be encountered at the perimeter or base of the site. This

temperature can then be used to predict whether the engineering material may be subject to heat stress.

- The leachate head within the site. Leachate is expected to provide a barrier to the migration of a hot spot. However, it is likely that the temperature of the leachate will be increased at points where the hot spot is close to the base of the site. Where possible, the temperature of the leachate should be measured and related back to the properties of the engineering materials.
- The nature of the engineering materials. Where manufactured materials are used, it is recommended that the manufacturer supply data for the sensitivity of the material to heat. This can then be related to the expected waste temperature, as revealed by site monitoring, and an assessment made of the likely impact.
- The nature of the engineering. Where clays are used, the desiccation potential of the clay can be determined from its plastic limit. However, as a worst case scenario, continued heating of the clay is likely to reduce significantly the permeability of the material.
- Geocomposite clay liners, particularly where used on caps, may be susceptible to heating from underneath.

Until more research is undertaken, an assessment of the effect of heat on the engineered containment should be considered on a site-specific basis.

5.2.2.3 Ongoing investigation into landfill engineering temperatures

Research work is being conducted in the US to monitor the effects of waste temperature on geomembrane liners. This involves placing thermocouples within both landfill engineering structures and the waste mass. A brief description of the research is given below.

Methodology for temperature monitoring of landfill geomembrane

Work is being conducted in the US to install and measure the temperature of the geomembrane and waste mass after landfilling, with the objective of determining the effect of waste temperatures on engineered geomembrane liner systems. Three sites representing different geographical and environmental locations were studied.

The general procedure consisted of:

1. installing thermocouples at the surface of the geomembrane, prior to waste placement;
2. installing thermocouples within the gravel drainage blanket and the waste mass, at various elevations;
3. connecting the thermocouples by leads to a remote monitoring station; and
4. making monthly measurements of thermocouple and atmospheric temperatures over a 2.5-year period.

The results of the study after 2.5 years show:

1. variable waste temperatures, with an average of 20ºC;
2. an average basal geomembrane temperature response of 20ºC;
3. an average temperature response of the geomembranes used in covers of 23ºC;
4. variable temperatures within the gravel drainage layer, with an average of 20ºC.

The temperature of the waste mass seemed to have no physical effect on the geomembrane. The cover geomembrane recorded a seasonal fluctuation with atmospheric temperature, although the temperature was still dominated by the waste temperature. The work is ongoing and waste temperatures are expected to increase with time.

[Ref Koerner *et al.* 1996]

The case study given above shows relatively low temperatures for the waste and little corresponding impact on the engineering materials. As the waste mass matures, the temperatures are expected to increase and the relationship between the waste temperature and its effects on engineering materials may become clearer.

Retro-fitting of temperature cells against engineered containment systems is likely to be impracticable. However, where landfill sites are believed to be sensitive to the development of hot spots, the installation of temperature monitoring probes into future cells should be considered.

5.2.3 Engineering structures in the landfill

5.2.3.1 High permeability zones

Hot gases are known to migrate along zones of higher permeability within the waste mass, such as layers of car fragmentiser waste, tyres and in-waste drainage layers. At one case study hot spot, the migration of hot gases through a highly permeable layer of car fragmentiser waste and tyres was thought to have occurred. It should be noted that there was no sign of burning or smouldering of the tyres or car fragmentiser waste, despite the hot spot being at sufficient temperature to auto-ignite upon excavation.

5.2.3.2 Tyres within landfills

Modern tyres are composed of natural rubber and oil-derived synthetic rubber elastomers, with smaller quantities of multiple carbon blacks, extender oils, waxes and other performance-enhancing materials. The flash point of whole and shredded tyres is in excess of 320ºC (Environment Agency 2002b).

By the end of the 1990s, the use of tyres in landfill engineering to form leachate drainage layers was common. The UK Department of Trade and Industry’s Scrap Tyre Working Group estimated in 1998 that approximately 4.9 per cent of the 399,213 tonnes of tyre arising had been used in landfill engineering in 1997 and forecast that approximately 4.4 per cent of tyres (of the 449,578 tonnes arising) would be used for this purpose in 2003 (ENDS 1999). This practice was noted at the time to pose a similar risk of fire as disposing of tyres in landfill. The Landfill Regulations (2002) are currently being amended and will stop the landfilling of whole and shredded tyres for disposal. However, it may still be possible to use whole tyres for engineering purposes.

There are two main risks in relation to tyres and hot spots. The first is the possibility of spontaneous combustion of the tyres within the landfill, although we are not aware of any documented cases of this actually occurring. Experience in the US has shown that self-ignition of shredded tyres occurs most frequently in waste greater than 6m deep. The US study also suggested that the potential for self-ignition of shredded tyres in a leachate drainage layer is small, provided that the layer thickness is less than 900mm (GeoSyntec 1998 cited Environment Agency 2002b). As tyres are extremely compressible, a large reduction in layer thickness is achieved on placement of waste.

Experience in the UK suggests that, even at shallow depths, tyre-filled trenches can be a contributing factor in the development of a hot spot.

Shallow filled tyre trench

At a landfill site in the UK a shallow tyre-filled trench, within 2m of the landfill cap and with a cross sectional area of 1m by 1m, formed the centre of a hot spot. The tyre-filled trench was used for the recirculation of leachate through a central injection point. The seal was not complete and air was drawn into the re-circulation point and through the tyres over a period of more than six months. The result was smoke rising through the cap and the complete combustion of the tyres, leaving only reinforcement wire. The combustion was localised, only extending within the tyre-filled trench and within 1m of the surrounding waste mass. It is not known whether the tyres allowed the development of the hot spot at a faster or slower rate than if the air had been drawn through typical landfill waste.
(Case Study)

The second risk is the possibility of an existing hot spot migrating towards a tyre drainage layer and igniting it. For example, a serious fire at a Cheshire landfill in 1999 appeared to have started in municipal waste and then spread to tyres, which were used on the landfill as a leachate drainage medium (ENDS 1999). It is estimated that the fire involved some 3,000 tonnes of tyre (several hundred thousand tyres) stacked to a depth of 3m at the bottom of the landfill cell.

This is a concern for sites with a known hot spot and where tyres have been used as an engineering material. Also of particular concern are sites where tyres have been used within the waste mass to provide gas permeable or leachate drainage systems. If a hot spot is allowed to develop and migrate to areas containing tyres within the waste mass, it could cause a fire that will be particularly difficult to extinguish. In addition, if the fire occurs within a high permeable zone there is a higher than normal risk of the hot spot migrating through the site.

The risk of this kind of fire occurring can be minimised by ensuring that active gas extraction systems, if present, are turned off on discovery of a hot spot, in order to prevent the system drawing hot gases away from the hot spot area. All appropriate steps should be taken to determine the proximity of a tyre layer to a known hot spot and to prevent the migration of the hot spot. The creation of firebreaks within tyre-filled leachate drainage systems is also worth consideration.

5.2.4 Environmental impact

The presence of a hot spot is likely to have some or all of the following environmental impacts.

- Potential increase in the range of trace gases in any bulk gas emitted to the atmosphere. These will include volatilised materials, and combustion and partial combustion products.
- Increase in odours, due to the following:
    - localised combustion odour due to emission of gases from the hot spot;
    - increased emission rate of gas through the cap due to the reduction in gas control at the site; and
    - increased emissions of landfill gas due to failure of the cap lining system.
- Increased emissions to atmosphere through reduced effectiveness of the cap.
    - Differential settlement of the cap leading to stressing of the liner system and eventually to failure due to tensile stresses.
    - Differential settlement of the cap leading to failure of the surface or near-surface gas extraction pipework, thereby reducing gas control.

    - Differential settlement of the cap, leading to condensate build up at low points within the gas extraction pipework and loss of gas control.
    - Desiccation of clay caps leading to a reduced permeability.
    - Melting of geomembrane caps, producing small holes and eventual total failure.
- A reduction in the ability to control off-site gas migration may occur. It is typical for the gas extraction system to be significantly reduced or turned off in areas affected by a hot spot, which may cause off-site gas migration to occur.
- Failure of the base or sidewall engineering may occur due to heating, leading to a reduction in the containment system and the potential for off-site migration of gas and leachate.
- Loss of in-waste monitoring, extraction and injection points due to melting of polyethylene pipes.
- If excavation of the hot spot is undertaken, then there is a short period of exposed waste and increased emission of landfill gas to the atmosphere.
- Failure of in-waste environmental management systems due to, for example, the melting of leachate collection pipework, tyre-filled leachate and/or gas collection and recirculation systems.

These points illustrate a number of potential environmental impacts, but there will also be site-specific factors in particular cases and so a full assessment of the environmental impact of landfill hot spots is beyond the scope of this report.

5.3 Prevention of hot spots in landfill

This section details the prevention strategies that can be employed to combat shallow and deep-seated hot spots. The methodologies have been taken from literature and from discussions with landfill operators and contractors working in the industry.

The number of hot spots that occur within UK landfills cannot be known for certain. There are two principal reasons for this. Firstly, the presence of a hot spot may not necessarily be detrimental to the environmental or engineering installations at the site. As a result, the hot spot may not have a significant impact on the surface of the site and any effects may not be seen during routine operational and monitoring activities. Failure to observe any effects may be more common for older and restored sites, where there are fewer people working on the site.

Secondly, routine monitoring of gas emissions and temperature at in-waste installations is not conducted at many sites. In addition, where in-waste gas monitoring is undertaken, it is typically used to balance the gas extraction system or as a measurement of predictive yields for flares and engines. As a result, the monitoring data may not be collected and interpreted with the intention of identifying the potential occurrence of a hot spot.

Preventing the development of a hot spot is primarily achieved through a good monitoring regime, and effective site management and waste acceptance procedures. These three prevention methods are discussed below.

5.3.1 Monitoring to identify the increased risk of a hot spot

Routine monitoring of the waste mass, with regular assessments of the monitoring data and actions taken where necessary, will significantly reduce the occurrence of deep hot spots. Where the site does not have sufficient in-waste monitoring points, inspection of the surface via routine site walkovers, regular topographic surveys and, possibly, aerial photography should be considered, in order to identify areas of excessive settlement. If these surveys suggest a developing risk, then in-waste temperature measurement should be considered and, if site conditions permit, routine thermal imaging should be used to highlight areas of potential temperature increase.

5.3.2 Site management and waste acceptance procedures

Waste acceptance procedures should be in place and enforced in order to minimise the risk of accepting hot waste loads or potentially flammable wastes. However, non-hazardous waste from municipal waste collection may still contain potential ignition sources, such as chemical canisters, household cleaning products and oils, which may trigger the development of a hot spot (see Section 3).

5.3.3 Management of landfill gas extraction system

The development of a significant number of hot spots is related to air ingress into the site. In many cases air ingress is due to a combination of faults in the containment system. Some of these may be the result of poor design, while others may be due to inappropriate operation of a gas extraction system. Since gas extraction systems operate under slight negative pressure, there is the risk that air will be drawn in if the suction is not well balanced or if the gas is pulled at a pressure that the management system cannot control. The published *Guidance on landfill gas flaring* (Environment Agency 2002c) gives details on the operation of a gas extraction system. The main items of concern are detailed below.

- Size the flare/gas plant according to gas production rates from the landfill abstraction points.
- Ensure sufficient well spacing to allow collection of gas without the application of large negative pressure or ‘over abstraction’.
- Ensure zones of influence for abstraction do not extend to exposed flanks, uncapped areas or unsealed sidewalls.
- Monitor and action changes in gas concentration.

5.3.4 Minimisation of air ingress to the site

Minimising air ingress to the site will significantly reduce the potential for developing a hot spot or for exacerbating an existing problem. Typical sources of air ingress to sites that could be avoided are detailed below (see Figure 14).

- Dilute and attenuated sites typically have gas containment systems that are relatively highly permeable. Therefore, the design of the gas extraction system must allow for control of off-site gas migration without drawing air into the site. This will require regular monitoring and balancing of the extraction system. In some sites, this is undertaken by operating separate perimeter and central gas collection systems. This allows the perimeter system to be operated specifically to control off site gas migration, while the central system provides the main feed to the engines and flares.
- Sites with a failed containment system may exhibit off-site gas migration. Where this occurs, increasing or re-balancing the gas extraction system will be necessary. This must be undertaken without drawing air into the site, especially at the perimeter of the site, as the hot spot may be close to the perimeter lining system.
- Hot spots are associated with air being drawn in at monitoring points through the cap. Typically, these points are at gas extraction and leachate wells. Air may be drawn in through poorly constructed seals around the monitoring points or where the seals have become damaged or worn. Routine monitoring of the seals around monitoring points should be conducted and any necessary repairs undertaken immediately.

Areas of particular weakness are geomembrane boot details, which may be affected by settlement, and clay seals, which can be affected by desiccation. Regular inspection and maintenance of the well seals is expected to reduce significantly the risk of a hot spot occurring at many sites.

- A significant number of sites report air ingress at leachate monitoring and abstraction points. This is usually because the design of these points does not allow them to be sealed completely until after the site is fully restored. This typically occurs where sites use concrete rings and concrete caps as leachate monitoring/abstraction points. The design of the monitoring points should include a method for maintaining an air-tight seal. This is particularly important in areas where the leachate point is under the influence of the gas extraction system. In addition, leachate monitoring points in uncapped waste batters have been identified as a cause of air being drawn into the waste mass.
- Leachate recirculation systems normally involve suction of the liquid. The design of these systems requires particular care to be taken to prevent air being drawn in through syphons and seals, as a result of the suction being applied to the gas field.
- On restored areas of the site, regular site walkovers should be undertaken to ensure that the integrity of the cap is being maintained. Areas requiring particular attention include those where there has been significant differential settlement and those at the perimeter of the site where the cap meets the sidewall engineering.
- Operational phases, by their nature, are uncapped. Nevertheless, hot spots have been recorded in large waste batters exposed to the prevailing wind direction, although there is insufficient data to assess the degree of exposure required to make this a significant influence on the development of a hot spot. There is sufficient anecdotal evidence to suggest that this may be an issue for exposed sites, particularly land raise sites, and placing a protective cap on the waste flanks should be considered as a preventive measure.
- Drainage and gas collection systems installed against the sidewall engineering are a potential source of air ingress if they are not sealed at the surface and the gas extraction system is in operation. Drawing air into the site at the perimeter has the potential to produce a hot spot close to the sidewall liner.
- The use of gas extraction systems in uncapped areas of waste is becoming more common as a method for controlling odours and emissions to the atmosphere, and for providing landfill gas for power generation. However, the design of these systems must reduce the risk of air being pulled into the waste mass and take account of the containment system for the site.
- Regular balancing of the gas extraction system is important in order to ensure that the suction is evenly dispersed through all the main collection pipes. Poor balancing will result in air being drawn into one sector, increasing the risk of a hot spot being generated at the point where the air is being drawn into the waste (around the neck-seal of one well or along a fissure in the cap). Balancing is more difficult, and therefore air ingress more likely, when suction pressures of more than 50mbars are applied to the gas wells.

6. Control and remediation

6.1 Control measures

Control measures are defined as those actions typically undertaken on site once the operator becomes aware of a hot spot problem. They include measures to identify and characterise the hot spot and to determine an appropriate remediation strategy. The following sections are based on current practice at sites with active management and control measures.

On discovery of a hot spot the following actions should be undertaken.

- Establish a monitoring regime to characterise the hot spot and the background site conditions.
- Identify areas of possible air ingress and seal them as soon as possible, in order to prevent oxygen feed to the hot spot.
- Identify whether the gas extraction system is in operation in the potential hot spot area, and the effect it is having on the hot spot (see Section 9.2.3).
- Consider short term responses, such as dousing or smothering the affected area, to reduce the initial visual and environmental impact.

6.1.1 Monitoring a known hot spot

Where a hot spot is suspected, a monitoring scheme should be developed for the site. This involves regular monitoring of temperature and gas concentrations at all available in-waste monitoring points. This monitoring is vital for providing information on the location, development and success of remediation strategies. The monitoring regime should be established as soon as possible, undertaken on a routine basis and continued until the operator is confident that the hot spot has been successfully remediated. The monitoring must be undertaken in a rigorous fashion to allow data to be compared over a long period of time; this is more likely to be years rather than months.

For many sites, the hot spot will be controlled rather than remediated. The monitoring regime should provide a method of assessing either the decline or re-ignition of the hot spot during any restricted use of the gas extraction system. Monitoring data are difficult to interpret if they are incomplete, because varied data sets do not show a consistent picture over time.

Typically, on discovering a potential hot spot, an initial survey is undertaken with down-hole monitoring at existing in-waste extraction wells and monitoring points. This gives a ‘snap shot’ of the hot spot on one particular monitoring round. A more detailed survey will then be required to confirm the location of the hot spot core and to determine its effects on the surrounding area.

The minimum data that should be obtained from a gas and temperature monitoring survey are detailed below.

6.1.1.1 Gas Monitoring

1. *Gas concentrations in the hot spot area.* The concentrations of methane, carbon dioxide, oxygen, nitrogen, carbon monoxide and hydrogen should be monitored to identify the conditions of the hot spot. Field monitoring should be calibrated with

regular laboratory analysis of gas samples. All of the monitored gases can provide information on the effectiveness of the control measures and help guide future remediation strategies.

2. After initial control measures to seal off air ingress, there will be a rapid fall in the concentrations of oxygen and nitrogen and, at the same time, methane and carbon dioxide concentrations will recover to background levels. Carbon monoxide concentrations may increase as result of the restriction in oxygen, but this will be followed by a slow decline as the hot spot becomes smaller. Hydrogen concentrations may rise initially due to the formation of water gas and the stress on the microbial community but should fall with time as the hot spot is extinguished, although only a small data set is available from the case studies examined.
3. *Background gas concentration*. This should be undertaken at several locations away from the suspected hot spot area, in order to establish the range of background values.
4. *Date and time of monitoring round*. Monitoring should be undertaken at regular time intervals to identify the effect of changes in atmospheric and operational conditions, and allow an assessment of the remediation strategies undertaken. Typically, on first identification of a hot spot monitoring is undertaken daily, reducing to weekly once the stability of the hot spot is known.
5. *Relative pressures of the monitoring points*. This is of particular importance when assessing the effect of the gas extraction system on the hot spot.
6. *Detailing any changes to the landfill environment.* This may caused by re-drilling gas wells, re-balancing the gas field or making alterations to the cap. Any changes to the site conditions that could affect the hot spot should be recorded, so that the influence on the gas concentration can be studied.

6.1.1.2 Temperature monitoring

1. *Atmospheric temperature*. Temperatures recorded within the waste, but close to the landfill surface, may be affected by changes in atmospheric temperature. Therefore, atmospheric temperatures should be recorded to allow an accurate comparison of results.
2. *Depth of temperature monitoring.* It is essential that down-hole temperature monitoring is undertaken at consistent depths and elevations over a range of locations. In areas close to the hot spot there can be a significant change in temperature with depth. Accurate and consistent measurements are therefore required to allow extrapolation between data points and to estimate the depth of the hot spot.
3. *Background temperatures of the waste mass*. This should be undertaken at several locations away from the suspected hot spot area. There is no single background value for a site, which means that a number of monitoring points should be established to obtain a range of possible background values.
4. *Temperature of leachate* The temperature of the leachate can be used as a guide for assessing the effect of the hot spot on the underlying engineering.
5. *Detailing any changes to the landfill environment.* This may include changes in gas extraction, leachate level or dousing. Any change to the site conditions that could affect the hot spot should be recorded, so that the effect on the temperature can be studied.

The data from the monitoring survey should be used for the following purposes.

1. Produce contours of temperature. These contours should be used to locate the potential hot spot core and to determine the likely temperature at increasing distances from the hot spot. Contour plots of both shallow and deep hot spots have been

successful used to identify the likely location of the hot spot core, as well as to pinpoint areas for further investigation.

2. Identify the temperature depth profile. This may enable the depth of the hot spot to be estimated (see Section 4).
3. Monitor the growth or decline of the hot spot with time and in response to the remediation works.
4. Identify when the remediation works are complete by comparing the monitoring data from the hot spot area to the established background conditions for the site.

In most cases, in-waste monitoring is conducted at existing installations such as leachate wells, gas extraction wells and in-waste gas monitoring points. However, the accuracy of the survey will depend on the spacing of these in-waste monitoring points. Several case studies report hot spot cores of only a few square metres in area. Therefore, where existing in-waste monitoring points are not sufficient to accurately locate and monitor the hot spot, it may be necessary to install additional monitoring points (see Section 6.1.5.3).

6.1.2 Site characteristics and engineering

Once a potential hot spot has been identified, the following information should be gathered to determine potential remediation techniques and to assess the potential impact of the hot spot on the environmental and engineering control.

1. Details (including depth) of installations such as gas extraction wells, leachate wells and monitoring points within the waste. This is needed to assess the potential for these installations to be used for monitoring and remediation works.
2. Type of site engineering and its potential sensitivity to elevated temperatures. In addition, the location of potential pathways for hot spot migration, such as in-waste gas or leachate collection systems, should be determined.
3. Current survey data of the site should be used to determine areas of settlement.
4. The head of leachate above the base of the site. This will allow an evaluation of the potential for the leachate to be used as heat protection or to douse the hot spot.
5. History of the site, including previous indicators of a hot spot, incidents of surface fires, list of potential waste that could act as a trigger and a review of gas monitoring data.

6.1.3 Gas extraction system

An early priority for sites with active gas management systems is to determine whether the hot spot is within the influence of the gas wells. Where this is the case, monitoring should be undertaken to determine whether the gas extraction system is contributing to the drawing in of air to the hot spot.

Many operators turn off or reduce the suction applied to the gas wells as a first response to the discovery of a hot spot. This may be unnecessary, however, where the source of air ingress can be identified and sealed. This allows the gas extraction system to continue to be used as a management tool for the gas.

The zone of influence should be established for each abstraction well in order to determine the influence of adjacent wells on the hot spot area. The apparent size of the affected area can be misleading when the gas extraction system is drawing hot gases away from the hot spot. For example, lower temperatures recorded at wells soon after turning down the gas extraction system may simply be caused by the reduction in hot gas being drawn to an individual well. This effect should be considered when reviewing the performance of remediation actions such as turning down the gas extraction system.

The main advantage of this technique is to minimise further air ingress to the hot spot area, thus limiting the hot spot development. Another advantage is that hot gases are no longer drawn into adjoining areas and so the potential for the hot spot to migrate is also limited. The main disadvantage is the reduction in the ability to control gas emissions.

6.1.4 Short term response

In some cases, it may be necessary to undertake immediate action prior to developing a planned remediation; for example, where smoke is seen emanating from the surface of the site. Typical immediate responses include covering with inert material and dousing.

Modifying the gas extraction system, backfilling hot spot wells or covering (‘sealing’) may limit the amount of oxygen reaching the hot zone and so control the hot spot. These methods may reduce emissions of smoke and control very shallow hot spots. However, they are generally ineffective at controlling deeper hot spots, which are likely to remain active below ground for considerable periods of time.

At many sites, dousing with water is undertaken in areas where the hot spot is first suspected, typically at gas or leachate wells. This can have the initial effect of reducing apparent temperatures and signs of smoke. Although there are reported incidents where dousing has been successful, additional control measures are generally required to achieve long term remediation of the hot spot. If water is to be used, it must be added in sufficient quantities to rapidly cool the hot area. If only small amounts of water are introduced into the hot area or the input is intermittent, conditions may lead to the formation of water gas, which is a mixture of hydrogen and carbon monoxide. This is both toxic and potentially explosive and has been observed to cause pressure surging. Dousing with water therefore requires the availability of a large, constant supply of water.

6.1.5 Locating the hot spot

It is essential that the exact location of the hot spot is identified in order to undertake successful remediation and to prevent a later re-emergence of the hot spot. If the hot spot is shallow, the likelihood of successful remediation will be substantially greater than if the hot spot is deeper. Initial steps to determine the location of a hot spot are detailed below.

1. On initial discovery of a hot spot, the location of the core is often assumed to be at the point of discovery, such as the smoking well or hot gas extraction point. However, the location of the actual hot spot core is often not at the point of discovery, which is merely where smoke and hot gases drawn through the waste by the gas extraction system or air currents are released.
2. At operational sites with no cap and no gas extraction system, consideration should be given to:
    - identifying recent loads that may have been deposited with a potential fire trigger;
    - identifying areas known to have suffered a surface fire, which may not have been fully extinguished;
    - undertaking surface thermal imaging surveys (see Section 7.2.1); and
    - installing shallow probes for temperature monitoring.
3. If the hot spot is thought to be shallow, consideration may be given to digging trenches to locate the hot spot.

Determining the depth of deep hot spots is difficult in areas with no in-waste monitoring facilities. Surface monitoring techniques, such as thermal imaging (see Section 4.3.1) and shallow probes, can identify the area affected by the hot spot but cannot pinpoint the depth of deep hot spots. Drilling is reported to have been used successfully to determine the depth of a number of deep hot spots. Alternative techniques, such as raising the leachate level to a level that smothers the hot spot (when the hot spot was at the depth of the raised leachate head) have also been reported. Care should be taken when employing this methodology on sites with a basal liner that is sensitive to additional loading. This method may merely chase the hot spot into the crown of the landfill or landraise without extinguishing it.

6.1.5.1 Geophysical survey

In practice, geophysics is usually used to determine areas of the landfill surface where leachate or methane is escaping and where air ingress is occurring, prior to remediation of the cap. There is little experience in the literature regarding the successful geophysical monitoring of landfill hot spots.

However, one possible technique for detecting changes in the waste mass, which could lead to identification of the hot spot, is based on changes in moisture content close to the hot spot. The assumption being that waste close to the hot spot will be significantly drier due to excess heat. Drier conditions may be detected using electromagnetic surveys or by measuring ground resistivity. Complications occur due to the heterogeneity of the waste mass producing a similar resistivity to dry materials (for example, the presence of layers of inert materials, building waste (concrete and brick) or paper).

Geophysical research is currently ongoing. Moore and Barker (2000 and 2002) discuss the application of time-lapse electrical imaging to landfills. Their work involves using electrical imaging lines to provide information on the hydraulic properties of the site. During leachate/gas extraction, the images show a general increase in resistivity across the zone. Additionally, the work showed that during periods of rainfall, the resistivity of the landfill material decreased as it became wetter. This confirms that time-lapse resistivity imaging may be able to monitor areas that are becoming drier (increasing resistivity) as a result of increased temperatures.

A recent study by Riviere *et al.* (2003) used two geophysical methods to characterise a deep-seated landfill fire. The first geophysical method – a 2D-electrical survey – had an investigation depth of approximately 30m, whereas the second method – an electromagnetic (Slingram) survey – only achieved an investigation depth of approximately 6m. The study concluded that the electromagnetic method is easier and faster to use on-site, and can be used to identify the general locality of the hot spot. This can then be followed by the electrical method, which is more time consuming and requires more data interpretation but yields more accurate results and can survey at greater depth.

Limitations to the application of geophysical methods include where a geomembrane is incorporated within the cap, as a geomembrane is highly resistive and limits the passage of current. Therefore, further research may have to be undertaken before a successful methodology for all sites is developed.

6.1.5.2 Thermal imaging

Thermal imaging, extending from a hand-held camera through to aerial photography, has been used for areas of elevated temperature requiring further investigation. However, these techniques do not provide the necessary data to determine the depth of a hot spot.

6.1.5.3 Installation of monitoring points

Investigation points, whether shallow probes or deep boreholes, may be required to locate the hot spot with sufficient accuracy for targeted remediation. Before proceeding with any installation works, the risks associated with drilling in a hot spot area must be carefully assessed, as there are very significant health and safety implications. Where possible, every effort must be made to determine the depth and extent of the hot spot prior to commencement of drilling.

Drilling work should begin at a safe distance from the hot spot, with investigation points subsequently drilled at decreasing distances from the suspected hot spot core. This method allows the spoil from each installation to be examined, and temperature and gas monitoring to be carried out before proceeding closer to the hot spot core. The appropriate depth of each installation should also be determined from an examination of the spoil and the monitoring data obtained during installation.

A comprehensive health and safety plan must be developed prior to undertaking any drilling work. Some potential health and safety issues are given below, although the list is not exhaustive.

- Exposure of smouldering waste to air may cause significant flaming to occur.
- Ongoing monitoring of gas concentrations at existing installations and gas monitoring at the new installations to identify potential hazards.
- The hot spot may have created voids within the waste.
- Hot arisings (perhaps smouldering) will need careful disposal.
- Potential for uncontrolled emissions to the atmosphere and to the working environment of drilling operatives.
- The partial combustion of waste components may generate potentially harmful trace gases that are not normally present in landfill gas.
- Flammable materials such as oil on equipment and vehicles close to the hot area may catch fire.

6.1.5.4 Shallow hot spot installations

Shallow monitoring points are typically installed in areas where the hot spot is likely to be shallow, or as a first measure to delineate areas for further investigation. The advantage of shallow monitoring points is that they are relatively quick and cheap to install, and provide a way of comparing and contouring gas concentrations and relative temperatures. The monitoring data can then be used to delineate the centre of the hot spot and to guide future monitoring or remediation strategies. This methodology has been used successfully at several shallow hot spots.

Typical installations for the investigation of shallow hot spots consist of small diameter probes or boreholes drilled into the waste to depths of 1–5m. The use of HDPE for shallow monitoring points is relatively convenient and cost-effective for the operator. However, metal installations are the preferred option, as they can withstand greater temperatures. Typically, a perforated metal casing is installed and fitted with a removable cap and gas monitoring tap.

Experience on site suggests that installation of shallow wells is susceptible to erroneous readings due to air ingress. This is particularly problematic where shallow probes are installed in uncapped waste, which allows air ingress through the waste mass to occur.

Consideration should be given to the sealing method around the monitoring points and to placing a temporary low permeability sealing layer over the waste.

As an alternative to shallow well installations, ‘spike surveys’ have been undertaken at various sites in order to characterise known shallow hot spots. At one particular site, the survey involved hammering a 1m metal rod into the waste and recording the temperature directly from the hole. This successfully identified further areas for study and delineated an area for future installations. However, the method only provided a snapshot of the waste temperature and did not prove to be an accurate method for taking combined gas and temperature readings.

An example of the installation of shallow probes is provided below.

Shallow investigative monitoring probes

A series of 24 semi-permanent monitoring points were installed over an area approximately 25m by 50m at the location of a suspected hot spot. The monitoring points were designed to record both temperature and gas concentrations. The installation of the probes was carried out using the bucket of a tracked excavator to push a 1.5m long steel rod into the waste surface, producing a 100mm-diameter hole. A 1.5m length of 50mm slotted HDPE pipe was then installed to 1.0m below surface level and the waste was allowed to close around the pipe. The top of the pipe was then sealed against the waste surface.

The survey was successful in allowing a contour plan of relative temperature to be produced and future works to be targeted accordingly.
(Case Study)

Shallow temperature monitoring probes have also been used to conduct initial surveys on the lateral extent of deep hot spots. Although this approach can be successful in determining areas for further investigation, it is unlikely to provide sufficient data to identify the hot spot location or to monitor the effect of remediation work.

6.1.5.5 Deep hot spot installations

In areas with no suitable in-waste monitoring points or where the spacing of existing installations is too broad, it may be necessary to install boreholes for the investigation and subsequent remediation of a hot spot. Boreholes have been successfully installed at a number of sites, although only after exhausting non-intrusive techniques such as thermal imaging (see Section 4.3.1).

An example of a deep borehole installation at a UK hot spot is discussed below.

Installation of investigative boreholes at deep hot spot

A grid of boreholes was installed around a leachate well thought to be at the centre of a hot spot. The purpose of the boreholes was to determine the extent of the hot spot and to allow temperature monitoring and dousing of the hot spot area.

The boreholes were drilled using a 200mm-diameter barrel auger to a depth of 20m unless the results suggested otherwise. Eighteen boreholes were drilled to depths that varied between 7m and 20m. The actual location and number of boreholes drilled was determined as drilling progressed. All the boreholes were then cased with slotted steel pipe surrounded with pea gravel and sealed with bentonite to a depth of 3m.

During the drilling, gas concentration analysis and temperature measurements were made at frequent intervals to ensure that no explosive concentrations were encountered. However, flames were observed in some of the wells during the drilling and these were thought to be the result of ignition of methane down the wells.
[Case Study]

When undertaking an investigation using drilling techniques, the boreholes should, if possible, be designed to allow for potential future remediation, principally dousing.

6.2 Remediation techniques

There are a number of remediation techniques available to the operator. These are based on the removal of one or more of the parameters in the fire triangle: fuel supply, oxygen and heat (see Section 3). The removal of fuel from the system can be undertaken in specific circumstances, for example where large volumes of combustible material have been landfilled. However, in most cases, removing the fuel is unlikely to be the preferred course of action.Nevertheless it is important that other techniques do not inadvertently increase the fuel supply or make the fuel more combustible by removing moisture.

The majority of successful remediation methods involve the removal of oxygen and heat from the system. This may be undertaken simultaneously or, as is often done, oxygen is removed from the system at an initial stage and cooling is then allowed to happen over a long period of time. However, given the insulating properties of waste, if the core of the hot spot is not cooled during initial remediation it may take months, or more likely years, for the hot spot to cool. During this period of cooling, re-introduction of oxygen is likely to re-establish the hot spot.

The typical range of remediation technologies undertaken in the UK and reported in the literature, are given in Table 25.

Table 25 Summary of remediation techniques

	Shallow hot spot (<5m depth)	Deep hot spot (>5m depth)	Element of fire triangle controlled
Seal off sources of air ingress	Common control measure but unlikely to extinguish fire. Can include smothering or placement of improved cap.	Commonly undertaken. Usually involves sealing specific points of air ingress. Smothering has less effect with depth.	Reduction of oxygen.
Excavation	Commonly undertaken	Less likely to be undertaken with increased depth.	Removal of heat.
Dousing	Commonly undertaken, often in conjunction with excavation.	Commonly undertaken, usually by injection into the waste mass. Requires a targeted approach to increase chances of success.	Removal of heat and reduction of oxygen.
Ponding (allowing leachate level to recover and flood hot spot)	Unlikely due to close proximity of hot spot to surface.	Effective if hot spot within permitted leachate recovery zone.	Removal of heat and reduction of oxygen.
Inject inert gas	Potential but unlikely to be cost effective.	Potential but only if exact location of core is known and injection can be targeted to hot spot core.	Removal of oxygen, some reduction of heat depending on the gas used.
Inject liquid carbon dioxide	Not reportedly undertaken for shallow hot spots.	Undertaken in Hawaii at a depth of 5–7m.	Removal of oxygen and heat.
Grouting	Unlikely due to cost.	Possibility, little published data but some reported success.	Removal of oxygen; seal off hot spot from fuel.
Perimeter cut-off trench	Potential in shallower waste, has been used to identify the hot spot location and restrict migration.	Less likely, as depth of hot spot makes solution impracticable.	Seal off hot spot from fuel and reduction in oxygen supply.

Current practice may involve using a number of techniques to remediate a hot spot. Examples include: delineating the hot spot area and covering it with a clay-like material to reduce air ingress; creating a firebreak by excavating deep trenches and backfilling them with clay material; and capping gas vents and suspending gas abstraction in the vicinity of the hot spot. Where relevant, discussion of these techniques is included in the following sections.

The monitoring strategy employed during the initial control of the hot spot should be continued throughout the remediation process. A long-term monitoring strategy should then be employed, based on the site-specific data and the general bulk gas indicators, to identify the increased risk of a hot spot.

6.2.1 Excavation

6.2.1.1 Technique

This technique involves removing the affected material, extinguishing all burning or smouldering waste and cooling the waste and hot spot area. Typically, this is done by excavating the waste mass, spreading or placing the waste in thin layers and then dousing it thoroughly. The waste should then be inspected to ensure that all smouldering is extinguished and that its temperature has fallen to acceptable levels prior to re-landfilling. It is important that any flammable materials are removed from the underside of vehicles in the area.

As with the other remediation techniques, knowing the location of the hot spot is necessary for successful remediation. However, excavation can be used as part of the investigation into the location of the hot spot. This has proved successful at several sites, where the suspected core has been located either by shallow probes or thermal imaging. Excavation has then been undertaken in a series of slip trenches, working from the edge of the suspected hot spot towards the centre. This approach enabled the waste to be doused prior to excavation and gas monitoring to be undertaken as work proceeded.

Other strategies that have been used during excavation of hot spots include flooding the excavation trench with water as the work approaches the hot area. This starts cooling the hot spot before it is exposed. The hot waste must be spread and doused quickly once it has been lifted. The direction of the wind must be considered in advance in order to minimise exposure of the working team as the waste is exposed.

Excavation is relatively successful for shallow hot spots, but becomes increasingly more difficult with depth. The main disadvantage of the method is the exposure of the hot spot to air. This tends to result in flaming of otherwise hot or smouldering waste. The other significant disadvantage is the uncontrolled emission of landfill gas and combustion products to the atmosphere. In addition to the potential off-site risk from odours, there are significant health and safety risks to the on-site workers involved in excavating hot waste. Flammable materials must be removed from any equipment and adequate supplies of water must be made available before work starts.

The advantages of successful excavation are that the hot spot can be located, the waste cooled and the hot spot can be clearly extinguished. Other less intrusive methods rely on monitoring to determine the effectiveness of remediation.

An alternative method for cooling has been proposed by Feliubadalo and Relea (1995). They suggest that excavated waste can be extinguished by crushing and describe a two-stage excavation method. The first stage, entitled coarse extinguishing, involves creating a hot spot cut-off trench and cooling the hot spot perimeter with water whilst simultaneously covering the fire area with soil. This is followed by spreading out the effected waste pile and extinguishing the fire by crushing the waste with machinery such as a dumper. The second stage, entitled fine extinguishing, involves using machinery and shovels to excavate, cool and crush the ignited materials. However, it seems unlikely that, having excavated the smouldering waste mass, crushing will be seen as a suitable alternative to dousing.

6.2.1.2 Practical application

Several operators have reportedly undertaken excavation and successful remediation of shallow hot spots. However, some of these operators expressed serious concern over the health and safety implications of the hot spot becoming uncontrolled on exposure to air.

An example extract from one of the case studies, which describes the excavation and remediation of a hot spot, is given below.

Shallow hot spot excavation

An initial subsurface temperature survey was carried out across the suspected hot spot area, which revealed that the hot spot area was of limited extent. As the hot spot was close to the surface and its cause remained unknown, it was decided that a trench should be excavated into the centre of the hot spot area. This would allow the suspected area to be examined and help determine if the recorded temperature anomaly was the result of a continued fire, retained heat from an extinguished fire or simply naturally-occurring landfill gases.

The excavation process involved digging out the waste material in the hot spot area, dousing the waste with water and then allowing the waste to cool before disposing it elsewhere on the landfill site.

The excavation was carried out by operator personnel, while the Fire Brigade provided constant attendance in order to extinguish any encountered burning materials. On excavation and exposure to atmosphere, the smouldering waste immediately caught fire. In areas where flames were encountered, samples were taken of any material that was suspected of causing or sustaining fire.

After four days of excavation work, the hot spot had been successfully extinguished. The excavated area was then covered in a 300mm thick layer of waste soils to reduce ingress of air to the waste.

[Case Study]

The successful remediation of a hot spot must involve the complete extinguishing of the smouldering material. Case studies report that simply dousing the excavated waste may not be sufficient to cool the hot spot. It may be necessary to spread the waste, saturate and then repeat the process until the waste is completely cooled.

6.2.1.3 Health & Safety implications

Excavating hot spots is potentially hazardous, mainly because excavation exposes the hot spot area to air. It has frequently been reported that smouldering waste suddenly bursts into flames on exposure to air.

Excavation should not be undertaken unless a full risk assessment of the potential consequences, together with a review of the advantages and disadvantages of the procedure, has been carried out. The following case study describes precautions that can be taken to minimise the hazards associated with excavation.

Hot spot excavation: health and safety aspects for Reid Street landfill, Melbourne, Australia

Reports of smoke coming from the landfill (a former quarry) were made throughout the 1980s and 1990s. It was not until 1999, when a closure plan was developed for the site, that remediation took place. This included extinguishing the underground fires and capping the site with an engineered low permeability cap.

Excavation methodology

1. A designated bunded area ('laydown area') was established to ensure that all water used to extinguish the fire and cool the waste remained within a controlled area.
2. Burning or excessively hot material was doused during excavation and spread in thin layers (maximum thickness 300mm) in the laydown area.
3. Further dousing and turning over of the material until flames had extinguished/material cooled.
4. Cooled material stockpiled in the laydown area.
5. Soil was made available next to the excavation in case temporary cover was required.
6. Excavation covered with soil at night.
7. Visual inspection of the excavated waste and laydown area continued for a minimum of five hours after work ceased and once after midnight during the excavation work.

Health and Safety precautions

1. Entry to the site was restricted to those that had completed a fire safety training course developed for the remediation project.
2. Wind direction was measured by two methods to ensure that the excavation was carried out on the windward side of the hot spot where possible.
3. At least one water truck (three in total) was always present at the site;
4. Full Personal Protection Safety Equipment used throughout the excavation, including self-contained breathing apparatus and full-length fire resistant overalls.
5. Spotter staff used to highlight and warn of potential problems during excavation.
6. Water (fine spray) used to minimise the smoke and dust released during the excavation.
7. Gas and vapour monitoring carried out throughout the excavation, with trigger levels detailed below.

Gas/vapour	Trigger point
Organic vapours	10ppm
Methane	3 per cent
Oxygen	19 per cent (min)
carbon dioxide	5 per cent

Smouldering continued for over a week after excavation and so further work was carried out. This included removing the upper 4m of waste around the hot spot and excavating beyond the perimeter of the hot spot to isolate it from adjacent waste and prevent the hot spot from spreading.

The exposed rock at the base of the quarry remained hot even after removal of the burning waste and so it was left to cool before the fire extinguishing works were deemed complete. [Ref: Parker *et al.* (2001)]

Excavation of shallow hot spots can be successful, but it should only be undertaken once all of the hazards have been identified and with the implementation of a comprehensive risk management procedure.

6.2.2 Dousing

Dousing is the injection of a liquid into the waste mass to cool the hot spot. It is used for both deep and shallow hot spots, with varying degrees of success. In general, dousing is considered to be effective at cooling the waste, however successful extinguishing of hot spots is less commonly reported. As with other techniques, the exact location of the hot spot core must be known in order for dousing to be effective.

Typically, water or leachate is injected or re-circulated into the hot spot area, either down existing wells or newly installed injection points. It is preferable to use water and to ensure that a reliable, constant supply is available to minimise the risk of the formation of water gas. Consideration can be given to the use of a surfactant agent, which is added to the water to overcome the capillary forces that can prevent it from penetrating the burning material. A mixture of 0.5 per cent Class-A foam by volume with water is recommended by Sperling and Henderson (2001). No examples of the use of surfactants in the UK were encountered during the research for this project.

Sperling and Henderson (2001) recommend, as a heuristic value, that 0.5–1.0m^3 of water is required for every 1m^3 of waste involved in the fire. However, a much larger volume of liquid may be required if the location of the hot spot core is not known with certainty.

It is essential when carrying out dousing that the landfill manager or other designated person keeps detailed records regarding the dousing, including, but not limited to, the following information:

- volume and rate of liquid doused;
- time and date of dousing; and
- location of dousing points.

This information can then be related to temperature monitoring in order to determine the effects of the dousing on the hot spot.

6.2.2.1 Deep hot spots

Dousing of deep hot spots is typically undertaken from existing gas extraction wells, leachate collection systems or, in some cases, from specific points drilled into the waste mass. To undertake successful dousing, the following information should be obtained:

- location and depth of hot spot;
- depth of installation(s) where liquid is to be injected; and
- maximum volume of liquid that will be permitted, under the licence or permit to inject into the waste mass.

It is essential that the relationship between the depth of the injection points and the hot spot is determined. If the hot spot is at a shallower depth than the installation, consideration should be given to installing a temporary packer into the injection point to ensure that the liquid enters the waste mass at the correct depth. Without knowing the actual depth of the hot spot, pouring a liquid down a gas or leachate well only has a slim chance of successfully extinguishing the hot spot. Since the hydraulic conductivity of waste is much lower along the vertical axis than the horizontal axis, dousing from above is less likely to reach the hot spot than introducing water close to the horizon containing the hot spot. The most suitable method for identifying the potential depth of a hot spot is through temperature surveys (see Section 4).

Dousing is often undertaken as an initial control measure and the hot spot is assumed to have ceased when temperatures at distant wells are seen to fall. However, this apparent drop in temperature may be caused by the cooling of waste adjacent to the hot spot area rather than the extinguishing of the core. It may also be a result of other actions such as reducing the gas extraction system or sealing off air ingress. Long term monitoring is required to confirm whether dousing has been successful.

Dousing of a hot spot has been undertaken from relatively shallow installations, approximately 5m in depth, installed at close centres above the suspected core of the hot spot. Liquid is then fed into the shallow installations to saturate the waste. The success of this technique depends on the depth of the hot spot and the pathways taken by the liquid as it passes through the waste mass. This technique can be considered for relatively shallow hot spots. For deeper hot spots, the closer the liquid injection point is to the core of the hot spot, the greater the chance of success, as discussed in the case study below.

Hot spot control by dousing down existing wells

On discovery of a deep hot spot close to a well, the gas extraction system in the area was turned down and leachate dousing commenced. A total of 57.5m^3 of leachate was pumped down three gas extraction wells and a soakaway in the hot spot area over approximately two weeks. Although it was difficult to focus the dousing on the hot spot centre, an immediate drop in temperature was observed, which was put down to these two control actions. Temperatures recorded at the hot spot well fell rapidly by 40–50ºC over the two week period.

Dousing was not continued, however, and temperatures gradually increased to 80ºC over the following four months.

(Case Study)

Other injection points such as in-waste horizontal gas collection pipes have been successfully used to extinguish known hot spots, or, at least, bring them under control.

6.2.2.2 Installation of remediation boreholes

If the hot spot is not located close to a suitable existing injection point, such as a gas or leachate well, then consideration should be given to drilling specific wells for the investigation and subsequent remediation of the hot spot. This has been undertaken with success at several sites, an example of which is given below.

Installation of investigative boreholes at deep hot spot

A total of 18 boreholes were installed at a spacing of approximately 5m, to depths ranging from 7m to 20m. The boreholes were used to investigate the location of the hot spot core, for dousing and for long term monitoring. Following detailed monitoring, dousing was undertaken at five of the boreholes. Dousing was undertaken over a 10-month period with continual monitoring of temperature and gas concentrations. Dousing was considered to be successful once the recorded temperatures returned to the level of the background and normal anaerobic temperatures for the site of 30–50ºC.

[Case Study]

The above case study highlights the long term nature of the dousing and monitoring that may be required to extinguish successfully a deep hot spot.

6.2.2.3 Disadvantages of dousing

Dousing needs to be carefully controlled to minimise all potential negative effects. The main disadvantage of this method is the introduction of liquid into the waste mass. Factors such as the availability of leachate, licensing requirements, the creation of leachate if water is used and the potential raising of the leachate head all need to be carefully considered before proceeding with hot spot dousing.

A range of other potential adverse effects are also cited in the literature, although their frequency of occurrence was not identified during this research work. They include:

- the formation of cavities;
- reduction in waste stability; and
- channelling and possible wash out of fines leading to increased waste permeability.

The use of insufficient water may create additional hazards. Water gas, a mixture of hydrogen and carbon monoxide, is generated when steam passes over hot carbon. This situation may arise if the water is added in small amounts or so slowly that the hot carbonaceous waste vapourises the water without being adequately cooled. The hydrogen will form an explosive mixture that can be ignited by the residual hot spot. Hence, if dousing is used, a steady supply of large volumes of water and wide bore delivery pipes are essential to minimise the risk of hydrogen formation.

6.2.2.4 Health and safety

A number of health and safety issues have been reported by several operators that have undertaken dousing. Some of these issues are detailed below.

- High temperature steam can be emitted from the points of liquid injection or from cracks within the capping system.
- Injection of liquid into the wells can result in the mixing of flammable gases and oxygen within the well. These gases have been known to ignite, explosively in some cases.
- Uncontrolled emission of gases from the injection points can occur.

6.2.3 Ponding

Ponding refers to increasing the leachate levels within the site to douse the hot spot. This method has been used where the depth of the hot spot was known and where the operating conditions of the landfill permitted.

The leachate level may be lifted either by adding liquid to the waste mass or by allowing it to recover to known levels. The advantage of this system is that the hot spot can be cooled without having to identify its exact location.

The disadvantages of this technique are the general problems associated with having a high leachate head. It may also merely force the fire into upper levels of the waste.

<u>Hot spot control by dousing and raising of leachate head</u>

Following the discovery of a deep hot spot at the base of a leachate well (‘the hot spot well’), leachate extraction was immediately discontinued. Leachate dousing then commenced down the hot spot well and at two nearby gas extraction wells (15m and 18m away). This dousing led the leachate head to rise by approximately 7m at the hot spot well. The high leachate head is thought to have extinguished the hot spot and landfill gas generation rapidly recovered.

(Case Study)

6.2.4 Subsurface injection systems

Subsurface injection involves cooling and smothering a hot spot with a fluid suppressant material. The suppressant smothers the hot spot by replacing or driving out the oxygen source and/or cools the material by removing heat.

Injection methods should be used in conjunction with other control activities, such as sealing any potential sources of air ingress and managing the gas extraction system. The key issue for the success of this method, as with others, is the accuracy with which the hot spot depth and extent are known. The discussion below is based on limited data received from Fire Stop, a US landfill fires remediation company.

6.2.4.1 Shallow hot spots

The control of shallow hot spots with suppressant materials is best conducted at ground level after excavating the hot spot material. Suppression of the hot spot material can be achieved by using Compressed Air Foam Systems or Air Aspirated Foam Systems. When carried out in a properly bunded and controlled area, this method can prevent any run-off or unwanted leachate. The local fire brigade should be consulted prior to the use of these systems.

6.2.4.2 Deep hot spots

Using a fluid to cool and suppress deep hot spots involves one of the following methods:

- injecting liquid carbon dioxide;
- injecting liquid nitrogen;
- injecting compressed nitrogen foam;
- injecting compressed air foam;
- water injection with foam; and
- combinations of the above.

There is little published data on these methods or examples where they have been successfully employed in the UK. It is believed that the primary reason for the low usage of these injection methods is the poor data available to identify with accuracy the hot spot core. Therefore, the estimate of the quantity of chemicals that may be required is uncertain and the costs may appear prohibitive.

Injection of liquid carbon dioxide was undertaken at the Ma’alaea landfill in Hawaii. It is reported that approximately 450kg of liquid carbon dioxide were injected into a landfill at a depth of 5–7m below the surface. The hot spot was reportedly extinguished within weeks, although smouldering continued for several months. This highlights a problem identified in UK landfills, in that continued smouldering indicates that the hot spot has not been sufficiently cooled to avoid re-establishment.

The main disadvantages of this approach are that the method relies on the introduction of a foreign material into the landfill, which will have various consequences. For example: the injection of carbon dioxide may generate unwanted gases in the landfill; water injection may cause problems with the leachate system or ground water and may also generate hydrogen; and compressed air foam puts more oxygen into the landfill. Other disadvantages are that the mobility of the suppressant material is difficult to control and the injection system may require many injection wells and pipes in order to achieve distribution at varying elevations.

Although these techniques have reportedly been used successfully in the US, there appears to be little experience of using these techniques in the UK. The fundamental issue of identifying the actual location of the hot spot core remains. Unless the remediation work is targeted at the hot spot core, the injected material will either miss the hot spot or require very large volumes to be successful.

An alternative to the introduction of inert gas is to allow microbial gas to smother the hot spot. In theory, a well-sealed landfill with good gas production generates a mixture of methane and carbon dioxide, which will force air out of the porous structure. If the site has a good gas management system, it may be possible to use this internally generated gas to exclude oxygen, thereby suppressing potential hot spots before they become a problem. However, the fact that a hot spot has been generated may indicate that the gas management system is inadequate and so this method cannot be used on sites where a hot spot has already developed.

6.2.5 Grouting

Grouting of the hot spot is a potential method for providing a containment system, sealing off areas of air ingress or even enclosing the hot spot core. The method involves injecting a fluid grout into regions of waste around the hot spot. The cement-like material will seal the pores of the waste and exclude oxygen, while water in the grout will have an additional cooling effect.

It is an expensive technique but could be effective for deep, localised hot spots that can be reached by drilling into the waste or accessed through existing intrusions such as leachate wells. Reference to grouting techniques is made in several papers, although no detailed UK case studies were identified as part of this work. In one anecdotal example, a hot spot located 5m below the cap was successfully put out using a 10:1 mixture of pulverised fuel ash (pfa) and cement, which was pumped into the waste below the seat of the hot spot using a drilling rig. In another example, a 20:1 mixture of pfa and ordinary Portland cement was injected to create a grout curtain around the affected area. This involved direct drilling a series of wells in a block around the identified hot spot. Another case involved using angled drilling to reach the region of the hot spot.

6.2.6 Perimeter cut-off trench

Perimeter cut-off trenches have been employed during the remediation of several shallow hot spots. This technique is used to control the lateral spread of a fire by excavating a trench and then backfilling with compacted clay around the suspected area of the hot spot. During the excavation process, the trench is usually monitored for gas concentrations, temperature and visible signs of a hot spot.

6.3 Re-ignition

If the original causes of a hot spot are not remediated then there is a high risk that the hot spot will re-ignite. It is likely that the heat or the method of treating the hot spot may have damaged the containment system and so particular attention should be paid to preventing ingress of air as control of the hot spot is relaxed. The low thermal conductivity of emplaced waste may result in the retention of sufficient heat to re-ignite residual fuel if oxygen is re-introduced. This could still occur up to several months after the monitoring has indicated that the original problem has been extinguished. Hence, re-starting gas collection from an affected cell should be closely managed and monitored to demonstrate that air is not entering the landfill and to ensure that indicators of a hot spot are not increasing.

6.4 Financial implications

The control and remediation of hot spots is costly and time consuming. It is also fraught with uncertainty over the precise location and extent of the hot spot, the likely consequences of intervention, health and safety issues and determining when the self-sustaining process has been halted. The costs fall into four broad categories:

- monitoring and confirming a hot spot;
- remediation of the fire;
- remediation of faults in the engineering or failures caused by the hot spot; and
- loss of income from gas utilisation.

The combined cost of these can be substantial. Anecdotal information suggests that remediation involving ground engineering may cost several hundred thousand pounds, and maybe as much as a million pounds. Since gas utilisation may be affected for several months, the loss in income from power generation may approach the same magnitude. This serves to illustrate that preventing fires is a better financial and environmental option than attempting to control an established hot spot.

6.5 Summary

Many different hot spot control and remediation strategies are employed in practise to deal with both shallow and deep hot spots. There appear to be no universally successful methods and a combination of techniques may be needed to contain, extinguish and cool a hot spot. Each of the methodologies discussed in this report have distinct health and safety implications, which must be assessed on a site-specific basis prior to the commencement of any work. Successful control and remediation generally involves the removal of oxygen and heat from the hot spot area.

All the methods involve significant cost, as well as loss of gas management and reduced gas utilisation for a period of time. Hence, it is preferable to prevent a hot spot from forming rather than remediate one once it has become established. Furthermore, remediated hot spots should be prevented from re-igniting by closely monitoring the re-start of the gas management system. Preventing a hotspot from developing is primarily down to having a good monitoring regime, and site management and waste acceptance procedures that avoid the introduction of hot material and oxygen into the waste mass.

7. Glossary of Terms

Coefficient of thermal expansion	The (linear) coefficient of thermal expansion is the change in length per unit length of material for a one degree Kelvin change in temperature.
Deep hot spot	A hot spot that occurs at a depth greater than 5m from the current waste surfaces.
Exclusion zone	An identified area surrounding the (potential) hot spot beyond which all vehicles, plant and personnel that are not involved in the investigation may not pass.
Fire point temperature	The temperature at which vapour released from a material will continue to burn after the pilot flame (ignition) is removed.
Flash point temperature	The temperature at which vapour released from a material or liquid will ‘flash’ momentarily when a flame is placed near it, but will not continue to burn.
Heat-deflection temperature	The deflection temperature is a measure of a polymer's resistance to distortion under a given load at elevated temperatures. The deflection temperature is also known as the 'heat deflection temperature' or 'heat distortion temperature'.
Hot spot	An area of raised temperature within a landfill where smouldering or combustion in the presence of oxygen is either occurring or likely to occur.
Pyrophoric carbon	Carbon-based material that has undergone pyrolysis.
Shallow hot spot	A hot spot that occurs within 5m of the current waste surfaces.
Spontaneous ignition temperature	The temperature at which self-ignition/auto ignition/spontaneous ignition occurs, given the presence of a supporter of combustion such as oxygen.
Thermal conductivity	Thermal conductivity is a property of materials and expresses the heat flux f (W/m^2) that will flow through the material if a certain temperature gradient DT (K/m) exists over the material.

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Figures

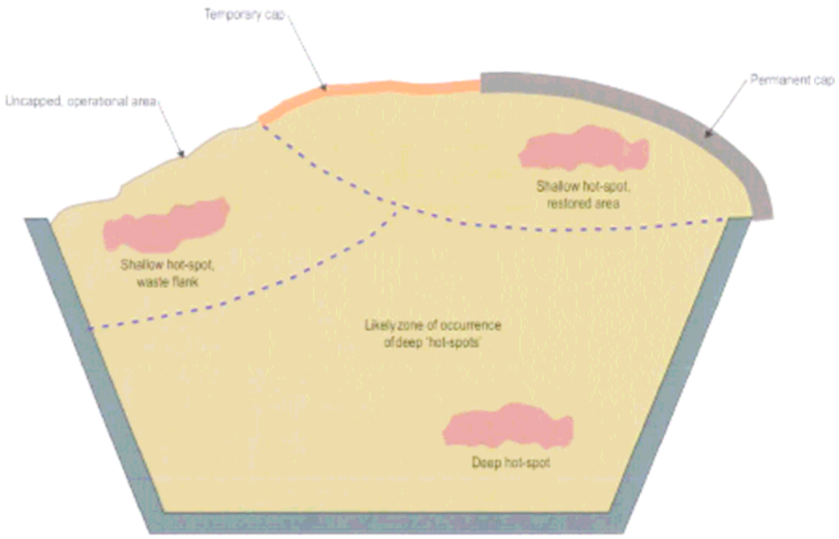


Figure 1 Types of landfill hot spot

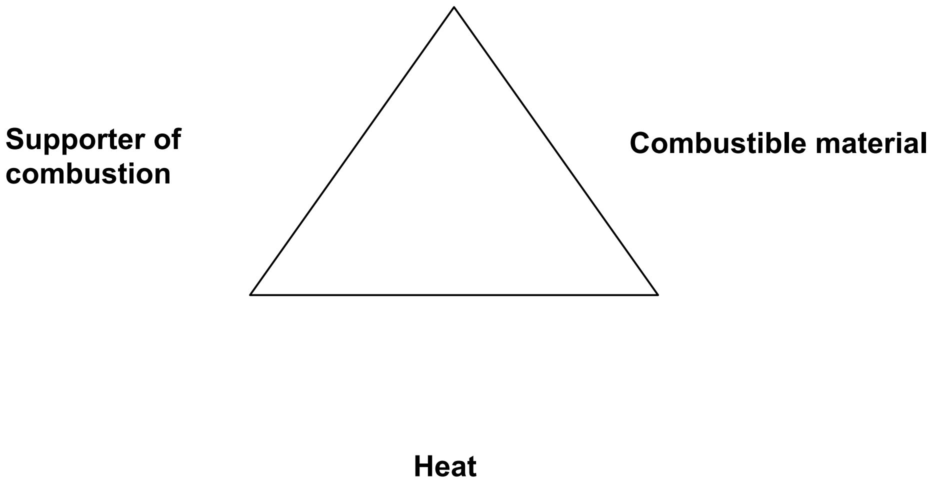


Figure 2 The fire triangle

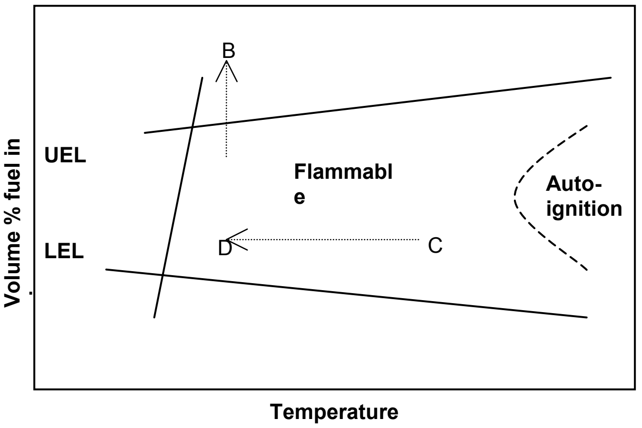


Figure 3 Schematic flammability diagram to demonstrate the effect of temperature on the flammability limits and auto-ignition

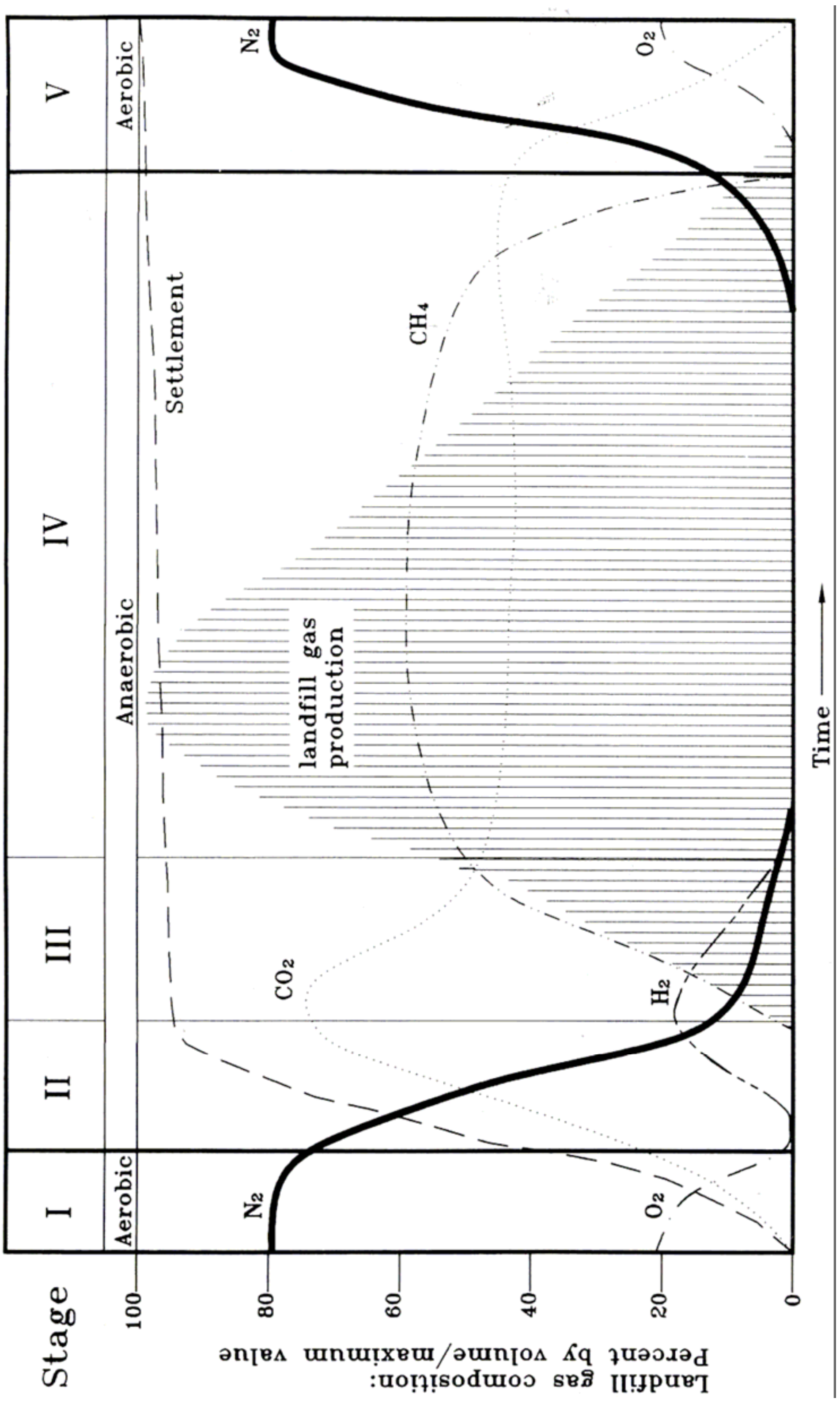


Figure 4 Change in composition of landfill gas

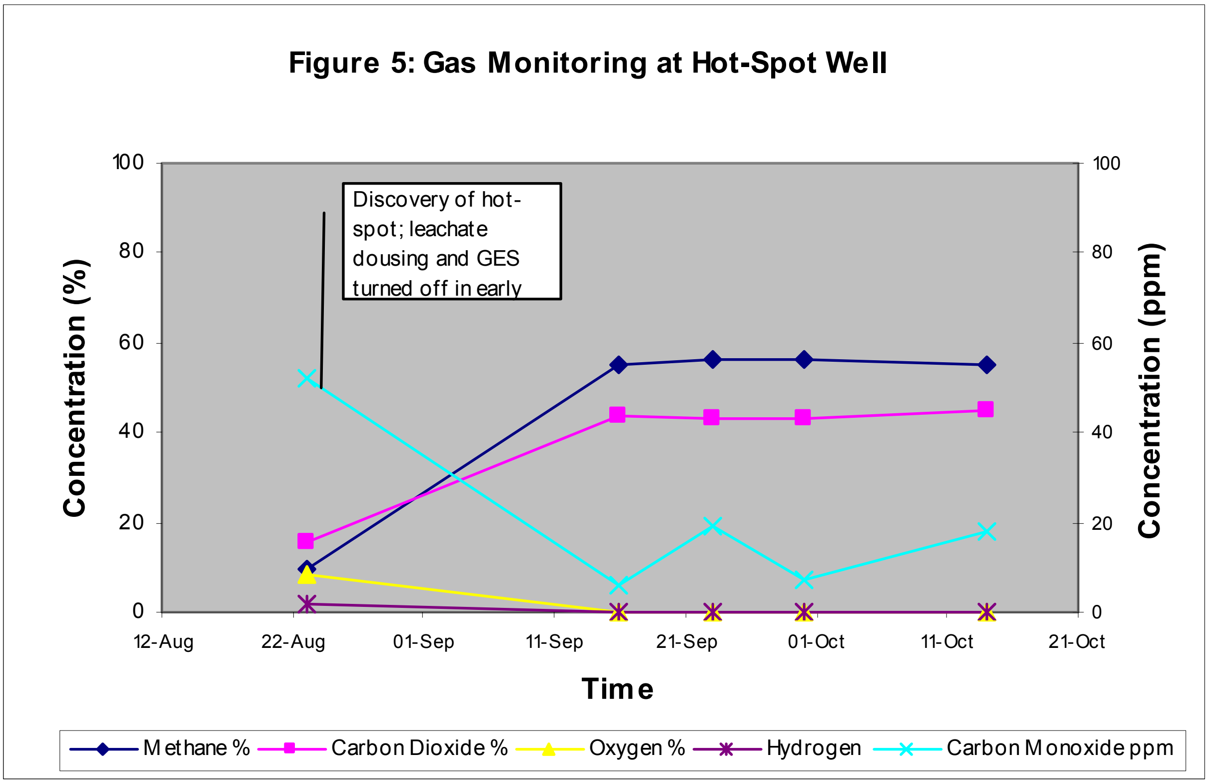


Figure 5: Gas Monitoring at Hot-Spot Well
Discovery of hot-spot; leachate dousing and GES turned off in early
Concentration (%)
Concentration (ppm)
100
80
60
40
20
0
12-Aug
22-Aug
01-Sep
11-Sep
21-Sep
01-Oct
11-Oct
21-Oct
Time
Methane %
Carbon Dioxide %
Oxygen %
Hydrogen
Carbon Monoxide ppm

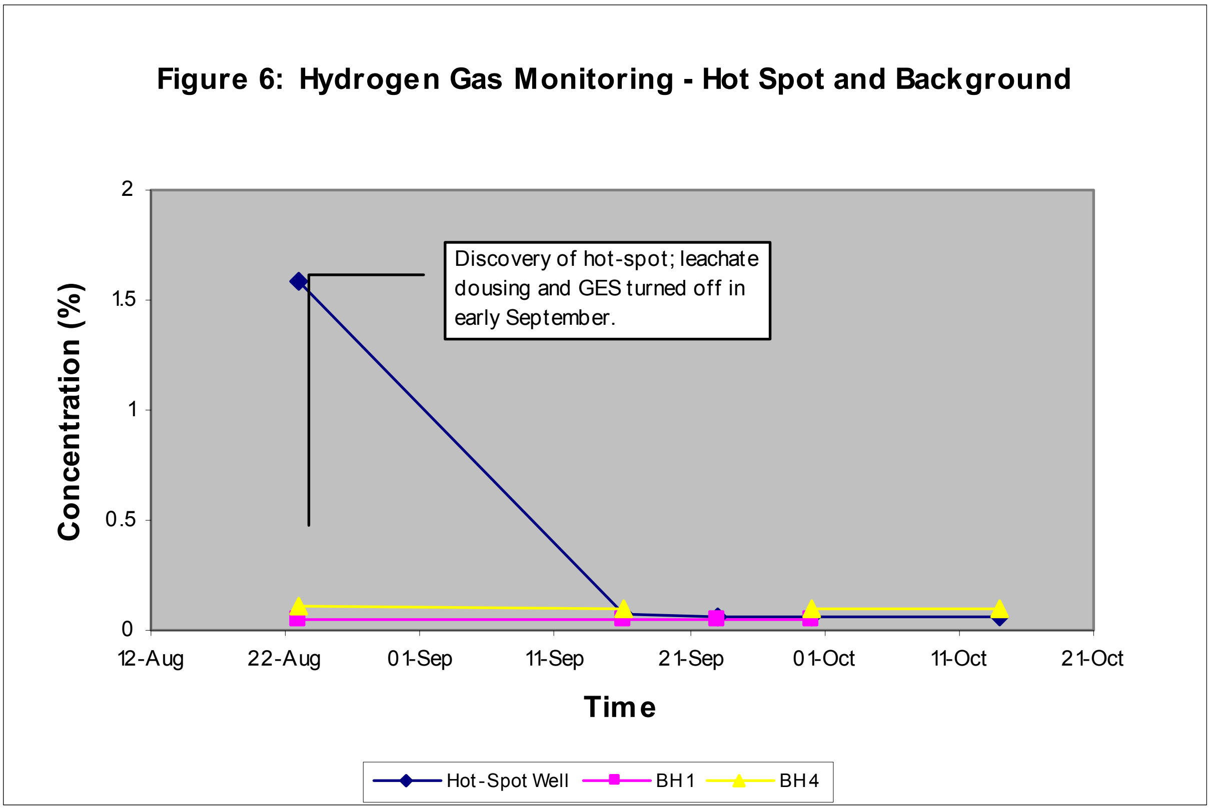


Figure 6: Hydrogen Gas Monitoring - Hot Spot and Background
Discovery of hot-spot; leachate dousing and GES turned off in early September.
Concentration (%)
2
1.5
1
0.5
0
12-Aug
22-Aug
01-Sep
11-Sep
21-Sep
01-Oct
11-Oct
21-Oct
Time
Hot-Spot Well
BH1
BH4

Figure 7: Temperature Monitoring Data (1)

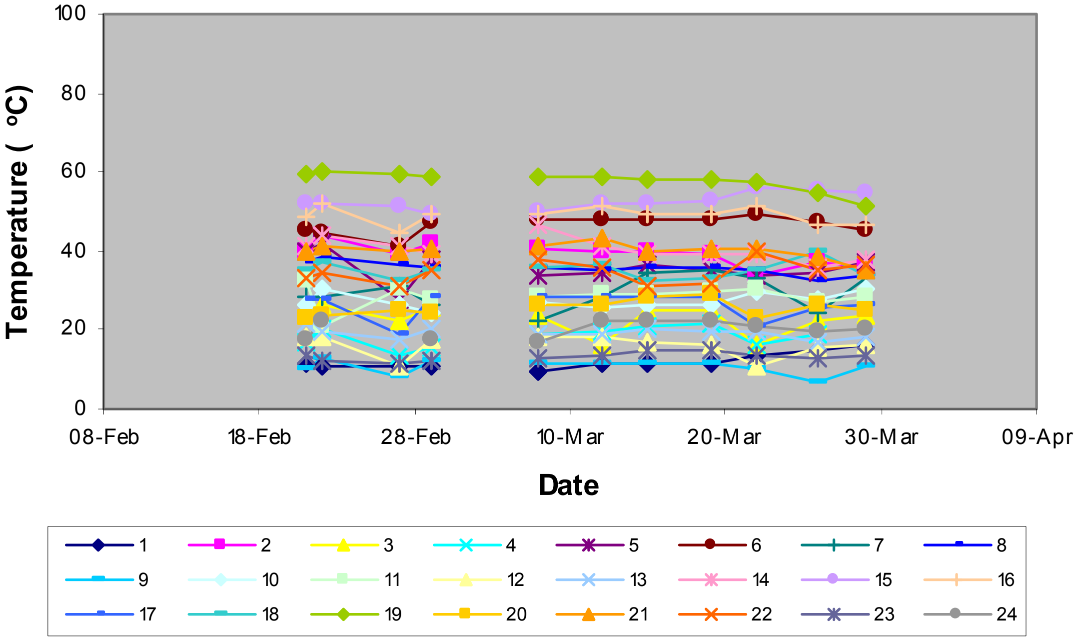
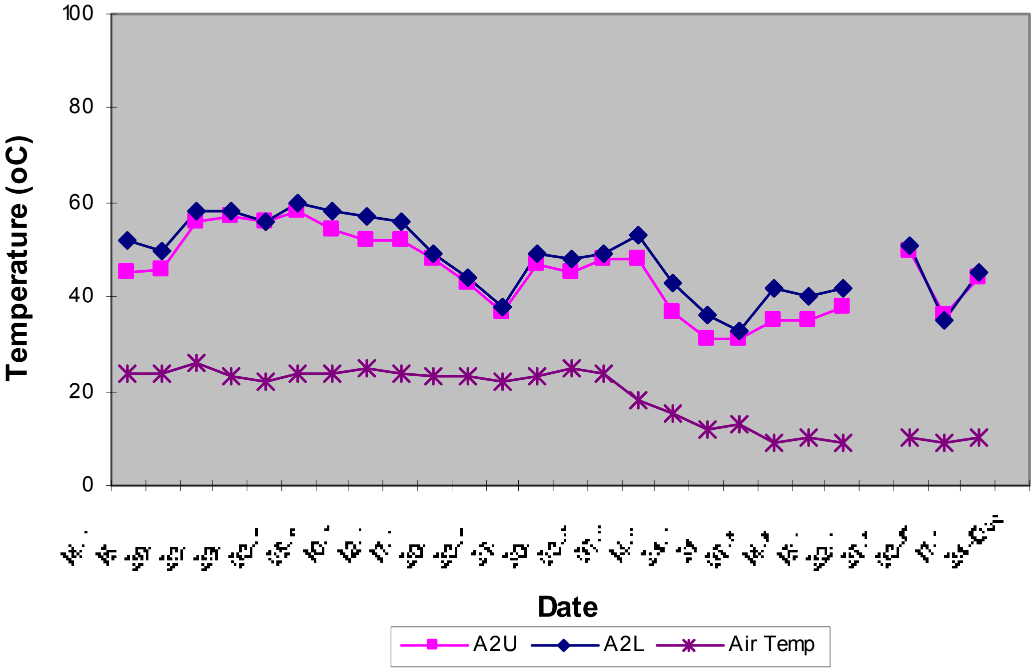


Figure 8: Temperature Monitoring Data (2)



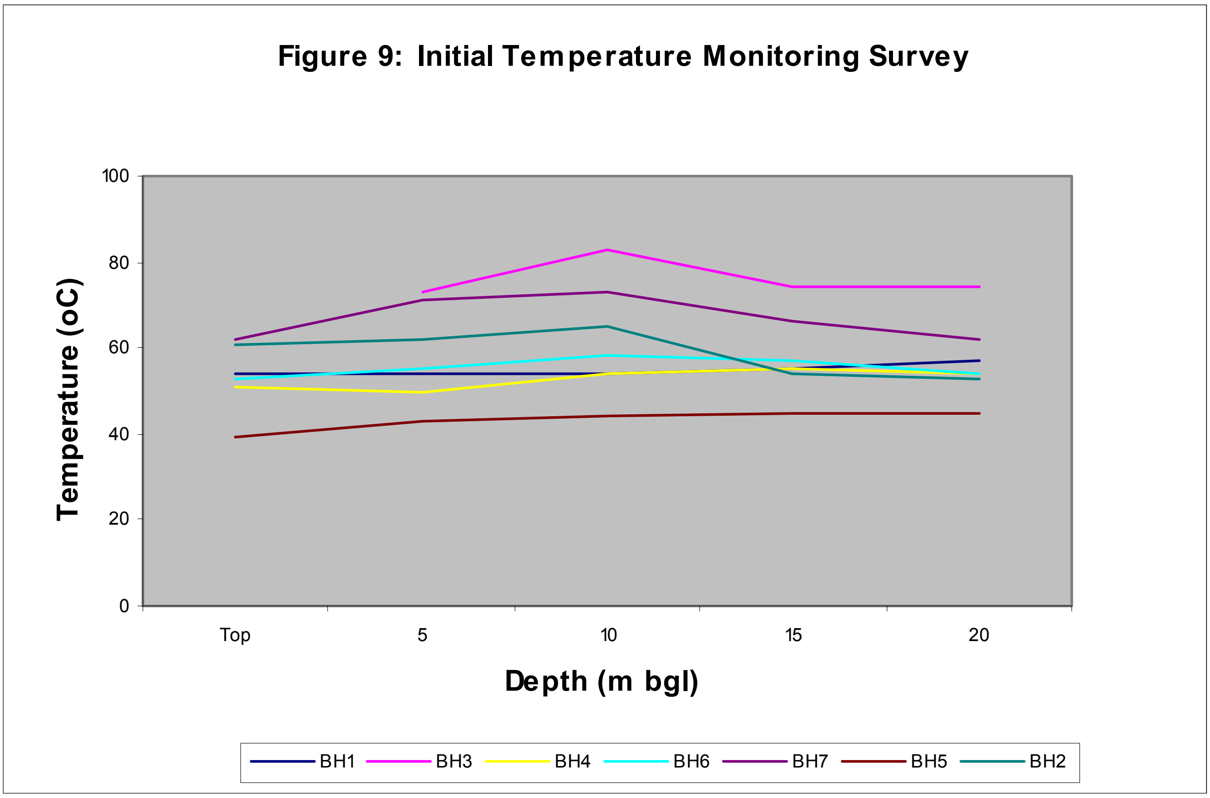


Figure 9: Initial Temperature Monitoring Survey

Figure 10: Horizontal air pathway

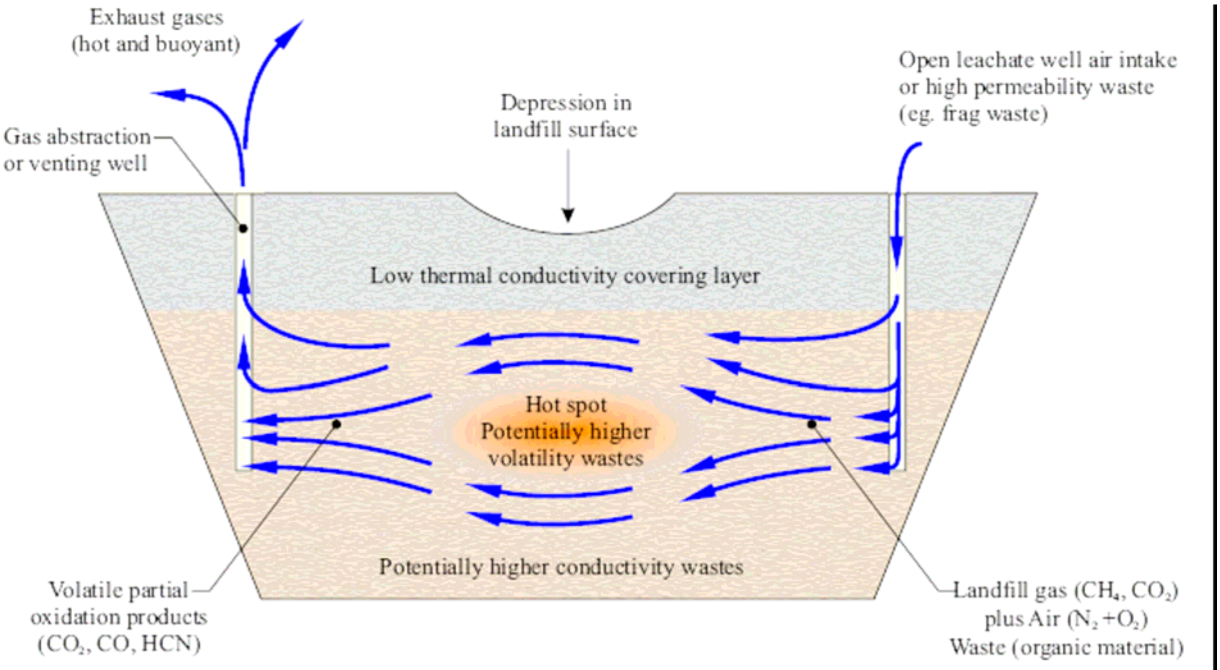
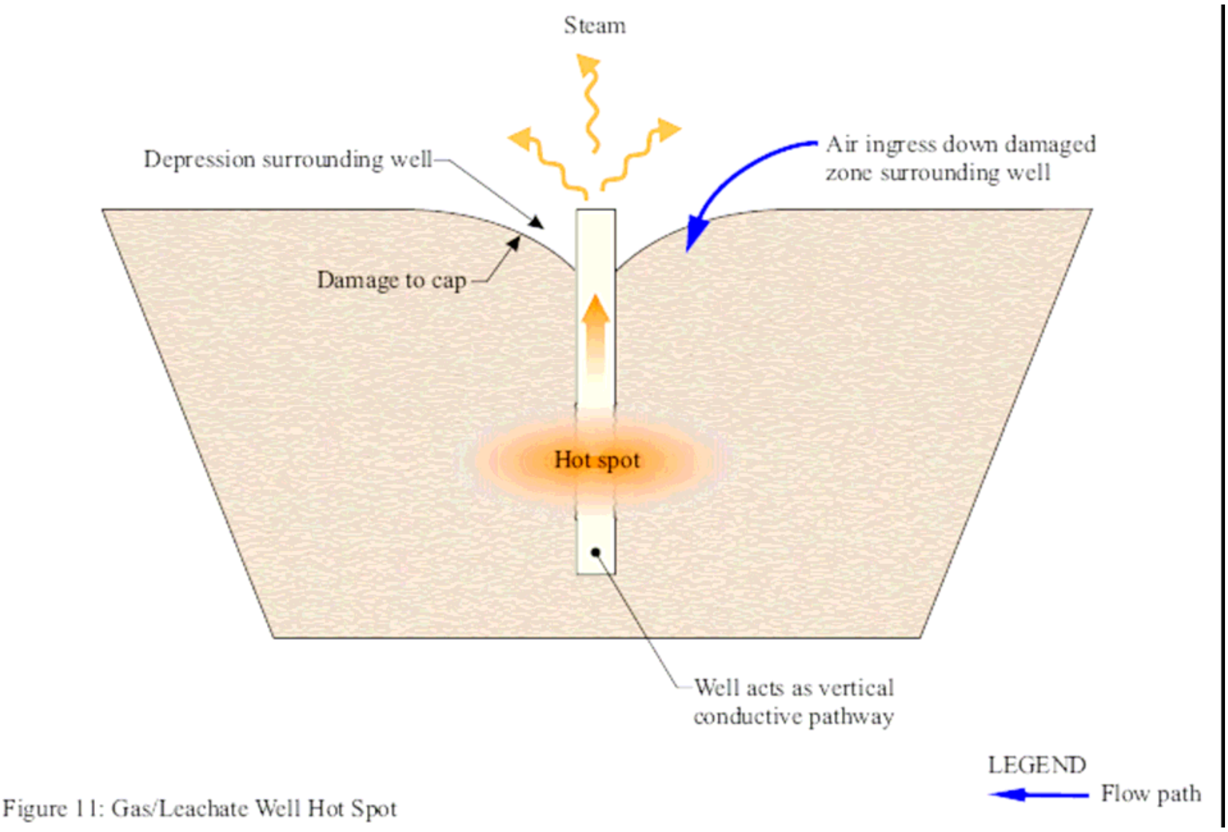
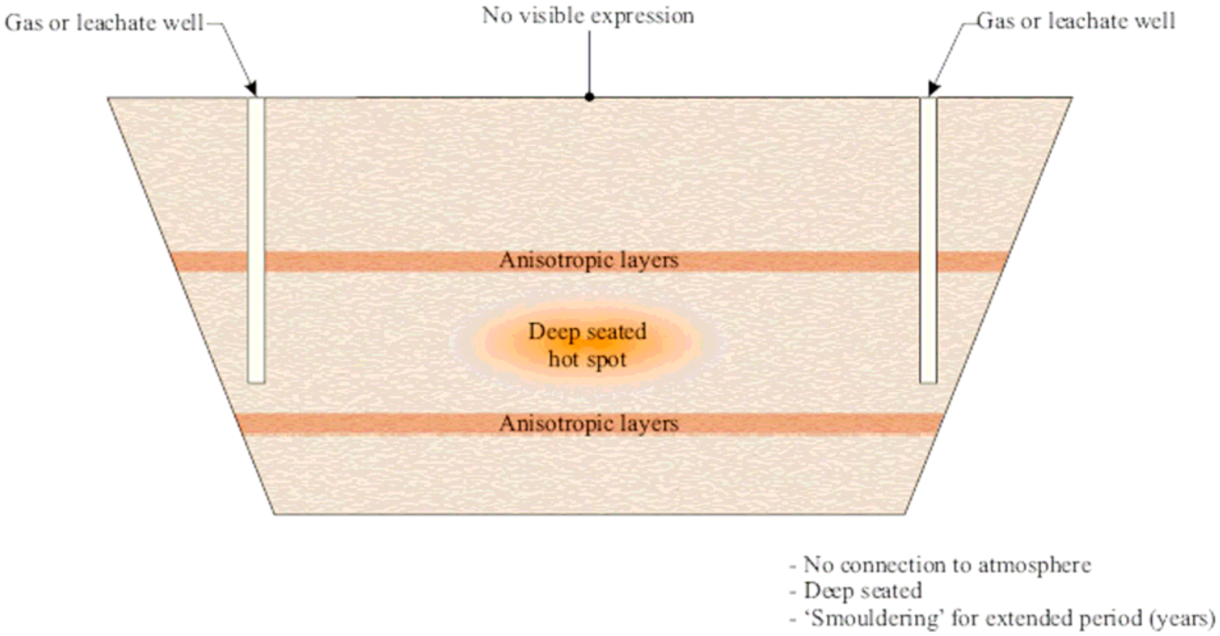


Figure 10: Horizontal Air Pathway

Figure 11: Gas/Leachate Well Hot Spot





- No connection to atmosphere
- Deep seated
- 'Smouldering' for extended period (years)

Figure 12: Confined hotspot

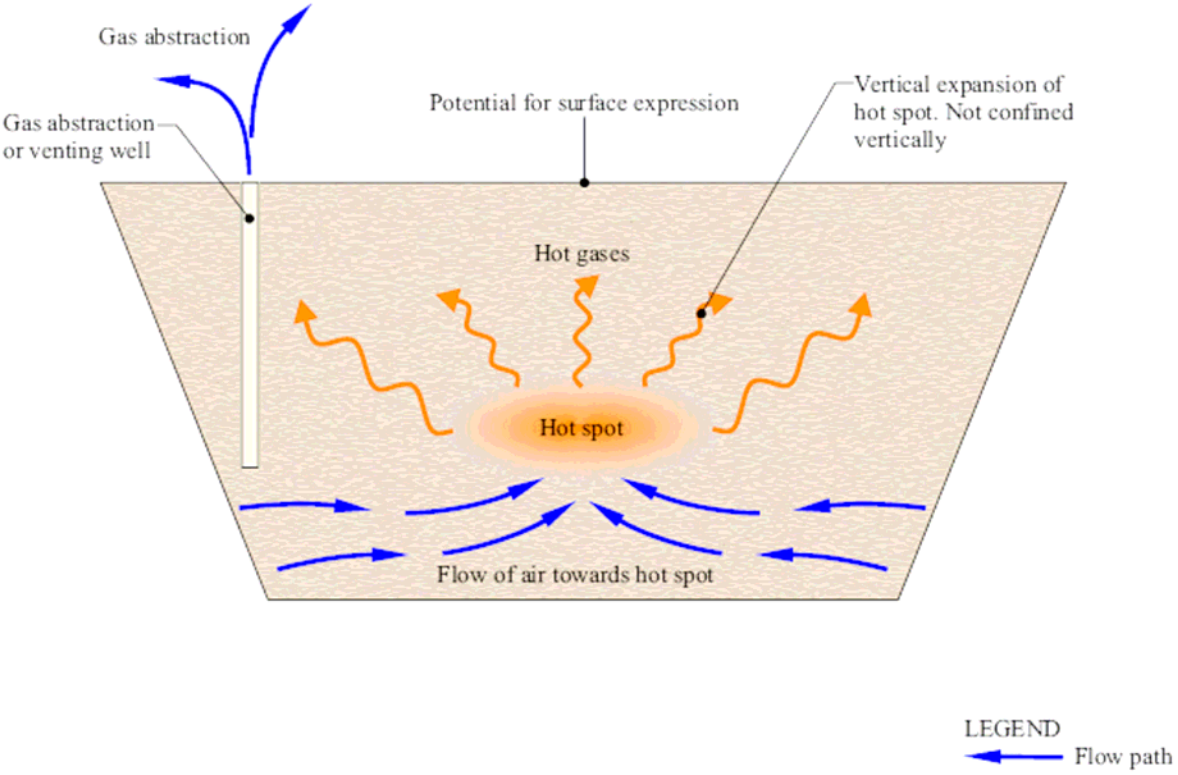


Figure 13: Unconfined hotspot

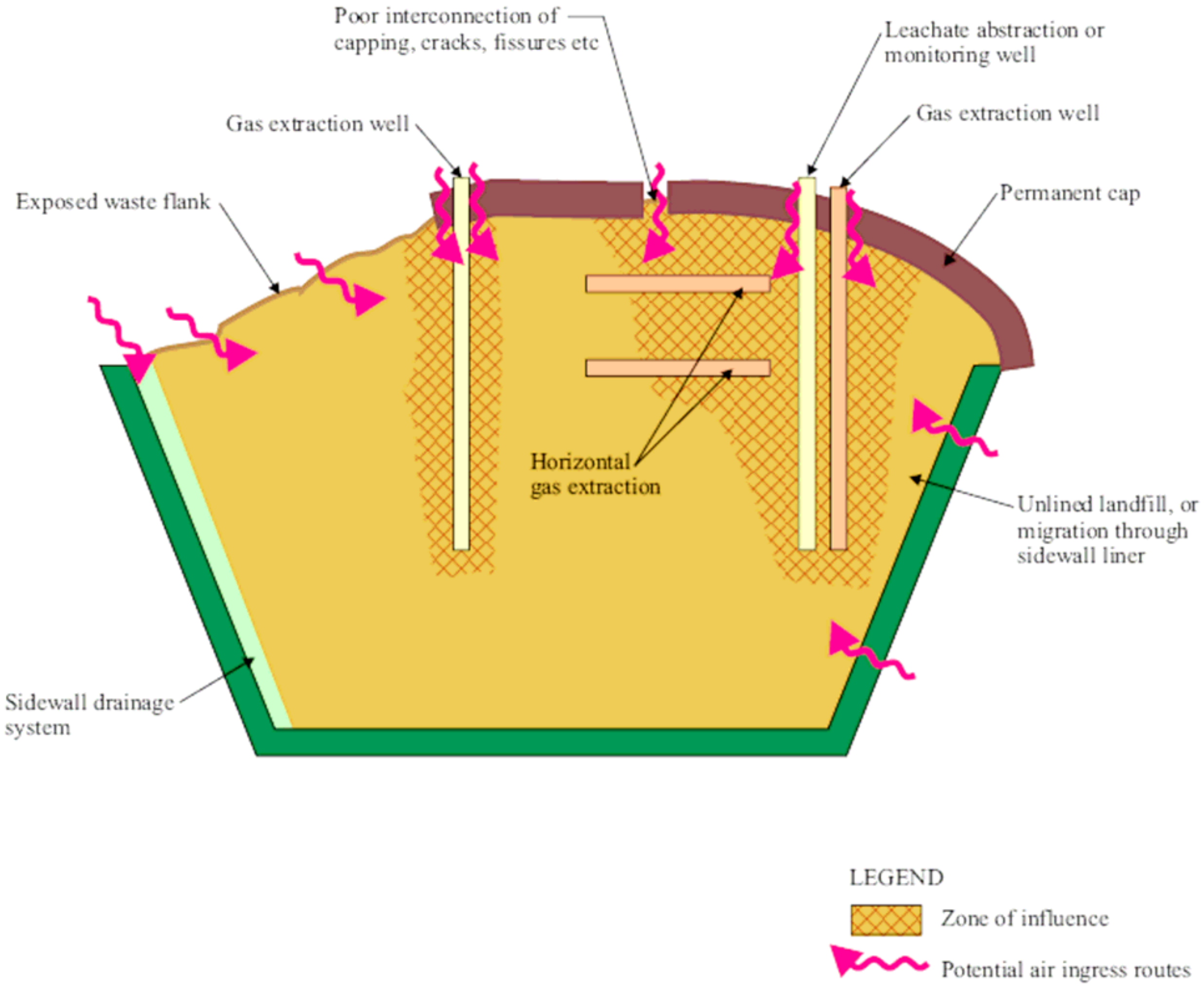


Figure 14: Potential routes for air ingress to waste

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Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

The Environment Agency. Out there, making your environment a better place.

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