Landfill Gas
Industry Code of Practice

The Management of Landfill Gas

This document is designed to represent good practice in landfill gas management in the UK. It has been written by industry, for industry, but is expected to be referred to by regulatory authorities in determining and demonstrating the exercise of best practice. In all circumstances this document does not replace site specific competent design, installation and operation.

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This report is intended to be a living document that will develop with time. Comments received will be assessed periodically by the steering committee that developed the document. Additional case studies and practical examples of landfill gas management will be especially welcome.

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1 Introduction and Scope

1.1 Aims and Objectives

This Industry Code of Practice (ICoP) addresses the management of gas produced from landfill sites accepting biodegradable waste. The ICoP represents current best practice and has been written by the landfill gas industry with input from the Environment Agency (EA) the Scottish Environment Protection Agency (SEPA) and the Northern Ireland Environment Agency (NIEA).

This document does not assume to instruct operators, but is a set of guiding principles, which, when followed, will demonstrate best practice. It is targeted at professionals and operating companies within the landfill gas industry and any person, contractor or company who performs tasks on a landfill site. It does not assume any particular level of knowledge. In most cases, it presents a high level overview of the subject matter. It is not a substitute for professional study, training or qualifications.

The landfill gas environment is complex and potentially hazardous. All persons present on a site, or making decisions about a site, must satisfy themselves of their appropriate level of understanding of the task or decision to be made.

1.2 Fundamentals of Landfill Gas

Landfill gas (LFG) is the end product of the decomposition of biodegradable waste. Methane (CH_4), a core component of LFG, is a highly potent greenhouse gas having between 21 and 25 times greater global warming potential effect than that of carbon dioxide (CO_2). Based on government models, it is estimated that landfill sites in England and Wales produce almost 3% of the United Kingdom's greenhouse gas emissions, with operational landfill sites contributing approximately 33% of this total. Whilst it is widely acknowledged that there are limitations to the accuracy of calculating emissions in this way, the importance of maximising the capture of LFG remains a high priority.

The rate of generation and the volume of LFG captured are affected by:

- the type of waste brought to a site
- the method of filling
- the choice of daily cover
- the design of the phasing
- the landfill engineering
- the leachate management system and leachate strategy
- the gas system design and its operation
- meteorological conditions

Consideration of all of these factors is a critical aspect of effective LFG management.

1.3 Landfill Site Variations

Each landfill site is unique and therefore no design detail or process will apply to all sites. Not all elements of this ICoP will need to be adopted by any particular site or operator. However, adopting these (or similar) approaches of equal or better standard, should be sufficient to establish good gas management practice.

The principle adopted throughout this document is the optimisation of LFG capture from each and every landfill site. This involves the good and efficient design of landfill sites that adequately balance the demands for all the environmental controls, including LFG. It further requires management of the control systems, data gathering and feedback, to fine tune the balancing and infrastructure installed.

1.4 Optimising Landfill Gas Capture

This document has been produced by representatives of the LFG industry to highlight issues commonly encountered in optimising LFG capture. It addresses essential considerations in achieving this goal and suggests possible solutions. This document identifies the principles which should be adopted and the methods to be used to measure the success of those principles through the application of key techniques, to ensure that systems operate correctly and safely.

1.5 Regulatory Guidance Notes

This document should be read in conjunction with the Environment Agency's and the Scottish Environment Protection Agency's landfill technical guidance notes and with consideration for the other legislative requirements and codes of practice produced for the industry.

1.5.1 Landfill Gas Guidance

The Environment Agencies of England and Wales, Scotland and Northern Ireland require that landfills are designed in such a way as to protect the environment. The documents below give specific guidance on various aspects of LFG management.

- LFTGN03 Guidance on the management of landfill gas
- LFTGN04 Guidance on monitoring trace components in landfill gas
- LFTGN05 Guidance for monitoring enclosed landfill gas flares
- LFTGN06 Guidance on gas treatment for landfill gas engines
- LFTGN07 Guidance on monitoring landfill gas surface emissions
- LFTGN08 Guidance for monitoring landfill gas engine emissions
- Guidance on landfill gas flaring
- Guidance on pumping trials
- H1 Annexe I additional guidance – Landfill
- EPR5.02 How to comply with your Environmental Permit: Additional guidance for landfill

1.5.2 Landfill Engineering Guidance

The documents below give specific guidance on various aspects of landfill engineering:

- LFE1 – Our approach to landfill engineering (V1)
- LFE2 – Cylinder testing geomembranes and their protective materials (V1)
- LFE3 – Using geosynthetic clay liners in landfill engineering (V1)
- LFE4 – Earthworks on landfill sites (V1)
- LFE5 – Using geomembranes in landfill engineering (V1)
- LFE6 – Guidance on using landfill cover materials (V1)
- LFE7 – Using non-woven protector geotextiles in landfill engineering (V1)
- LFE8 – Geophysical testing of geomembranes used in landfills (V1)
- LFE9 – Compliance testing earthworks on landfill sites using nuclear density gauges (V1)

These have been included as landfill engineering is an important factor in the management of LFG

1.5.3 Monitoring Guidance

The documents below provide technical guidance on the monitoring of landfill leachate, groundwater and surface water within and around landfill sites:

- LFTGN02 Monitoring landfill leachate, groundwater and surface water
- LFE10 – Using bentonite enriched soils in landfill engineering (V1)

1.5.4 Other Technical Guidance

- EPR1.00 How to comply with your Environmental Permit
- H1 Environmental Risk Assessment
- H2 Energy efficiency
- H3 Part 2 Noise assessment and control
- H4 Odour management guidance
- H5 Site Condition Report –guidance and template
- H6 Environmental Management Systems
- H7 Guidance on the protection of land under the PPC Regime
- Regulatory Guidance Notes (RGNs)

1.5.5 Other ICoP Documents

- ESA ICoP 1 DSEAR for the Waste Management Industry
- ESA ICoP 2 Area Classification for Landfill Gas Extraction, Utilisation and Combustion
- ESA ICoP 3 Area Classification for Leachate Extraction, Treatment and Disposal
- ESA ICoP 4 Drilling Into Landfill Waste
- ESA ICoP 5 Landfill Operations
- ICoP Perimeter Gas
- ICoP The Management and Prevention of Sub-surface Fires

This list is not exhaustive.

2 Health and Safety Considerations

When working on and around landfill sites it is necessary to develop strict health and safety guidelines and undertake appropriate risk assessments. Health and safety on site is the responsibility of everyone. Operating companies have a responsibility towards their employees and contractors, while all personnel have a joint responsibility for their own and their colleague's safety. Landfill sites are covered by both generic and site specific health and safety legislation. In all cases, health and safety must take priority over production, economics and environmental control.

2.1 Health and Safety on a Landfill Site

All landfill sites will have their own health and safety controls and systems and in all cases these should be pre-eminent; the advice in this ICoP should never overrule site rules, risk assessments and data. Where there is a perceived contradiction or conflict between the site's systems, contractor's own systems or this document the contradiction should be raised with the site's management team prior to undertaking any work.

In all cases, site specific risk assessments should be in place before any activities are undertaken.

Any accidents or incidents should be advised to the site's operational management team as soon as is practicably possible after the accident/incident occurs.

2.1.1 The General Environment

Any active landfill site accepts waste materials that could, in an uncontrolled state, represent a risk to health and safety. Heavy goods vehicles and heavy plant machinery will be in operation at the site in the course of its normal business. Waste materials already placed in dormant or closed areas will be decomposing and, if uncovered, are likely to give rise to odour and the release of chemical or biological materials which could lead to direct contact with receptors. Waste can be brought to the surface through excavation or drilling and the materials that arise should be assessed on a site specific basis, taking into account the characteristics of the wastes deposited in that area of the site. The waste composition can vary significantly from area to area within the same site. Care should be taken to understand the waste deposition history of the site before engaging in activities that expose personnel to old waste, especially on sites where hazardous or special wastes have been deposited.

Where possible, site specific information on waste should be used; where this does not exist, a precautionary worst case should be assumed.

2.1.2 Impact Injuries

Large numbers of vehicles pass through an open landfill each day, whilst heavy plant vehicles are in operation in some areas. Traffic control rules should be in place on the site, to minimise the risk of incidents arising and the rules should be adhered to at all times.

The following three defined risks are associated with an active landfill and therefore should be considered;

- impact between vehicles
- impact between vehicles and people
- impact of people with stationary objects on the site

While all vehicles should be installed with working audible reversing alarms, this should not be assumed to be 100% effective. Passive controls which separate and protect workers from moving vehicles such as fenced areas or the use of a 'banksman' (staff with a particular role to watch for and warn of traffic).

2.1.2.1 Impact Between Vehicles

Impact between vehicles can not only damage the vehicles but can cause bodily harm. Impacts can be avoided by being vigilant while driving, obeying the site speed limit, obeying the traffic signs and being visible - see and be seen - clean windscreens, hazard lights and headlights in poor visibility. If in doubt about routes or traffic controls, ask the site management.

Due to the nature of the activities on most sites, the internal site roads can accumulate quantities of mud and dirt. Provided that vehicles are suitable and in good repair and the speed limit is adhered to, the dirt on the road should not pose a hazard. However the turning and braking abilities of vehicles may be adversely impacted by these materials on the roads and staff should be made aware of the risks and receive appropriate driver training.

2.1.2.2 Impact Between Vehicles and People

Impact between vehicles and people can cause serious injury and possibly death. Impacts can be avoided through all parties being vigilant while on the site. Drivers should obey the traffic regulations and maintain visibility. All people on the site should, at all times, wear high visibility clothing, safety boots and a hard hat and be aware of what is happening around them.

If the nature of the works requires all of the worker's attention then either their work place should be cordoned off or a second person should be in attendance to monitor the traffic movements. Vigilance and visibility should always be maintained

2.1.2.3 Impact of People with Stationary Objects

The nature of materials at a landfill site includes objects that can be penetrative to the human body. Foot access to exposed areas of waste should be limited to as little as is absolutely necessary and if required then appropriate Personal Protective Equipment should be used. This should comprise boots with steel toecaps and insoles with ankle protection.

2.1.3 Other Hazards Associated with a Landfill Site

2.1.3.1 Rat Urine

Rat urine in water that penetrates the human skin through thin membranes or through cuts and abrasions can cause leptospirosis (Weil's disease). Contact with any surface waters should therefore always be minimised. If an activity does include the possibility of contact with potentially affected surface waters, the user should employ simple precautions such as waterproof dressings on any cuts or abrasions, protective waterproof gloves and goggles. Good hygiene facilities should be provided and good hygiene practices adopted.

2.1.3.2 Leachate

Leachate (water contaminated with waste) will be encountered when excavating or drilling into waste. All exposure to leachate must be minimised by active pumping and the wearing of protective clothing. Any worker exposed to skin contact with leachate should wash the affected area immediately. Where there is a risk of splashing, goggles should be worn. If leachate does contact eyes an eye wash should be used immediately and then health advice sought.

2.1.3.3 Steep Slopes

At some sites, steep slopes are present which need to be considered for all work activities planned or proposed. Injury or death could be caused through a fall down one of these steep faces and as such, provisions to avoid the risk where possible and to minimise where necessary should be applied. There is also a risk of injury through materials or objects falling down the slopes. Therefore, access to areas of a site where steep sidewalls or slopes are present and where active operations are being undertaken on the slope or at its crest should be avoided wherever possible.

2.1.3.4 Poor Weather Conditions

Poor weather conditions are often experienced at sites. Any operations that may involve an element of risk from poor weather conditions (such as the unrolling of geotextile materials in high winds) should be avoided where possible, where this is not possible, appropriate risk assessments and method statements should be agreed with the site's operational management team.

2.1.3.5 Excavations

Workers in any excavation area should have access to appropriate monitoring and alarm equipment and should be sufficiently trained to understand what precautions and actions would need to be undertaken in the event of an alarm.

2.1.3.6 Gas Inhalation

Inhalation of landfill gas (LFG) should be avoided. LFG is deficient in oxygen and contains harmful trace components. As such LFG may cause nausea and dizziness, as well as other harmful health effects, which could lead to accidents. A Safe System of Work must be in place for any activity where there is the potential for exposure to landfill gas. The most current gas composition data for the area where work will be undertaken should be reviewed prior to the commencement of any work. Company guidance on the selection and use of appropriate control measures should be followed.

2.1.3.7 Asbestos

If there is a risk of exposure to asbestos or if asbestos is encountered during drilling or excavation operations, the following waste handling procedures must be implemented:

- comply with all requirements of the “Control of Asbestos Regulations 2006”.
- all people near the drilling or excavation operations should wear appropriate respirators.
- a water truck equipped with appropriate spraying equipment or similar should be available to minimise the possibility of dust generation
- an area of appropriate size should be prepared to contain the cuttings or excavated material.
  - a waste container lined with polyethylene should be placed as close as is reasonably possible to the well or excavation.
  - a small level area (known as a berm[1]) next to the borehole or excavation where drill cuttings or excavated materials will be handled should also be lined with polyethylene and covered with clean earthen material to protect the polyethylene. The berm will help contain the cuttings and facilitate loading into the container.
  - the polyethylene and earthen cover will be considered to be part of the waste.
- all cuttings that are not already damp upon removal from the borehole or excavation should immediately be wetted.
- all cuttings or excavated materials should be kept damp and covered.

[1] A level area used to separate two areas of activity

- after wetting, all cuttings or excavated materials should immediately be placed into the container or moved to an approved storage area, prior to being landfilled in the appropriate landfill cell.

2.1.3.8 Fire / Explosion

Soil should be stockpiled adjacent to operations in areas of exposed waste for fire fighting purposes. The most effective way to extinguish landfill surface fires is to smother the fire with soil (which eliminates available combustion oxygen).

Construction equipment should be equipped with vertical exhaust and spark arrestors.

Motors utilised in waste excavation areas or ATEX defined zone areas should be explosion proof.

Start-up and shutdown of equipment should not be done in areas of exposed waste or ATEX defined zones.

Only zone compatible equipment should be used within DSEAR defined zones (unless the equipment has been shown to be safe to use through risk assessment).

The use of explosives should not be permitted unless in exceptional cases and where appropriate permissions, risk assessments and method statements have been agreed.

2.1.3.9 Exposure to Refuse or Waste Water

Where possible, workers should avoid contact with exposed waste. Irritants or hazardous materials maybe present. Viral diseases maybe present (for example, Weil's disease) and all staff should be adequately trained and protected. The waste materials at the site may contain many chemical substances, including but not limited to the following:

- Hydrocarbons
- Metals (zinc, copper, nickel)
- Mercury and compounds
- Arsenic
- Poly-aromatic hydrocarbons
- Polychlorinated biphenyl (PCB)
- Chlorinated solvents
- Sulphates and sulphides
- Sharp objects
- Phenols

Protective clothing and minimisation of any contact must be practised at all times. Appropriate Personal Protective Equipment (PPE) must be issued to all staff involved in handling waste. (for example, waterproof gloves, filter masks and job specific overalls).

2.1.3.10 Open Boreholes or Excavations

Workers should not leave open wells or excavations unattended. Open boreholes must be covered to prevent accidental entry. Wells must be barricaded, flagged, and protected sufficiently to prevent entry of dirt and run off water.

2.1.3.11 Medical Facilities

All workers and visitors should be made aware of the location of medical facilities on site and be aware of the emergency action plans designed for the site.

Where contact with waste is expected and cannot be avoided, suitable decontamination areas for the use of all personnel involved should be available and maintained. Generally, these decontamination areas will comprise of a dirty area, a washing area and a clean area.

All workers or visitors should be notified of the first aid trained technicians on site when any works are being undertaken.

2.1.4 Risk Assessment for Working on a Gas Producing Landfill Site

Before any work is undertaken, a risk assessment should be prepared and appropriate action taken to mitigate against identified risks.

2.1.4.1 Explosion

The degradation of waste materials generates a number of gases. Methane (CH_4) is generated and can represent a fire/explosion hazard. Between the concentrations of 5% and 15% by volume in air methane, is explosive. At other concentrations, the risks are less, although with concentrations higher than 15% mixing can cause concentrations to drop into the explosive range or can asphyxiate if oxygen is depleted.

Hydrogen sulphide (H_2S) is a possible degradation product and is also a flammable gas. Its lower explosive limit (LEL) in air is approximately 4.5 %. There is a very low risk in the landfill environment, since this concentration is very unlikely to be reached.

In order to ignite, the flammable gas must be present in its explosive range and have an ignition source. There is the potential for an explosion in any confined space where gas is present in its explosive range. An explosion could cause burns of varying degrees, and impact damage through the mobilisation of solid objects either of which could cause death.

To minimise the risk, the following measures should be applied:

- no smoking on site (a cigarette can act as an ignition source)
- no naked flames
- no unearthed or faulty electrical equipment should be used on site

Only ATEX (***AT****mosphères* ***Ex****plosives)* approved equipment should be used in defined zoned areas. Details of the application of ATEX to landfills, LFG control and drilling can be found in the appropriate ICoP.

All confined environments should be monitored prior to them being entered. Entry should only be allowed if the monitoring indicates that it is safe to do so. All confined spaces should be adequately vented to prevent the accumulation of hazardous gases and the confined space should be placed as far as possible from the areas of placed waste.

Most landfill sites have an active gas extraction system that draws the gas under suction from the landfill to an adjoining generation facility. Interference with this system without sufficient knowledge or appropriate supervision or approval and training should be prohibited.

A system of 'Permit to Work' or similar should be in place and designed such that any planned actions involving a contractor or other party will require permission from the site’s operational management team prior to the works being undertaken. Great care must be taken whilst working adjacent to the gas extraction system to ensure that no damage occurs.

2.1.4.2 Asphyxiation and Toxicity

The human body requires oxygen; a deficit of oxygen can cause breathing and function difficulties and can ultimately lead to death. The degradation of waste materials can generate gases that, if present in sufficient concentrations, can cause a hazard to health. Principal among the gases generated at a landfill site that can lead to asphyxiation is carbon dioxide (CO_2). Carbon dioxide is a colourless, odourless and non-combustible gas. It is both toxic and an asphyxiant.

CO_2 Concentration	Symptom / Effect
>3 %	Laboured breathing, headaches
5 -6 %	Heavily laboured breathing and headache
12 – 25 %	Victim becomes unconscious
> 25%	Death can occur

Table 2-1: Effect of CO_2

It is unlikely that carbon dioxide concentration would develop to harmful concentrations in open spaces or ventilated buildings. Prior to entry to any confined space (including an underground structure) the atmosphere within the space should be monitored for carbon dioxide and/or oxygen depletion. The space should not be entered unless it has proven safe to do so.

Other gases such as carbon monoxide, sulphur dioxide and hydrogen sulphide are present in LFG. Carbon monoxide is clear and odourless and is highly toxic by inhalation. Sulphur dioxide is a colourless gas with a sharp pungent odour and is toxic by inhalation.

Hydrogen sulphide (H_2S) is a colourless gas with a distinctive "rotten eggs" odour (up to a threshold of 0.5 parts per billion) and is highly toxic.

H_2S Concentration	Symptom / Effect
> 20 ppm	Loss of smell
20 -150 ppm	Irritation to eyes & respiratory tract
> 400 ppm	Toxic effects occur
> 700 ppm	Life threatening

Table 2-2: Effect of H_2S

2.1.5 Interaction with the Site and its Gas Controls

The gas control system is designed to extract LFG from the body of the landfill and the gas treatment system is used to dispose of it by combustion. The safe collection and combustion of the LFG is one of the primary purposes of landfill gas control. Unplanned interference, damage or disturbance of these systems increases the risk that gas pressures in the landfill will increase, leading to a greater potential for uncontrolled movement from the waste mass into adjoining areas and buildings.

If the flare or engines are turned off, the concentration of LFG in the body of the site will increase and therefore the potential for explosive or harmful concentrations to develop will increase.

Any contractor or visitor should consult with the site's operational management team to determine whether the gas control system is working and ensure appropriate controls are in place.

2.1.6 Vermin

If left exposed for a significant period of time, the exposed waste may attract vermin such as flies, birds and rodents. As such, it is essential that, at all times, the area of exposed waste being excavated or placed is minimised. All exposed waste should (as quickly as possible) be covered with a soil or other temporary cover to discourage the presence of vermin.

2.1.7 Odour

When older waste is exposed it is likely to give rise to odour. Although unlikely to be harmful to health, the odour is likely to be disagreeable to both workers and neighbours. As such, the area of exposed waste should be minimised and a suitable Odour Management Plan put in place.

2.1.8 Safe Digging Procedure

When working near buried gas pipes and before excavation takes place, an area should be marked out inside which the safe digging procedure will take effect. Appropriate working practices should be employed and these will either be determined or approved by the site's operational management.

2.2 DSEAR and ATEX

2.2.1 What is DSEAR?

DSEAR (Dangerous Substances and Explosive Atmospheres Regulations 2002) is the way the UK has enacted ATEX directives. These regulations require employers to control the risks from fire and explosions.

Dangerous substances can put people at risk from fire and explosion. DSEAR regulations place a duty on employers and the self-employed to protect people from the risks from fires, explosions and similar events in the workplace. This includes members of the public who may be put at risk by work activity.

Dangerous substances are any substances used, or present at work that could, if not properly controlled, cause harm to people as a result of a fire or explosion. The most relevant dangerous substances for the landfill environment are the gases associated with it such as methane, hydrogen sulphide and hydrogen.

2.2.1.1 What does DSEAR require?

Employers must:

- find out what dangerous substances are in their workplace and what the fire and explosion risks are
- put control measures in place to either remove those risks or, where this is not possible, control them
- put controls in place to reduce the effects of any incidents involving dangerous substances
- prepare plans and procedures to deal with accidents, incidents and emergencies involving dangerous substances
- make sure employees are properly informed about and trained to control or deal with the risks from the dangerous substances
- identify and classify areas of the workplace where explosive atmospheres may occur and avoid ignition sources (from unprotected equipment, for example) in those areas

See www.hse.gov.uk/fireandexplosion/dsear.htm

2.2.2 What is ATEX?

ATEX is the name commonly given to the framework for controlling explosive atmospheres and the standards of equipment and protective systems used in them. It is based on the requirements of two European Directives:

- Directive 99/92/EC (also known as 'ATEX 137' or the 'ATEX Workplace Directive') on minimum requirements for improving the health and safety protection of workers potentially at risk from explosive atmospheres. The text of the directive and the supporting European Union (EU) produced guidelines are available on the EU website http://ec.europa.eu/enterprise/sectors/mechanical/documents/legislation/atex/.
- Directive 94/9/EC (also known as 'ATEX 95' or 'the ATEX Equipment Directive') on the approximation of the laws of Members States concerning equipment and protective systems intended for use in potentially explosive atmospheres. The text of the directive and EU produced supporting guidelines are available on the EU web site http://ec.europa.eu/enterprise/sectors/mechanical/documents/legislation/atex/.

2.3 Control of Substances Hazardous to Health (COSHH)

2.3.1 What is COSHH?

The Control of Substances Hazardous to Health (COSHH) Regulations 2002 is the regulation that requires employers to control substances that are hazardous to health.

The regulations cover chemicals, products containing chemicals, fumes, dusts, vapours, mists and gases, and biological agents (germs). If the packaging has any of the hazard symbols, then it is classed as a hazardous substance. It also covers asphyxiating gases.

Also covered are the germs that cause diseases such as leptospirosis or Legionnaires' disease as well as germs used in laboratories.

COSHH doesn't cover lead, asbestos or radioactive substances because these have their own specific regulations.

The most relevant substances for the landfill environment include condensate, leachate, LFG and its associated trace components as well as fluids used for maintenance activities such as lubricants.

3 The Composition of Landfill Gas

Landfill gas (LFG) is generally produced through the breakdown of organic compounds in anaerobic conditions (in the absence of air). LFG composition changes over the life of a landfill site as different stages in the degradation process are reached; (see *3.2 The Phases of Landfill Gas Production*).

The factors that affect the composition of LFG at any point in time are typically:

- waste composition (in particular the amount of readily degradable organic material)
- age of tipped waste
- density of the tipped waste
- moisture content and its distribution through the waste mass
- acidity / alkalinity (pH)
- nutrient availability (to feed the microbes)
- temperature
- presence of toxic agents and chemical inhibitors

For the bulk of a landfill site's life, the gas generated will consist of approximately:

- 60% Methane (CH_4)
- 40% Carbon Dioxide (CO_2)

A wide variety of trace gases is also present.

The introduction of active extraction will introduce air (nitrogen and oxygen) which will alter this balance. For further information on this effect (see *8.1 Fundamental Principles of Balancing*).

3.1 The Bulk Components of Landfill Gas

3.1.1 Methane (CH_4)

The primary component of LFG is methane (CH_4), an odourless, flammable gas at normal atmospheric temperatures and pressures. It is explosive at concentrations of between 4.4% and 16.5% (by volume) in air at 20 ^{o}C and 1 bar atmospheric pressure. These limits are known as the lower explosive limit (LEL) and upper explosive limit (UEL) of methane. However, these concentrations are only a guideline as the presence of other components in LFG alters the explosive range. As a consequence of this, the flammability limits of LFG will vary and should not be taken for granted. Refer to LFTGN03.

3.1.2 Carbon Dioxide (CO_2)

The second major component of LFG is carbon dioxide (CO_2) which is an odourless, non-flammable gas normally present in the atmosphere at a concentration of 0.04% by volume. It is also a normal product of human metabolism (for example) and acts upon vital functions in a number of ways. In higher concentrations it increases breathing and heart rates and changes body acidity levels. At high levels, it displaces oxygen in the body and becomes an asphyxiant. The occupational safety levels set for CO_2 by the HSE are 0.5% (by volume) for an 8-hour period (long term exposure) and 1.5% (by volume) for a 15-minute period (short term exposure). See EH40/20053 for more information.

3.2 The Phases of Landfill Gas Production

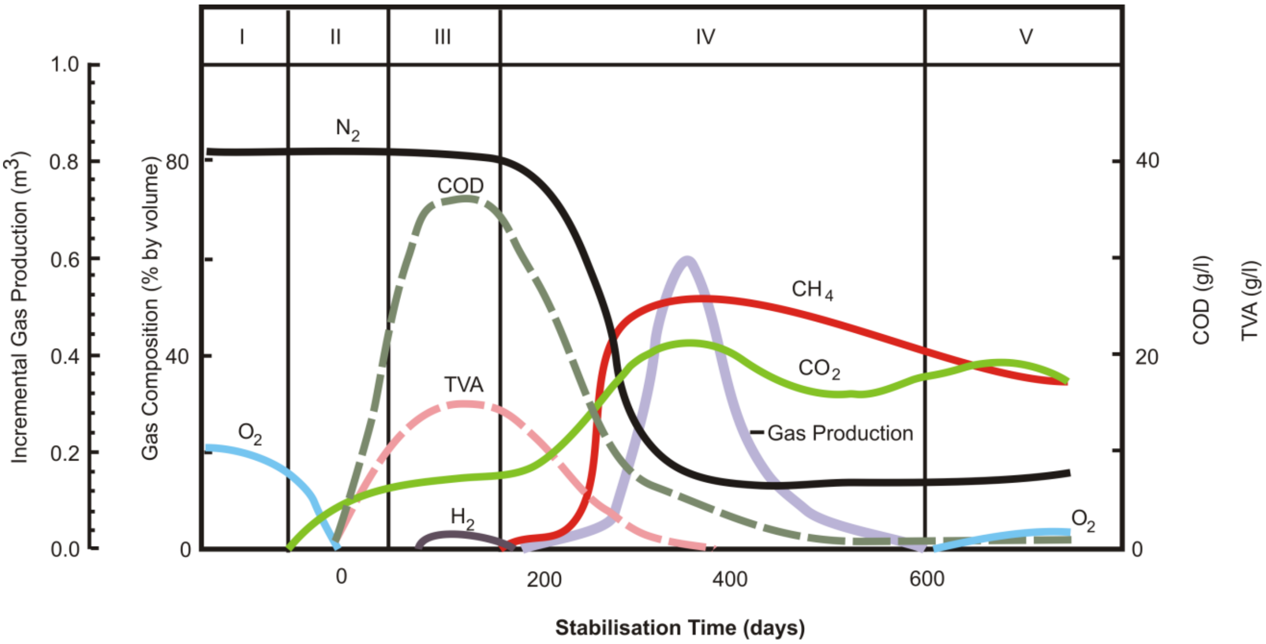


Figure 3.1: Landfill Gas Composition v Time (Farquhar G.J. & Rovers F.A. (1973))

Phase I of the process involves the consumption of any oxygen present within the waste, primarily by aerobic microbial activity. This process mainly results in the evolution of carbon dioxide gas, water and heat. Providing there are no sources of air ingress to the waste to replenish the oxygen consumed at this stage, then the concentration of oxygen will reduce. Nitrogen levels will also decay as the gases produced purge it out from the waste mass.

Phase II of the degradation process involves the conversion from aerobic to anaerobic conditions within the waste mass, the results of this process being the production of ethanoic acid (acetic acid), ethanoates (acetates), ethanol, ammonia, carbon dioxide, hydrogen, water and heat. The hydrogen and carbon dioxide produced during this process continue to purge the remaining nitrogen from the atmosphere within the body of the waste.

Phase III of the degradation process is that where the methanogenesis process commences with methane and carbon dioxide being produced. During this period the hydrogen levels peak, as do the Chemical Oxygen Demand (COD) and Total Volatile Acid (TVA) concentrations in the leachate.

Phase IV is where a period of equilibrium is reached in the degradation process. The conditions present in the body of waste provide a steady state condition during which methane and carbon dioxide are evolved in a ratio of typically 3:2 (60:40%) by volume. This period can extend for many years, until the organic compounds in the waste mass are converted to gas.

Phase V represents the final stage of the degradation process during which the gas composition within the body of waste gradually assumes that of atmospheric air.

3.3 The Properties and Behaviour of Landfill Gas

Typically, LFG has a similar density to that of air, but if the carbon dioxide percentage is relatively high, then due to the increased density, it may tend to lay in culverts, chambers and unventilated areas. Entry into any such areas on, or around a landfill site must be made only after consideration of the potential health and safety risks and after analysing the atmosphere using a suitable personal gas meter. The risks posed by LFG are potentially fatal and the need for reliable and effective gas control is fundamental to landfill management.

Property	Value	Comments
Constituents	Methane (CH_4) 60% v/v Carbon Dioxide (CO_2) 40% v/v	Proportions may vary but these values will be used for calculation purposes. Carbon dioxide is not flammable
Molecular mass (Mr)	27.2 kg/kmol (60% CH_4)	Methane has a molecular mass of 16 Carbon dioxide has a molecular mass of 44 Therefore, landfill gas containing 60% Methane will have a molecular mass as follows: M = [(60 x 16) + (40 x 44)] / 100
Explosive limits	5 – 15% v/v	Assumed as for pure methane in air
Relative density (air – 1)	0.94	Air has an average molar mass of 29 kg/kmol

Table 3-1: The Properties of Landfill Gas

3.4 Trace Components in Landfill Gas

See "Priority Trace Components Of Landfill Gas". Despite LFG being predominantly a mixture of methane and carbon dioxide typically in the ratio 60:40 respectively, it will also contain many minor constituents, the nature of which is defined by the waste itself.

The minor constituents of LFG will vary according to the makeup of the waste, its age, and the level of degradation. They usually constitute no more than 0.5% of the total gas volume. However, the minor constituents are responsible for the distinctive smell of LFG and for its corrosive nature. These characteristics have been changing as more organic waste is diverted from landfill, for example, leading to increased levels of hydrogen sulphide (H_2S) and thus making odour control all the more important. This has been recognised by the Environment Agency and industry alike.

As well as the implications that certain trace components may have on health and safety considerations, and the potential for LFG to cause nuisance, certain components can also act to interfere with monitoring equipment (specifically portable analysers). For example, H_2S, although only usually present in parts per million (ppm), can often be inaccurately represented as carbon monoxide on certain portable instruments. It is important that this 'interference' is recognised and understood when interpreting results. The application of specific filters or the taking of Tedlar© bag samples for laboratory analysis can help to overcome misidentification or misinterpretation of results.

3.5 The Changing Nature of Waste

As the composition of waste changes, primarily as a result of UK waste policy, the nature of LFG will also change. As long as a putrescible content remains, bulk gases will essentially remain in the same ratio, but the presence and abundance of specific trace gases will change. The impact waste diversion and recycling strategies will have on gas composition is not yet fully understood, although it is widely recognised that certain changes in the composition and nature of LFG is already taking place. Waste producers or market trends (such as recession) will also impact on the nature of waste, having a further downstream impact on the nature of LFG, (see *Appendix A The Changing Nature of Waste*).

4 Regulatory Framework

Landfilling of solid waste in the United Kingdom (UK) is subject to a large number of UK Regulations which are transposed from EU directives. This section highlights the regulations that have an impact on the way that the landfill, and more specifically LFG, is managed in the UK.

4.1 European Directives

There are a significant number of directives affecting the landfilling of waste, including some which may not immediately appear relevant, such as the **Groundwater Directives** (80/68/EEC) and (2006/118/EC) or the **EC Habitats Directive** (Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora).

However, the key directives relevant to landfilling of waste and regulation of LFG are:

- The **Waste Framework Directive** (Directive 2008/98/EC of The European Parliament and of the Council of 19 November 2008 on Waste and repealing certain directives). This revised Waste Framework Directive also saw the repealing of Council Directive of 12 December 1991 on hazardous waste (91/689/EEC)
- The primary aim of Council Directive 1999/31/EC of 26 April 1999 on the Landfill of Waste (the '**Landfill Directive**') is "to prevent or reduce as far as possible negative effects on the environment, in particular the pollution of surface water, groundwater, soil and air, and on the global environment, including the greenhouse effect, as well as any resulting risk to human health, from the landfilling of waste, during the whole life-cycle of the landfill"
- The **IPPC Directive** (Directive 2008/1/EC of the European Parliament and of the Council of 15 January 2008 concerning integrated pollution prevention and control) is a directive aimed at controlling environmental pollution. This version of the directive codified all previous amendments to the directive
- On 21 December 2007 the Commission adopted a proposal for a **Directive on Industrial Emissions**. The proposal recasts seven existing directives related to industrial emissions into a single clear and coherent legislative instrument. The recast includes in particular the IPPC Directive and the Waste Incineration Directive, for example. On 8 November 2010, the European Council ratified the proposal. Following publication in the Official Journal of the European Union on 17 December 2010, the Directive (2010/75/EU) came into force on 6 January 2011

4.2 National Regulations

The Directives are, by nature, measures that bind the Member States in terms of the results to be achieved. The Member States are free to choose the form and means of achieving this result. To do so, the Member States have a deadline within which they must 'transpose' the directives into law at the national scale.

Directives are regularly enacted and repealed. National regulations are amended or superseded altogether in response to changes in Directives. Therefore, it is critical to regularly review the regulations which apply to your country and specific operation (in terms of location, nature of waste and scheme layout).

At the time of writing, those relevant to the UK include:

- Waste (England and Wales) Regulations 2011
- Environmental Permitting (England and Wales) Regulations 2010
- Landfill (Scotland) Regulations 2003
- Landfill (Scotland) Amendment Regulations 2003
- Pollution Prevention and Control Scotland Regulations (2000 and 2010)
- The Pollution Prevention and Control Regulations (Northern Ireland) 2003
- The Pollution Prevention and Control (Amendment) Regulations (Northern Ireland) 2011

4.3 Permits

As stated above, since the implementation of the PPC Regulations in 2000 landfilling of waste (and other operations) has to be carried out under a Pollution Prevention and Control Permit issued by the Environment Agency, Scottish Environment Protection Agency or the Northern Ireland Environment Agency. In England and Wales these are now referred to as Environmental Permits.

4.3.1 Application

In order to obtain a permit an operator must submit an application that covers all aspects of the operation to be permitted demonstrating BAT (Best Available Techniques); this should include an Operational Management Plan for the site that includes control of emissions to land, waste and air: The application also needs to consider environmental risk, (see *5 The Principles of Landfill Gas Modelling*) for more information on modelling.

Forming part of the Operational Management Plan is the Gas Management Plan which is the operator’s management statement regarding the management of LFG and therefore is an important document. The GMP should be written following the guidance laid out in Landfill Technical Guidance Note 03 (LFTGN03) as well as the ‘best practice’ information contained within this ICoP.

4.3.2 Permit Issue

On issue, the permit will define what activities are covered. These fall into two categories: Listed and Associated (England and Wales). In terms of LFG management, Gas Utilisation Plants with a thermal input above 3MWth (approximately 1.1 MWe) will be Listed whereas plants with an input below 3 MWth will be Associated.

Permits typically cover the following categories of requirements:

- monitoring (for example, LFG supply to the compound, in-waste monitoring, perimeter borehole monitoring, engine and flare emissions, trace gas monitoring and surface monitoring)
- notification requirements (if things go wrong)
- accident prevention and control
- personnel competency
- incidents and non-conformances
- maintenance
- odour
- dust
- noise and vibration
- waste disposal and management
- closure and decommissioning
- record keeping

4.3.3 Permit Operator

For LFG management, permits vary in terms of which activities they cover; for example, they may include the landfilling of waste and the utilisation of LFG within a single permit, or the activities may be separated under different permits (England and Wales). The permit is generally only split if the two activities are managed by different companies, for example a site owner and a gas management contractor. The permit may also be split if the gas is received from multiple landfills for centralised utilisation.

The company responsible for the permit is referred to as the 'Permit Operator or Holder.' This may be the landfill operator or a gas management contractor. Whoever is the Permit Operator has ultimate responsibility for:

- ensuring the permit requirements are met
- liaising with the regulating authority (Environment Agency, Scottish Environment Protection Agency or the Northern Ireland Environment Agency) in relation to the permit

The Permit Operator is specified in the permit and depends on the type of permit held. Regardless of which type is held, an understanding of the permit requirements is required to ensure compliance.

4.3.4 Permit Management

Everyone who is affected by the conditions of the permit must be aware of the requirements which are relevant to them. This is specified within most permits.

An awareness of permit requirements can help you:

- understand why a site is being managed in a specific way
- understand what the Environment Agency, Scottish Environment Protection Agency or the Northern Ireland Environment Agency expects when conducting audits and assessing the site

Failure to comply with a permit can have a number of serious implications;

- environmental harm
- legal action against the permit holder
- increasing levels of attention from the public and regulatory authorities
- financial implications
- negative corporate image

4.3.5 Assessment of Permit Compliance

The operator should manage permit compliance (self-regulation) and notify the Environment Agency, Scottish Environment Protection Agency or the Northern Ireland Environment Agency of any breaches. This should be backed up by internal or external (BSI) audits against management systems.

The Environment Agency, Scottish Environment Protection Agency or the Northern Ireland Environment Agency are responsible for regulation and enforcement of the permit requirements; they may choose to audit or review the operator’s performance at any time.

Sites are rated by the Operator Pollution Risk Appraisal (OPRA) scheme (EA), Compliance Assessment Scheme (SEPA) and the Compliance Scoring Scheme (NIAE). Non-compliance issues are scored and information shown on public register.

4.3.6 Permit Changes

Where a change is required to be made to the operation of the landfill, such as permitted annual waste inputs, the permit will need to be varied. Such changes have an impact on all aspects of site management including LFG generation and management and will require an amendment to the Landfill Gas Risk Assessment (LFGRA).

Also, where additional utilisation is planned for the site, further assessment of the impact on emissions may be required. In this instance it is unlikely that a full LFGRA will be required, but rather a revised dispersion modelling assessment or H1 screening may suffice, (see *7 Gas Collection Infrastructure*).

4.4 Planning Considerations

Landfill sites and LFG utilisation compounds will require planning permission to be granted in accordance with the Town and Country Planning Acts. Planning permissions regulate the use of a parcel of land for a particular development. Development can be loosely defined as any material operation carried out in, on, over or under the land or a change in use of that land.

Permission will be approved, refused, or regulated by the Local Planning Authority (LPA). Where there is a two tier structure to the Local government administration, the Waste Planning Authority (County Council) will act as the Regulatory Authority.

Permission will normally be granted subject to planning conditions in relation to visual amenity, noise, restoration, final profile, and restrictions to development. It is important that details put forward within the planning application are correct, as the permission will reference the application documents and therefore forms part of the Consent.

Noise limits will usually be imposed along with the requirement to regularly monitor noise levels emanating from the LFG compounds. The LPA can also use its powers under the Town and Country Planning Acts to enforce against breaches of planning conditions.

These planning conditions will cover such areas as:

- operating hours
- vehicle movements
- restorations
- noise limits
- building heights
- other conditions set by the LPA

5 The Principles of Landfill Gas Modelling

Quantifying the volume of LFG likely to be generated over the gas producing life of a site requires prediction and will always be prone to a degree of error or uncertainty. However, the use of a recognised modelling system together with the most accurate waste data available will provide the best approximation of likely gas generation rates. Certain models will assign degrees of confidence to the forecast based on the modeller's confidence in the accuracy of the input data. Such models will then produce a range of likely production rates. Local site knowledge and experience is also invaluable when attempting to calibrate (verify) a gas generation model with site specific data.

5.1 Why Model?

LFG modelling is undertaken for a variety of reasons, but ultimately the desired outcome of any LFG modelling exercise is a reasonably accurate forecast of gas production rates over time and a prediction of the likely peak production rates. This provides a view of environmental risk and, therefore, assists in the specification of suitable control measures. The four primary reasons for producing a gas model are:

- assessing risk
- specifying equipment
- maximising opportunity
- evaluating performance

5.1.1 Assessing Risk

It is important that the risk associated with the placement of certain waste types into a specific landfill environment is assessed in terms of immediate or local risk (i.e. migration or odour) as well as consideration of the wider global impact for example, the contribution of greenhouse gases to atmosphere. If the risk is understood, then appropriate control measures can be identified and implemented and gas capture optimised to manage risks.

The potential environmental impact of a site and therefore the assessment of risk is best defined by the principle of: Source – Pathway – Receptor.

Source: the origin of the gas, for example a landfill site

Pathway: the route the gas takes, for example through fissures in rock

Receptor: where the gas collects, for example, caves, basements and cellars

Landfill sites are a clear **source** of emissions which require risk assessment.

It is important to identify potentially viable **Pathways** between the identified source(s) and receptors. For example, lateral migration could occur at uncontained sites where the surrounding rock is permeable, such as limestone. Monitoring should be used to provide information relating to the presence or absence of pathways. For example, where lateral migration is suspected, gas monitoring wells can be drilled to detect migrating gas.

Potential **Receptors** must also be identified and monitoring equipment installed for example, where residential property borders a landfill site.

Once the risk assessment process has been completed and where any unacceptable risks are identified, mitigation strategies can be devised to reduce or eliminate the risk. For example, taller stacks may reduce the impact of engine emissions on local air quality.

5.1.2 Specifying the Right Equipment

The physics associated with the transportation of LFG around a collection system must be understood in order to specify suitable equipment. One of the basic principles that needs to be understood is the anticipated LFG production rates over time in order that an appropriate system can be designed. Effective gas system design will take into consideration peak production rates so that equipment such as pipework, process plant and flares can be sized accordingly for future requirements.

5.1.3 Maximising Opportunity

The European Union has committed to a target of 20% of all energy consumption to be supplied from renewable sources by 2020. In order to meet these binding targets, the UK has committed to derive 30 - 40% of its electricity from renewable sources; therefore, renewable energy has become a key component of the UK government strategy. The technology for electricity generation from LFG is well established and the environmental benefits are measurable. In the UK, economic interests are aligned with political imperative and the favourable regulatory environment has resulted in premium prices for renewable energy. In order to maximise this opportunity, an understanding of anticipated production rates will enable appropriate sizing of electrical connections and utilisation equipment.

5.1.4 Evaluate Performance

Although not perfect, models will provide a benchmark against which actual extraction rates can be compared. It must be noted that due to the inaccuracies that exist with modelling, (see *5.7 Limitations of Modelling*) and the fact a model will be compared against real data on extraction rates (verification), local knowledge is essential to ensure effective interpretation.

5.2 Modelling Scenarios

Typically, different models are used for a number or purposes including:

- permit application
- operational decision making
- Pollution Inventory (PI) reporting
- Landfill Gas Risk Assessment (LFGRA) model reviews

5.2.1 Permit Application

This model is completed to form the basis of the LFGRA and generally uses a model such as GasSim or other regulator approved model, and therefore deals with worst case. The model uses a combination of actual data, such as waste inputs and trace gas analysis, and default values set within the simulator. Data are input using differing Probability Density Functions (PDFs) depending on the certainty and/or variability of the data.

GasSim uses a “Monte Carlo” simulation technique to select values for parameters in the model by random selection from the PDFs. This process is repeated many times (200+) to give a range of output values. Once produced, the model is refined to ensure that it accurately reflects actual data collected from the site. The ‘worst case’ is generally taken to be the 95th percentile value of the output.

The LFGRA addresses any issues highlighted in the model and therefore the suitability of the proposal. One output from this model could be the requirement for an additional air quality assessment.

The LFGRA, and therefore the simulation model underpinning it, needs to be revisited if significant changes to the site operation are planned that were not assessed in the original LFGRA. Examples could include additional waste inputs or installation of additional engines.

Note: There is currently no formal requirement for the LFGRA to be revisited on a regular basis, unlike the Hydrogeological Risk Assessment (HRA).

5.2.2 Operational Decision Making

Most operators have their own in-house models which have been developed over many years using spreadsheets or custom built simulator software. Historically, models used empirical formulae, but more recently some form of decay equation is used. These models need to be accurate as the viability of a business and the investment justification is dependent on the modelling. It is usual to include much calibration and validation to ensure that they are as near to reality as possible. These models are usually run at least annually, and sometimes quarterly or monthly, at which point the model is recalibrated to actual gas yields from the site.

5.2.3 PI Reporting

Like the LFGRA, this typically uses a model such as GasSim which is the PI reporting tool preferred by the Environment Agency and Scottish Environment Protection Agency. However, unlike the LFGRA, it is used retrospectively to give a fair, albeit often worst case, representation of what LFG related emissions where released from the site in the past year. Modellers often use iterative measures and ‘tweaks’ to ‘force’ GasSim to more accurately reflect reality. For example, the actual LFG surface emissions cannot be measured from a site; therefore, they are back calculated using this model.

5.3 Landfill Gas Modelling and Model Selection

LFG is generated from the anaerobic degradation of biologically active wastes placed in the landfill. Each tonne of each type of waste has a total potential for gas production and a rate of production depending on its composition and the conditions within the landfill site. There are a number of different models that can be used to generate gas curves which use a mix of empirical data and algorithms to calculate the production of LFG over time. Rate of filling, type of waste and conditions within the landfill, will control the size and shape of the gas production curve. The following section discusses these factors in more detail.

Basic gas modelling for the purpose of forecasting production rates will consider the following inputs:

- waste input rates expressed in tonnes per annum (tpa)
- waste composition divided into fractions (for example, domestic, civic, industrial, commercial, inert)
- waste moisture content and degradation rate

Inputting the basic data into a model with pre-determined default values attributed to the degradable fraction (available carbon content) and the degradation rates (rate of carbon release) associated with each type of waste stream will provide a basic curve.

However, in reality there are other site specific factors and conditions that will affect production rates. More evolved 'next generation' LFG models often allow the modeller to take these into consideration. For example, industrial waste will not be identical in all parts of the UK and it can therefore be assumed that the degradable fraction will vary depending on the source. Default values can, therefore, be amended to reflect site specific factors. Making this type of adjustment will materially affect (either increase or decrease) the total amount of degradable material assumed to be in the waste mass, impacting the total volume of gas produced or the total area under the curve.

The biggest factors driving the rate of release of gas are associated with local site conditions, the most influential of these being the moisture content of the waste. If the waste is saturated or too dry, the rates of generation will be inhibited. The total volume of gas produced will remain the same but the tail of the curve will be elongated – production will continue over a longer period, albeit at a lower rate. Conversely, if moisture conditions are conducive to optimum rates of decay, then the curve will be 'peaky' with high volumes being produced rapidly, followed by a rapid and steep decline and production will be over in a shorter period (see *7.8.4 Decommissioning*). This latter scenario may be preferable from a purely environmental perspective (assuming all appropriate control measures are in place), as it may reduce the aftercare period associated with a site, and the liability that exists within it.

Due to the varied nature of waste, even within the same site, models have been developed to recognise this and allow the level of detail to be considered on a cell by cell basis. The output of such models is essentially an accumulation of a number of distinct cell specific gas curves.

5.3.1 Gas Output Curve

Figure 5.1 illustrates the typical output from a gas model. In this example, waste placement started in 1991, with a year's lag before gas production really takes off. A sudden increase in waste inputs or putrescible content is illustrated by a sharp increase in gas availability between 2003 and 2004. Site closure in 2005 is reflected by the start of the 'tail' of the curve'. The green line represents the theoretical bulk gas production rate, the blue line anticipated collectable volumes (that is, expressed as a % of the production rate, this essentially becomes the site's collection efficiency). The inclusion of actual data into the forecast allows verification and calibration of the model, (see *5.4 Verification and Calibration*).

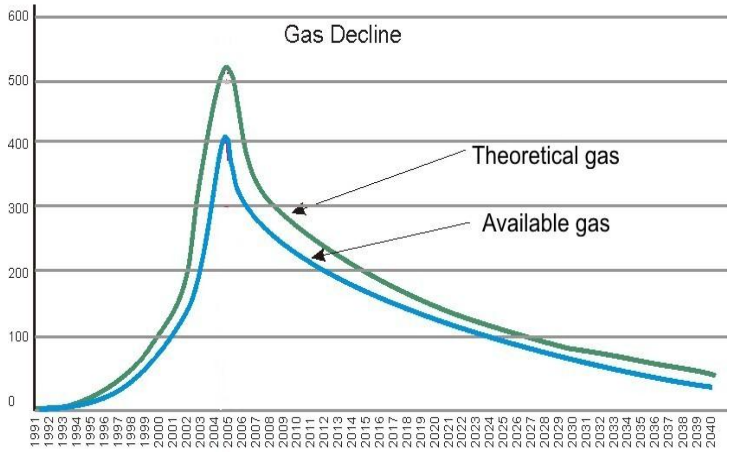


Figure 5.1: Typical Gas Output Curve

5.4 Verification and Calibration

Once a gas model has been created, collecting accurate data to validate the forecast is essential. Recalibrating the gas curve on a regular basis (for example annually) will hone its accuracy through each year of use. Failure to regularly calibrate an initial model regularly is likely to result in significant error which will accumulate over time and may grossly over or under estimate the total volume of gas being produced. The principle of 'initially validate and continuously calibrate' should be adopted.

It is important to understand the difference between validation and verifications. Model validation generally refers to detailed, peer-reviewed studies that have been carried out by in independent party such as the model supplier or a regulatory agency. Model verification refers to checks that are carried out on model performance at a local level. This basically involves the comparison of predicted versus measured performance. Where there is a disparity between the predicted and the measured values, the first step should always be to check the input data and model parameters in order to minimise the errors. If required, the second step will be to determine an appropriate adjustment factor that can be applied.

Verification and calibration will involve a regular review of the following items with adjustment of the model as necessary

Waste inputs Models should be continuously updated with the latest information as it becomes available. Particular consideration should be given to the changing nature of waste inputs as a consequence of waste diversion initiatives or market trends.

Moisture content The condition of the in situ waste, should be assessed regularly from drill logs and through evidence obtained from other intrusive investigations. It should be considered that moisture content can change over time as a consequence of seasonal variations, engineering standards and surface water and leachate management strategies.

Leachate levels The impact on both gas production and collection efficiencies should be considered. As discussed in Leachate Management Systems and Strategies, true or resting levels should be taken into account. As with the moisture content, these will inevitably vary across the site, depending on factors such as management strategies, waste type and engineering.

Capping An understanding of the percentage of the landfilled areas that have been capped and the standard of that cap is important to identify acceptable collection efficiencies for the site. This will change through site life, depending on the capping and restoration policy for temporary and permanent caps, (see *6.3.8 Capping*).

Site specific data Although there is no direct way of measuring gas generation rates, predicted collection rates can be compared to those obtained on the site; therefore a direct comparison should be completed regularly.

Point source Monitoring This should be undertaken on a regular basis or as defined in the site's permit, (see *8.3 Defect Identification and Maintenance*), and will include analysis of lateral sub-surface emissions, surface emissions from capped and uncapped areas and air quality and odour.

Improved data quality will ensure the best potential for the gas model to produce a reasonable prediction of the likely LFG production. However, no model will be 100% accurate and a process of adjustment based on recovered volumes of LFG over time will allow the model to be continually fine-tuned. It is important to note that the most accurate LFG production model will be based on the actual gas volumes collected within the remit of undertaking good gas management and thus only likely to be achieved retrospectively.

Figure 5.2 below has been derived from a baseline forecast model produced from basic waste data (the green curve). It has then been verified using historical extraction data (the yellow blocks) to produce a forecast curve that more closely reflects actual site performance (the blue curve). During the gas producing life of a site, there will be numerous short, medium and long term influences on both gas production rates and collection efficiencies and as such any major known exceptions should be factored into the historical extraction data, as part of the calibration exercise.

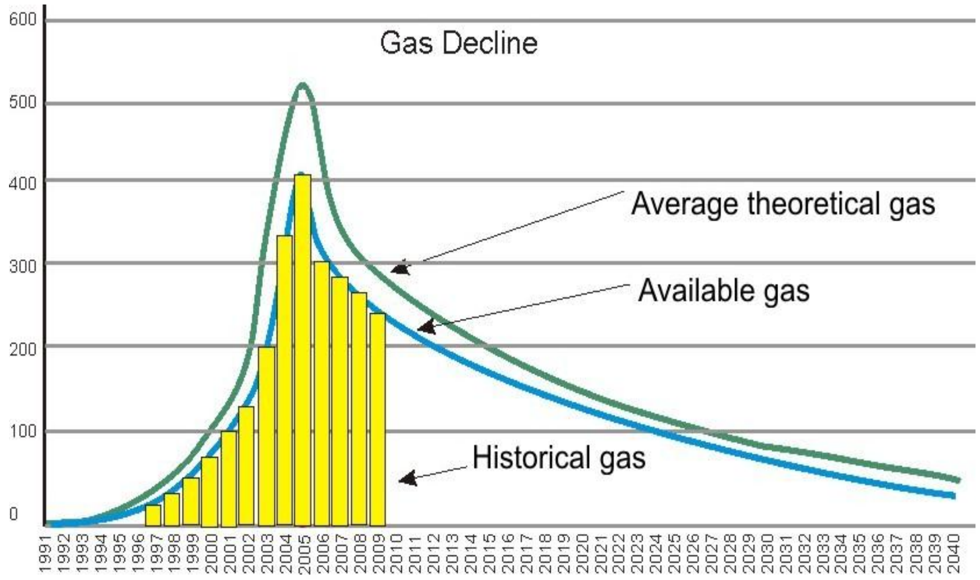


Figure 5.2: Comparison of Theoretical Gas Production Rates against Actual Extraction

5.5 The Impact of UK Policy and the Changing Nature of Waste

As both the potential (size of the peak and tail) and rate (shape of the curve) depend primarily on the composition of the waste being tipped, it is important to understand the impact of the composition of the waste mix and their impact on the size and shape of the curve specifically in relation to waste diversion from landfill (for examples of these influences, see *Appendix A* The Changing Nature of Waste).

5.6 Long Term Trends

By knowing the volume, type, and concentration of waste tipped into a site, it is possible to calculate a theoretical gas production curve for the life of the site.

Modelling software, such as GasSim, can predict the gas production over the life of a site. The rate of production will depend on many factors, but particularly:

- waste type: quantity and type
- moisture content

The total degradable element (available carbon content) of each of the five waste streams is further sub-divided into degradable fractions:

- readily
- moderately
- slowly

These fractions are assigned a rate (or range of rates) of degradation that represents the different release rates of carbon from the various components present, for example; kitchen waste will release its available carbon more readily than cardboard.

5.7 Limitations of Modelling

As described above, limitations exist with any chosen approach to the modelling of LFG. To effectively manage LFG, it is important that these limitations are understood and accepted. As with all modelling, the output is only as good as the data going in.

Record keeping requirements have changed over time and, historically, there was no requirement to retain accurate tipping records (which is the key to producing accurate models). This, coupled with the fact that landfill sites are by their very nature non-uniform environments, means 100% accurate modelling is impossible to achieve. Accurate waste inputs in both volumes and waste types are now compiled in accordance with the site's permits, which enables more accurate modelling to be achieved.

5.8 Atmospheric Dispersion Modelling (ADM)

It is essential to understand the potential impact of any emissions on the local and wider environment in order to confirm that the risk to the environment from any facility is within acceptable levels. This can be achieved through Atmospheric Dispersion Modelling (ADM).

ADM is the mathematical simulation of how air pollutants disperse in the ambient atmosphere. It is performed with computer programs that use mathematics to simulate pollutant dispersal.

Where combustion capacity is being reduced, for example, engine removal or flare downsizing, it is less critical to update ADM and in most circumstances unnecessary as the environmental impacts from combustion are likely to have reduced from those previously assessed.

It is important to consider air pollution impacts on sites of ecological interest such as Special Protection Areas (SPA), Special Areas of Conservation (SAC), Ramsar sites, Sites of Special Scientific Interest (SSSI) and Local Nature Reserves, as well as human receptors.

5.8.1 Limits for Exposure

Environmental Assessment Limits (EALs) and/or Air Quality Strategy objectives for human and ecological receptors, can be found in the appropriate guidance and regulations, such as:

- Horizontal Guidance Note H1 – Annexe (f) Air Emissions (in England and Wales)
- Air Quality Standards Regulations 2010

5.8.2 Locations Where Objectives / EALs Should Be Applied

The location at which the test should be applied will be dependent upon the nature of the receptor (human or ecological) and the averaging period. Examples of where the air quality objectives should/should not apply in the case of human receptors are given below:

Annual Mean: This objective ***should*** apply at all locations where members of the public might be regularly exposed. Building façades of residential properties, schools, hospitals, care homes etc. This objective ***should not*** apply at building façades of offices or other places of work, hotels, gardens of residential properties, kerbside sites, or any other location where public exposure is expected to be short term.

24-hour mean and 8-hour mean: This objective ***should*** apply at all locations where the annual mean objective would apply, together with hotels and gardens of residential properties. This objective ***should not*** apply at kerbside sites or any other location where public exposure is expected to be short term.

1-hour mean: This objective ***should*** apply at all locations where the annual mean and 24 and 8-hour mean objectives apply. Kerbside sites (for example, pavements of busy shopping streets). Those parts of car parks, bus stations and railway stations etc. which are not fully enclosed, where members of the public might reasonably be expected to spend one hour or more. Any outdoor locations where members of the public might reasonably expected to spend one hour or longer.

5.8.3 Initial Screening (Tier 1)

The requirement to undertake an ADM is usually determined through prior risk screening. Screening methods, such as H1, are described in Environment Agency guidance. This guidance sets criteria for screening out insignificant emissions to air, which do not warrant further assessment.

Air emissions are considered to be ‘insignificant’ if:

- Maximum Process Contribution (long term) <1% of the long term EAL (or Environmental Quality Standard); and
- Maximum Process Contribution (short term) <10% of the short term EAL (or Environmental Quality Standard).

Any emissions which do not meet these qualifying criteria cannot be regarded as being ‘insignificant’, and further assessment is required.

This further assessment (which can be regarded as stage 2 of the Tier 1 screening) requires consideration of the existing and future background concentrations at the site. If these are elevated, Tier 2 or Tier 3 impact quantification may be required.

Tier 1 assessment is usually conservative – pollutants emitted in very small quantities may not meet the criteria for ‘insignificance’. This is often a result of elevated background levels, particularly when short term treatments are applied.

5.8.4 Detailed Modelling (Tier 2)

Models are available which use site specific meteorological data and special representation. However they may not include the wide range of features that are available in an ‘advanced’ model. The dispersion modelling feature in GasSim software may be regarded as being Tier 2 compliant.

Since Tier 2 models do not take account of topography or building effects, they may not be appropriate in all cases, particularly complex terrain. However, given that they require less run time (and cost) than an advanced model, they are a useful tool where the Tier 1 screening has shown an issue but Tier 3 assessment is unnecessary.

In cases where topography or building effects should be a consideration, Tier 2 assessment may be disregarded altogether, with the assessor moving to Tier 3 assessment after Tier 1 screening.

5.8.5 Advanced Models (Tier 3)

The two most commonly used advanced models in the UK are AERMOD (from the American Meteorological Society) and ADMS 4 (from Cambridge Environmental Research Consultants). Both have been accepted by the Environment Agency and Scottish Environment Protection Agency as being fit for the purpose of predicting impacts from landfill sites (point and areas sources). Dispersion models are used to estimate or to predict the concentration of air pollutants at any given human or ecological receptor, and use more advanced mathematics to account for the influence of:

- topography
- local meteorology
- building wake effects (‘entrainment’)

Advanced models also allow predictions of impacts from multiple sources over a range of averaging periods.

The construction and completion of an advanced model will typically require the services of a person who is experienced in air quality assessment to ensure that the correct model treatments have been used and guidance followed.

5.8.6 Key Emissions for Consideration for Landfill Sites

In relation to LFG engines, the emission which is typically of most concern in relation to limits is nitrogen dioxide (NO_2). Other emissions which may be considered at Tier 1 screening are particulate matter (PM_{10}) and carbon monoxide (CO). Since Volatile Organic Compounds (VOC) are a mix of compounds, this cannot be assessed directly, although VOC surrogates are sometimes substituted (for example, benzene). This approach is unlikely to be appropriate for a gas engine exhaust as it will greatly overstate the potential impact by assuming the entire VOC is this highly toxic pollutant.

Sulphur dioxide (SO_2) and hydrogen chloride (HCl) may also be of concern if the raw LFG contains an elevated sulphur or chlorine content. Both of these combustion products are of concern for both human and ecological receptors and for this reason they should be included in Tier 1 screening assessments. Concentration at the exhaust of the engine or flare may be calculated using the US-EPA AP42 methodology.

It is considered highly unlikely that other pollutant / pollutant groups (such as dioxins, for example) will be an issue on the majority of sites, based on previous research undertaken by the US-EPA and others.

In relation to fugitive emissions from landfill sites, a very wide range of pollutants may be of concern. A model such as GasSim is typically the simplest way of accounting for this range of trace pollutants from area sources. Data can be exported from GasSim to an advanced model, if further detail is required.

Raw LFG is likely to be odorous and therefore odour may be an issue at landfill sites. It would be unwise to use predicted uncollected LFG volumes as input to an advanced model as this may lead to a large over estimation of impact. The opposite is true for the ‘fresh waste’ type odours, which will be ignored. If a detailed odour assessment is required, it is suggested that specific guidance / advice is sought from an experienced assessor and the regulatory body. The Environment Agency has also published guidance on this issue.

5.8.7 Assessment Scenarios: Engines and Flares

The permit for a site will provide concentration limits for engine exhaust emissions to which the operator must adhere. It would be normal to model the engine emissions at these limits (with maximum tolerance figures in some cases) to provide reassurance to the regulator that these limits are acceptable.

For existing engines (where an additional engine is to be added, for example), it may also be of use to provide a scenario where monitored emissions are applied as in many cases these will be significantly below limits.

5.8.8 Reporting Requirements

The Environment Agency has provided guidance on the requirements for reporting of any ADM assessment. A report may be rejected by the regulator if all required information is not reported. The main aim of the reporting protocols are to ensure that the model maybe audited fully and that all input data is traceable / defensible.

5.8.9 Implications of Modelling

ADM may highlight an impact of concern. If this is the case, mitigation options should be considered. For engine / flare emission modelling, these may include:

- increasing stack heights to improve dispersion
- minimising emissions (through adoption of scrubbing technologies or engine management).

For the modelling of area sources mitigation would typically involve upgrading containment or adapting the filling schedule (such as subdividing cells to allow more rapid capping).

5.8.10 LFGRA Model Reviews

It is best practice for an operator to maintain an up-to-date simulator risk assessment model that can be checked against the model used for the LFGRA. This model is updated at least annually, using actual data for the site including waste inputs, trace gas analysis and emissions monitoring data. Where this model differs significantly from the LFGRA, (where gas production varies by ± 25% from the original assessment), the Environment Agency advises that the LFGRA is revisited.

6 Landfill Design and Operation

Landfill gas (LFG) is generally extracted under vacuum from the waste mass. With poor containment, large open (uncapped) areas and poor access to waste, the installation and maintenance of gas management infrastructure and the application of a vacuum without drawing in air, can be difficult.

Therefore, a good landfill operator considers the permanent and temporary containment systems, the topographical geometry, phasing and cellular geometry and the interaction of all associated landfill activities and control systems (such as leachate management, migration and odour management) in order to balance the often conflicting demands of all of the landfill activities and to optimise the collection of LFG. However, the design must accept that the landfill itself, as well as the production of LFG, is a dynamic activity and any control systems must mirror that dynamism to achieve the optimum levels of gas collection.

6.1 The Challenge

A landfill site is in effect a very large anaerobic digester. Therefore, in order to promote good gas generation, the waste placement and management should ensure sufficient water is present for gas production while restricting gas escape and air ingress.

For a landfill site these two main controlling conditions can be seen to be in conflict. However, with sufficient forward planning and design, they can competently coexist. Historically, it has been common to adopt the concept of a water balance for the design, shape and life of an individual landfill cell. It should be just as common to adopt the approach of a 'gas balance' design, where the size, shape, operation and time to cap of each cell is considered with regard to when significant quantities of LFG will be generated, how it will be collected and how the system will accommodate traffic and other operational influences. In some circumstances, conflict can arise between different parts of the operator's business. Where conflicts arise, health and safety considerations should have the highest priority, followed by environmental compliance and then financial business considerations.

6.2 Operational Planning

In order to minimise the uncontrolled release of greenhouse gases, LFG management must be a primary consideration at the conceptual design stage of a landfill or landfill phase / cell. Once waste placement has commenced, landfill activities should continue to take gas management requirements into account. Forward planning, coupled with regular reviews is essential in obtaining these goals.

An understanding of the interaction and consequential impacts of all landfill associated activities is essential and none should be managed in isolation. Regular and formal communication between the responsible management teams is key and the production of a rolling Operational Management Plan is advised that considers short, medium and long term strategy, across all landfill activities.

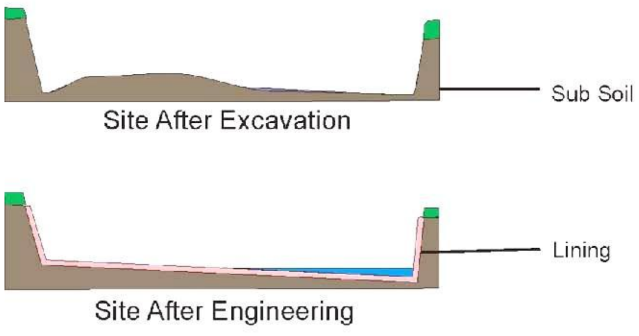
6.3 Operational Considerations

6.3.1 Engineered Containment

The degradation of the waste in a landfill under anaerobic conditions will generate LFG. Within the mass of the landfill site, this will generate pressures that will ultimately result in the escape of the gas. Without any gas collection, the only method to prevent escape would be the use of the low permeability containment. While this barrier form of control represents one part of the gas control, the major concern of engineered containment is to prevent the migration of liquids.

Modern landfill sites have engineered barriers on the base and sidewalls of the landfill which form the initial part of the gas control system. Landfills are also capped with engineered barriers, on a temporary basis during operational phases, and permanently on completion. Effectively designed and installed containment will considerably hinder the migration of gas. Temporary containment can also significantly improve collection efficiencies during the operational life of a site. Equally, poorly designed or installed containment, either permanent or temporary, can have an adverse impact on the ability to effectively manage LFG, for example, deteriorated lining systems which are common on older landfill sites.

Figure 6-1 shows a site where the base is levelled and sloped to facilitate leachate drainage and collection and a lining installed at the base and sides and a site prepared for tipping.



Engineered cell

Cell prepared for tipping

Figure 6.1: Containment

The lining can be clay, plastic or other impermeable substances. It needs to be of sufficient strength to allow for lateral and basal movement of the surrounding subsoil. Vegetation must be cleared around the perimeter to prevent roots penetrating the lining.

Containment is often considered as the first aspect of gas management. It is not uncommon for landfills to operate over a significant period of time and, as such, sites can often have a range of engineering standards applied. Generally, the newer the landfill cell or phase, the higher the standards of engineering. It is also not uncommon for there to be no physical separation between areas of a site with different specifications of engineering. This can lead to complications with gas control as different approaches are required in order to reach the LFG management objectives. An example of this is where LFG can migrate behind an engineered barrier from an adjacent uncontained phase.

It should also be considered that engineering can fail, and in such cases it is not always practical to resolve, for example a sidewall failure at significant depth beneath current waste level.

6.3.2 Waste Type

Landfill waste is typically heterogeneous (varied in composition) and is prone to exhibiting preferential flow paths or restrictive flow barriers. An effective LFG collection and control system must account for the type of waste in place or the type of waste anticipated to be deposited. For example, a high input of low permeability material (such as clay) may restrict flows and therefore reduce the radius of influence of each well. Alternatively, a large percentage of bulky construction waste (such as concrete and rubble) may create flow paths and lead to increased spheres of influence.

6.3.3 Landfill Phasing

It is critical that the phasing of landfill operations for the life of the site and for each cell is planned with consideration for effective gas management. This means maximising timely access to waste and minimising disturbance and damage to installed collection infrastructure. It is important to produce a conceptual design of the final gas management system before landfill commences. The landfill phasing plan must be reviewed on a regular basis to reflect the changes in all the relevant parameters.

6.3.4 Operational Areas

Depending on the waste type (and its condition), and on the anticipated life-span of the operational area, temporary, sacrificial or even permanent extraction systems may be required in operational areas. These systems may consist of impact wells, horizontals or drilled wells and pipework may be flexible or rigid, temporary or permanent. Irrespective of the approach selected, disruption from operational activity must be anticipated, and although any disruption should be minimised through careful planning, management of these systems will be labour intensive and frequent damage / failure should be expected.

6.3.5 Flanks and Batters

Landfill activities will often create steep flanks of waste during filling. Flanks are a potential source of significant gas emissions as a consequence of several driving factors.

Horizontal pathways are created due to the ‘onion skin’ effect associated with the placement and compaction of waste in thin layers, and the laying of daily cover. Access to install, maintain or replace gas collection infrastructure is often limited if consideration for appropriate access is not given during the operational phase.

Where infrastructure is installed it can be expected to have a limited life expectancy with wells prone to ‘shearing’ as a result of differential settlement and lateral stresses within the waste.

Flanks are often not engineered to any effective degree of impermeability to gases. This is normally as a result of the fact that the flank will eventually be covered with waste when operations move on to adjacent phases or cells. However, due to the nature of landfill, it is often the case that flanks can be left open for considerable periods of time due to site phasing and input rates. The importance to gas collection of effective covering and sealing, including odour management, must be taken into account when the decision regarding timing or quality of any barrier installed is made. Ideally, flanks should not be so steep as to prevent access for drilling.

Consideration should be given to temporary capping if flanks are to be left open for long periods before being filled against / over (typically 6 months). Flanks can be a major odour source and are a potential source for air ingress. Appropriate control measures should be taken. Specialist rigs are available which can drill on slopes.

Figure 6.2: Drilling on a Slope

Figure 6.3: Good Waste Flank, with Temporary Capping

6.3.6 Leachate Management Systems and Strategies

At the point of conceptual design for the landfill or operational phase / cell, consideration must be given to the interaction of the leachate management system and the leachate management strategy on gas collection. Leachate drainage blankets can provide a pathway for gases and loss of vacuum. Chamber design and the ability to effectively seal engineered leachate features, such as leachate chambers, will allow for connection into the active gas extraction system, increasing collection and reducing the potential for point source emissions. The leachate monitoring points and strategy must be capable of providing data on ‘true’ or resting leachate levels to accurately identify levels across the base of the site. This will provide the ability to distinguish between any true basal and ‘perched’ leachate levels (occurring as a result of the varied permeability of the waste mass).

Leachate recirculation is also a fairly common practice; however, the primary objective of a leachate recirculation scheme must be fully considered as this could have a consequential impact on gas management. If recirculation is adopted purely to reduce disposal costs, and is practised in isolation of other site activities, then this can often have a detrimental impact on the ability to manage gas due to flooding of gas wells. If done correctly, for the purpose of influencing gas production rates (by adding moisture to the waste) then this method can, theoretically, act as a positive driver on the rate of gas production and stabilisation of the waste mass.

6.3.6.1 Pumping Systems

The installation of compressed air systems is a common way of providing energy for the operation of leachate pumps. However, it must be remembered that any fault or leak in these systems can potentially add air to the landfill environment, especially within leachate chambers or if air lines are buried within the waste mass. The consequences of introducing excessive levels of air into the waste mass are covered in the ICoP *The Management and Prevention of Sub-surface Fires*. Regular checks on the integrity of any pneumatic system must be maintained.

6.3.6.2 Leachate Wells

Leachate wells penetrate the cap and therefore must be sealed in the same way as a gas well. Leachate wells are the most common point of air ingress as they are often not inspected as regularly as gas wells.

Leachate well - damaged seal

Damaged top hat seal

Leachate well - sealed after repair

Damaged seal detail

Figure 6.4: Good and Bad Examples of Leachate Well Sealing

6.3.7 Daily Cover

Daily cover is used to prevent dispersal of waste overnight or when the site is unmanned. Materials used include soils, membranes and clay slurry. Where daily cover is applied in the operational area, consideration must be given to the potential future impact of this practice on the behaviour of gases. The movement of both gases and liquids, and their inevitable influence upon each other, will be affected if the impermeable cover material is not removed effectively before the placement of waste resumes. The removal of cover must be undertaken in a way that does not create odour problems. The application and distribution of vacuum will be influenced as a consequence of existence of semi-impermeable layers within the waste. The distribution of liquids will also be affected where the natural vertical flow of liquids towards the base of the site is hindered, leading to 'perching'. Once these layers are covered with waste, they cannot be retrospectively removed; therefore, careful removal of them in the first place is the only way to prevent such issues, except where biodegradable synthetic cover materials are used, (see *LFTGN03*).

6.3.8 Capping

Air is only drawn into the waste mass when it is under active extraction, that is when gas wells have been drilled and vacuum applied. The importance of minimising air ingress into the waste mass is critical. One way of achieving this is through the placement of an effective seal or cap over the waste mass once waste placement is complete. Usually consisting of synthetic liners or engineered clays, timely installation is paramount in minimising uncontrolled emissions or ingress of air.

The two main types of cap are: temporary and permanent. Consequently, there are numerous specifications for each of these. Synthetic liners or reworked, engineered clay are the two main types of permanent cap, but it is not unusual, especially when a working area is either open for a long time or a partially completed area is expected to be re-tipped, to apply temporary capping. These are to a lower standard than permanent applications, but do go some way to reducing water and air ingress and odour release. In respect to gas management, the sooner capping is completed and the higher the standard, the better.

As with extraction systems installed in operational areas, disruption to active extraction during installation of the cap must be minimised to avoid step changes in collection efficiencies. This can be achieved through staged disconnection and reconnection of strategic areas on the system. This may be a more labour intensive approach and involve careful planning and additional temporary infrastructure, but the release of uncontrolled emissions will be minimised.

Good

Bad

Figure 6.5: Good and Bad Examples of Capping

Once installed, it is important that capping integrity is monitored and maintained according to its requirements. This will ensure both the release of emission and the potential for air ingress is minimised.

6.3.9 Overtipping

This has become a common practice in landfill due to greater waste settlement being experienced than originally envisaged. As with any other intensive activity in areas of active extraction, meticulous planning is crucial in achieving maximum collection efficiencies. An overtip plan must be prepared to minimise odour release and ensure effective gas control is maintained. Generally, this can be achieved by operating a compact tipping area. Existing infrastructure will need to be raised or sacrificed and replaced systematically.

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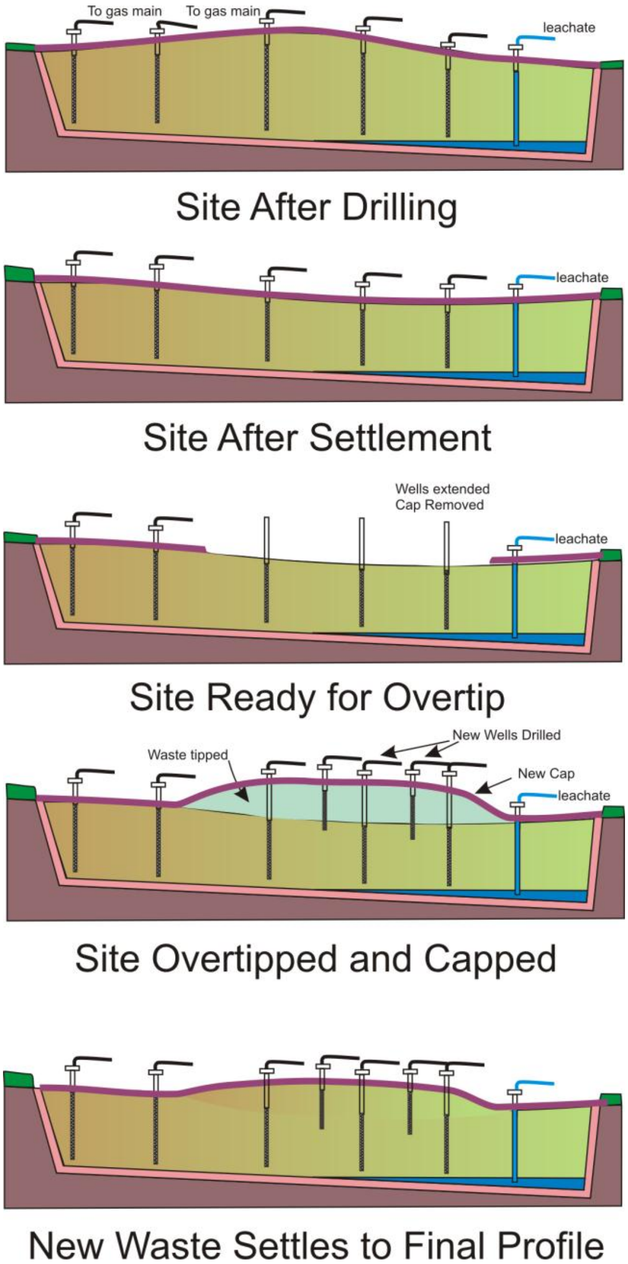


Figure 6.6: Overtipping

7 Gas Collection Infrastructure

The principal objective in designing an active gas collection system (GCS) is to create a preferential route through which Landfill Gas (LFG) will flow in order to optimise the controlled collection and treatment of gas, therefore, minimising the uncontrolled release of emissions to atmosphere or to the immediate environment.

To achieve this objective, a vacuum must be exerted as evenly as possible on all of the LFG producing waste mass, to encourage the LFG into the collection system. The installation of LFG collection wells and LFG transmission pipes into the waste mass allows this vacuum to be distributed. The design of any collection system must, therefore, ensure that:

- sufficient vacuum is available to reach all parts of the waste mass
- the collection pipework is gas tight
- the wells are suitably designed
- the pipes are sized correctly for the expected flows and pressure losses

Pipework must also be kept clear of blockages that may form due to accumulation of condensate, collapse or failure. This chapter outlines some essential considerations and suitable approaches for LFG collection infrastructure design and installation.

The design of the fixed gas infrastructure should be undertaken in association with the design of the other components of the landfill site. It is not appropriate for the design to be done in isolation. The design components should consolidate all landfill infrastructure and accommodate temporary stages of landfill development to include flexibility to add sections or wells in response to collection efficiency feedback.

System design should also accommodate the planned waste settlement for the site, especially on air tight critical areas, such as around well penetrations of low permeability caps.

7.1 Material Selection

One of the initial considerations before any infrastructure is installed, either in or on the body of the waste, should be the materials to be used. As with any design, they need to be fit for purpose. It must be understood that the landfill environment is a very dynamic and aggressive one. The potentially hostile and degrading nature of the various chemicals associated with the waste in place, combined with the natural stresses and strains associated with waste placement and settlement must be considered. Essentially, everything placed into this environment will have a limited life expectancy and will suffer losses in efficiency. However, endeavours must be made to ensure maximum design life expectancies are achieved and efficiencies maintained with the usual consideration for value.

Generally, the collection pipes and gas main(s) will be constructed from medium or high density polyethylene (MDPE or HDPE). This material is resistant to chemical attack from LFG condensate, flexible enough to move as the site settles, is readily available and relatively easy to install. Generally, six bar rated pipe (SDR 17.6) will be used, as this is strong enough to withstand being buried. Stronger pipe is generally not required and weaker pipe has a tendency to distort and flatten.

Pipe should be joined using electrofusion joints or by butt-fusion. Mechanical joints may be installed above ground or in chambers where they can be easily inspected. MDPE pipe should generally be black, as this is more resistant to ultraviolet (UV) in sunlight. The actual specification of pipe used should be designed considering the purpose, load and stresses for each individual application.

MDPE pipe is subject to thermal expansion and contraction as high as 3% per 10 ^{o}C. This means, where pipe is surface laid, it must be securely staked or secured with material such that the movements will not create snaking of the pipe and cause low spots to form. This is especially important crossing a slope, as repeated expansion and contraction can cause the pipe to move down slope and create the potential for condensate to collect in local low spots.

Flexible single wall or twin wall MDPE drainage pipe may be used for temporary systems. The advantage is that the pipe may be more easily man handled and drained of condensate. It is also easier to install, remove and reinstall, requiring only mechanical joints. It is however not robust and may be easily damaged, so is not suitable for permanent systems.

7.2 Gas Collection Wells

To facilitate the collection of LFG, wells are installed into the body of the waste at varying stages of the life of the landfill. The design of these wells will vary depending on their purpose, however, the most commonly used designs can be categorised thus:

- permanent / drilled well
- sacrificial / well
- scavenging well

In line with current best practice, well spacing for permanent wells is generally on a 40 metre triangular grid. This assumes that each well will have a radius of influence of around 20 metres. For temporary or pin type wells (odour or migration control) well spacing may be less.

Consideration will be given to drilling wells at different depths in the deep parts of the site in order to extract gas from different layers in the waste. In normal, saturated waste, drilling to 80% of the depth of waste is typical. Where, for example, perching (trapped leachate) is present, shallower wells might be drilled, so as not to breach the perch level. Similarly, over tipped waste maybe more active than exhausted waste and shallow wells may be required to maximise extraction.

Gas wells will generally be drilled into the waste mass at the site. However, in exceptional circumstances, consideration will be given to off-site extraction wells to tackle persistent migration problems.

Multi-stage wells, where a single well extracts from multiple depths, can also be installed. The gas well design will depend upon the site engineering, the depth of waste and whether the system is in an active area or a completed phase of the landfill. Three principal designs of gas well may be used:

- a drilled well using a rotary barrel or flight auger
- a shallow impact well (the hole being created by an impact drill)
- a horizontal well trenched into the waste

Each design is useful in differing situations. The standard well installed will generally be a drilled gas well. Impact wells are useful in very shallow areas (<10 metre depth) or in areas that are temporarily tipped and will be over tipped at a later date. Horizontal wells are useful in shallow waste and more usually installed in the active tipping area to control surface emissions.

Traditional gas wells may need to be installed as part of a temporary system. The gas wells may have the same specification as permanent gas wells or, if they are to be sacrificial, they may be drilled to smaller diameters and have smaller casing sizes.

7.2.1 Drilled Well

A rotary drilling rig is used to create a void which is cased and back filled to produce a gas well. The void is typically greater than 300 mm in diameter and has MDPE or equivalent perforated well casing installed. A gravel pack surround is installed to protect the pipe, and to allow gas passage into the pipe and support the seal. Plain pipe is installed at the top of the well and a seal installed in the annulus between the casing and the well surround to prevent air directly entering the well during operation. The length of plain pipe must maintain a minimum depth below the containment interface. Usually a depth of at least 2 metres is considered adequate for permanently capped areas and up to 10 metres may be required in operational or temporary capped areas. When installing a new well, waste settlement must be taken into account. As a rule of thumb, an allowance of 20 - 30% of the depth of the waste should be used. On that basis, on a 20 metre deep landfill, the typical plain length installed below ground level should be at least 4 metres and the gravel filled annulus must stop before this point.

Flight auger **Barrel auger** **Impact drill**

Figure 7.1: Drilling Techniques

Gas wells are usually constructed using a proprietary MDPE or polypropylene based well screen with casing joined by threaded or butt-fusion connections, providing a flush internal and external fitting.

Location specific design decisions to be made include:

- well positioning and spacing
- drill depth
- diameter of the hole and the casing (and therefore the width of the gravel pack

Specification of the well casing:

- length of plain casing
- method of perforating the slotted casing
- method of joining the casing
- material used to fabricate the casing
- size and specification of the gravel pack
- depth and specification of the well seal

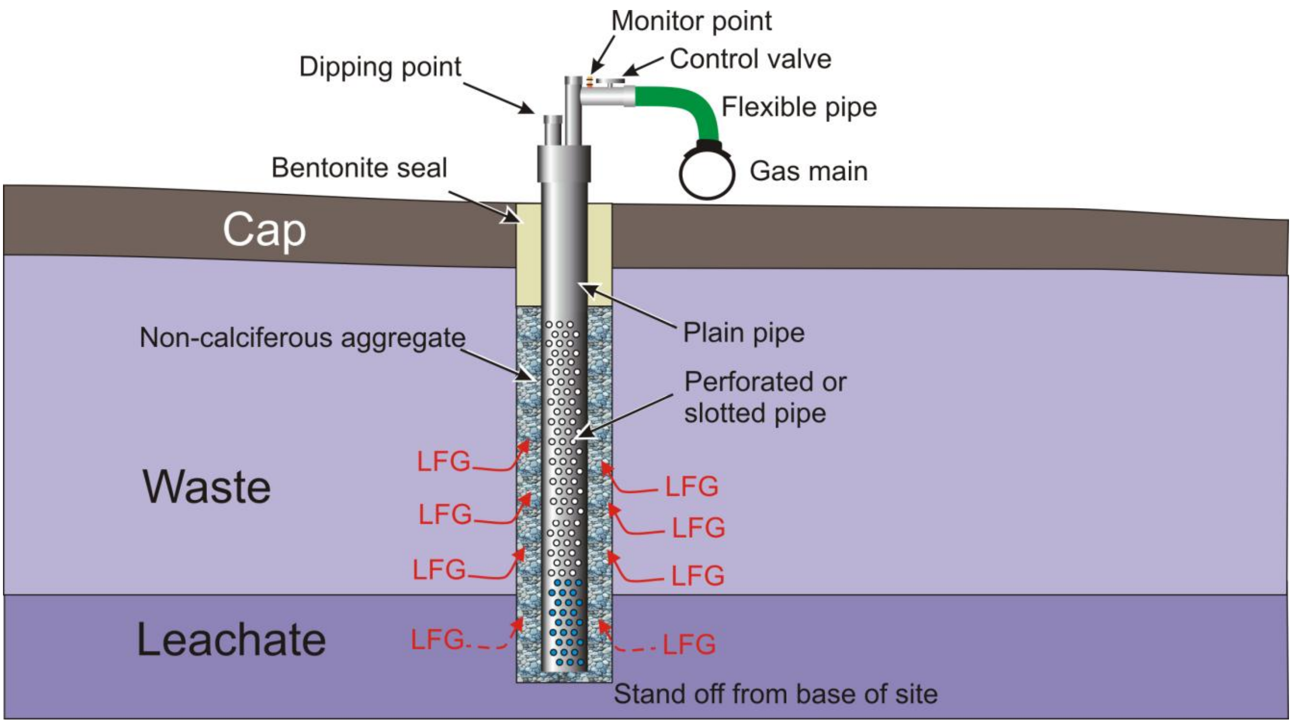


Figure 7.2: Typical Gas Well Design

7.2.1.1 Well Positioning and Spacing

Drilled wells should be installed at regular intervals in either a square or triangular pattern. Spacing design should include not only the geometric context but also the anticipated gas permeability of the waste and the design suction pressures. Typically, wells will be on 40 metre spacing. However, experience of operating and measurement of cross suction between wells will enable more site and area specific well spacings to be defined. Smaller or larger spacing can therefore be justified by previous work on site. For example, greater spacing could be justified where:

- the site is deep
- the waste is particularly permeable
- the waste is capped
- the site is large and regular in shape

7.2.1.2 Drilling Depth

The depth to drill the hole will depend on:

- the depth of the waste
- the type of engineering at the base of the site
- the confidence associated with basal position
- leachate levels

It is normal to drill to at least 80% of the known waste depth or to 3 metres above the known base. Wells can be logged as they are drilled, but the material brought out of the hole cannot be relied upon to indicate when the basal engineering is being approached. The safe depth must therefore be calculated from surveys. The location of the hole should be set out on site and the location measured by survey. These X, Y, Z co-ordinates should be compared to the top of basal seal survey at the well location and the height difference determined.

7.2.1.3 Stand-Off

A suitable ‘stand-off’ should be set to allow for error in the surveys, measurement of the drill rods and to provide a factor of safety in order to ensure containment is not compromised. The stand-off should be a minimum of 2 - 3 metres depending upon the depth of the site and accuracy of the figures. A further stand-off should be applied to account for settlement and any associated movement of the well string. As the site settles, it could potentially drive the well casing downwards and towards the liner on the site. Whilst most of the settlement is taken up either by collapse of the casing or movement of the ground relative to the casing there may be some scope for damage to the liner. This is especially true if steel casing is selected. A greater stand-off should therefore be used on wells with steel casing or sites with particularly sensitive receptors below the lining. Telescopic casing is designed to take up this movement therefore no extra stand-off will be required. Rigid plastic casing may require a greater stand-off depending upon the depth of the waste and expected settlement.

Where there is no basal liner it may be permissible to drill right to the base.

7.2.1.4 Well Diameter

The well diameter should be sufficient to fit the design well casing and the gravel pack without risking the gravel pack bridging between the side of the drill hole and the well casing. The size of the gravel pack should be designed to meet the following criteria:

- adequate gas transmission to the well perforations
- sufficient to prevent bridging

The gravel pack should be made of calcite free gravel which should be small enough to easily flow within the annulus, but larger than the maximum perforation size.

The well casing should be sized to keep the gas velocity below 10 m/s with the expected flow from the gas well. This will be linked with the well spacing and expected gas production from an area. Leachate levels in the site and the requirement for installing a pump in the gas well will also need to be determined before selecting the well casing diameter. If a pump is to be installed, the well casing should be sized to accommodate the pump.

7.2.1.5 Well Casing

The well casing should be constructed from either MDPE, steel or equivalent. PVC casing has a tendency to leach its plasticiser and become brittle over time. The choice of well casing will be the subject of individual and circumstance specific calculations; however as a guide MDPE casing should generally be SDR 11 for sufficient mechanical strength. MDPE casing is stronger if it is joined using butt-fusion rather than threaded connections. Alternatively, a proprietary telescopic casing system could be installed. Steel casing will require threaded connections to join the casing lengths. An end cap should be installed on the base of the casing to prevent the casing from sinking into the waste. Steel casing is stronger and more able to resist settlement but is more expensive, more difficult to work with and just as prone to efficiency losses such as blinding. The choice of material will be determined by design requirements.

The top section of casing should be installed in plain pipe. This section should extend 4 metres below the base of the cap. The length of plain casing will depend on the well depth, type of capping and expected settlement. If steel is chosen, the top sections of casing should be installed in 1 metre lengths to allow sections to be removed to accommodate settlement. Plastic casing maybe easily cut therefore should be installed in a single length. Below the plain section the casing should have perforations cut to provide approximately 10 - 12% open area. In test rigs, MDPE casing with offset holes has been shown to be twice as strong under vertical loading as slotted casing. Holes or slots should be smaller than the minimum gravel size.

Prior to installation, the well pipework should be fitted with an end cap at its base. This is to prevent the ingress of too much debris into the well during installation.

7.2.1.6 Gravel Pack

The gravel pack needs to fill the space between the casing and the hole and allow the seal to be installed. The pack needs to allow gas through and needs to be large enough to not fall through the holes in the casing. Gravel should be rounded rather than angular or of sufficient size to prevent tight packing (and hence decrease the ease of gas flow). Gravel should be free of calcareous stone as this has a tendency to react with the LFG to blind the gravel pack and the holes in the casing.

Figure 7.3: Gravel Pack Installation

7.2.1.7 Well Seal

In order to prevent air entering directly into the well, a good seal needs to be installed. It is insufficient to rely on the capping layer alone (even if this is booted to the casing). Plastic liners should not be welded to the casing due to settlement. Ideally, the seal should be formed from bentonite to a depth of at least 2 metres on a capped site and 3 metres on an uncapped site. Correct hydration of the bentonite seal is essential. The bentonite should be granules rather than pellets, as pellets are difficult to hydrate properly. The bentonite should be pre-mixed or tipped directly into standing water. Regular rehydration may be required, especially in the drier months. Bentonite slurry can be pumped in under pressure using special equipment.

Bentonite hand pouring

Good (well hydrated) bentonite seal

Figure 7.4: Installation of Bentonite Gas Well Seal

Damaged boot seal

Poor bentonite seal in fresh waste (poor hydration)

Figure 7.5: Damaged and Poor Seals

The bentonite should be allowed to form a slight hollow below the surface to allow for rainwater to pond and aid hydration.

Bentonite is best poured one dry bag at a time and the poured bentonite fully hydrated before the next bag is used. Thus helps to prevent bridging.

7.2.1.8 Gas Well Identification

Each well should be uniquely numbered.

Many numbering systems are in use but the essential factors are:

- site identification
- unique number

In addition, it may be useful to code the phase or cell and to identify the item as a well (rather than a leachate drain or knockout pot).

A typical number system could be: My Site / GW / 1020

Barcodes can also be used to facilitate automatic data load and prevent transcription errors.

The gas well ID code should be written on the well with indelible ink or paint (preferably white or yellow) or by a label permanently attached to the well, not the wellhead. If a wellhead is reused, any ID code must be fully removed.

7.2.2 Sacrificial / Temporary Gas Wells

Typically, sacrificial or temporary gas wells will be installed in areas where they may be prone to damage or expected to be made redundant within a short period. They are a cheaper alternative to permanent wells as they are usually drilled to a smaller diameter (~200 mm) using a rotary barrel or flight auger technique. Alternatively, impact / push wells can be used.

As with permanent wells, they will usually be constructed using a proprietary MDPE or polypropylene based perforated pipe joined by butt-fusion to give a flush internal and external fitting or using steel casing, joined by threaded connections.

The annulus of the gas well will be filled with a washed, non-calcareous gravel pack and the gas well annulus sealed with a bentonite seal.

7.2.3 Impact / Wells

Impact wells are generally simpler than a drilled gas well, having fewer design variables. They are created by hammering or pushing a metal pin into the waste and then removing it to create a void. They will typically be installed to a maximum depth of 6 metres and cased with 63 mm 10 bar MDPE pipe and 10 mm single sized gravel. A 1.5 - 2 metre bentonite seal is installed as per a typical drilled gas well. The casing is usually a single length drilled on site and a 2 metre plain length at the top. Alternatively the well casing itself could be driven in and left installed if appropriate.

Push wells are gas wells created by driving a metal spike into the waste to create a void. This is then cased, gravelled and bentonited, to create a shallow gas well. The maximum depth that can be achieved with this technique is approximately 6 metres.

Push wells may be installed in the active tipping area or in cells that will be surcharged in a relatively short period of time. If they are installed in active areas then the connecting pipework and push wellhead may be buried to allow extraction whilst tipping continues. Push wells can be connected using a 63 mm ElectroFusion (EF) elbow as a wellhead.

Push wells will primarily be used in areas that are due to be surcharged but are causing odour issues or gas generation is taking place at an early stage of the cell operation. They can be installed on relatively close spacing (10 to 20 metres) so give greater coverage of an area than a typical gas well. As they are sealed with bentonite they can be installed and extracted without the requirement for additional lifts of waste unlike horizontal wells. They may also be used to address shallow gas migration and can be used close to the edge of sites where the depth of waste might limit the installation of permanent specification gas wells.

Void made with impact drill

Pipe installed

Gravel pack poured

Bentonite seal poured

Figure 7.6: Impact / Push Well Installation

7.2.4 Horizontal Wells

In general, horizontal wells can be installed in shallow waste areas, or in areas with active tipping. The advantage of horizontal wells is that they can be placed in active tipping areas and may be extracted from whilst tipping continues. This makes them ideal for odour control in the active cell. In order to be effective, however, horizontal gas wells need to be installed before the landfill cell has started producing significant quantities of LFG.

Horizontal wells are more variable in design as they need to be tailored to site specific conditions. Generally, they will be formed of one or more legs of perforated MDPE pipe, connected to a header of plain pipe. The horizontal well may be trenched into the waste to a depth up to 1.5 metres (any deeper brings danger of collapse of the trench and health and safety issues that are unnecessary) or installed under the tipping face. Pipes may be surrounded with stone to protect them or laid directly into the waste. Horizontal wells are more likely to fail through condensate blockage or pipe breakage on the transitions from horizontal to the vertical. Right angle tees or elbows should be avoided between the horizontal and vertical planes. Joints should not be located at the point of exiting the waste.

If horizontal wells become buried under many lifts of waste, then they are subject to failure due to blockage or crushing, and will need to be replaced with a new well at a shallower depth. This makes them of limited use in controlling migration from deep parts of the site. As they are installed only about 1 metre below the surface, they require at least one lift of waste on top to form a seal to prevent ingress of air into the well. This makes them of limited use in areas that are not going to receive further waste or be sealed in some way. If horizontal gas wells are to be selected, then they are best trenched into the waste mass and backfilled with as dug material. They can be surrounded in gravel or similar granular material but this does not necessarily improve gas flow or life-span.

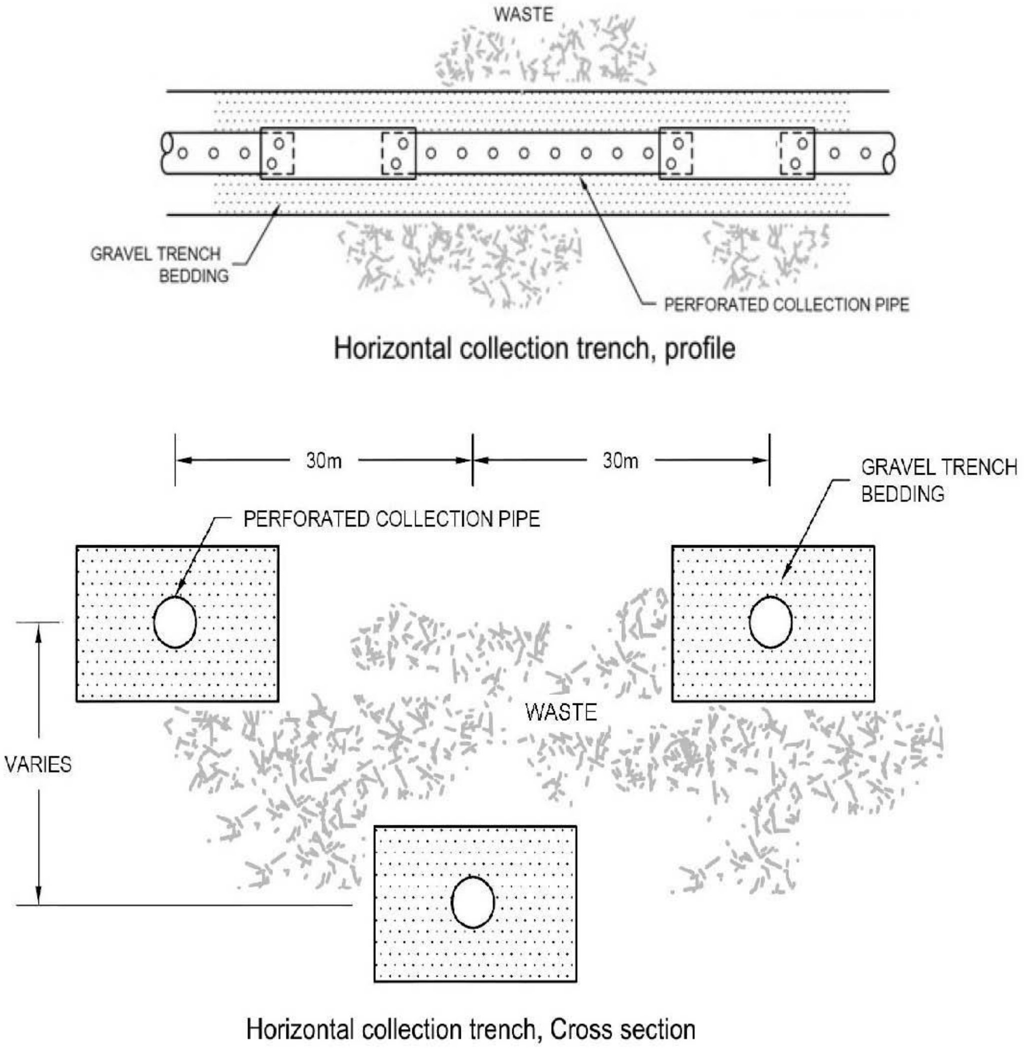


Figure 7.7: Horizontal Wells

7.3 Extraction Issues & Techniques for Piggyback Lining (3D) Systems

Increasingly, the industry has to face issues associated with engineering standards on 'legacy landfills' specifically where different standards of engineering have been applied at the same site. This is briefly discussed in Engineered Containment, however, this section describes in more detail an increasingly common and very specific complication associated with combining varying standards of engineering. Historically, it has not been uncommon for new landfill phases or cells to overlap or 'piggyback' previous areas of waste fill. However, since implementation of the PPC regulations, landfill operators have been required to install improved quality, low permeability lining systems on the base or sidewall of the 'piggy-backing' areas. Essentially this creates a separate landfill on top of an old landfill and continuity between the two masses is prevented or at very least hindered. Access to retrofit systems is often limited.

As well as creating problems associated with the management of liquids (leachate), problems associated with the effective management of LFG are becoming increasingly common. The waste underlying the new containment system is, more often than not, still producing LFG. If prior consideration has not been given to the ability to install and maintain long term gas (and liquid) extraction from this body of waste, adverse environmental consequences (for example, migration) become increasingly likely. It is therefore important to consider the long term management of this underlying waste mass prior to the placement of the containment on top. This problem is illustrated in simplistic form below.

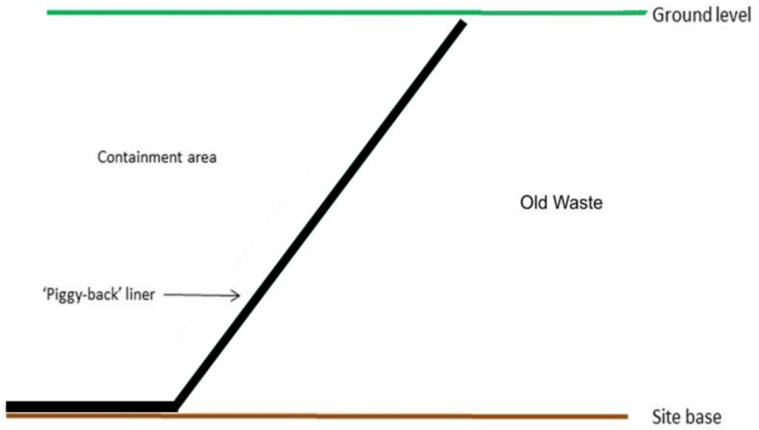


Figure 7.8: Piggyback Liner over Underlying Waste

Retrofitting of systems to capture this underlying gas can prove complicated and costly. There are the obvious issues and risks associated with drilling through the overlying containment directly into the underlying waste mass waste. This could potentially create pathways for liquids to pass from the 'contained' area into the 'uncontained' area. However, with careful consideration many of these risks could be reduced or eliminated by suitable engineering. Where this approach is considered absolutely necessary, the potential risks associated with either approach need to be carefully assessed, (are the risks associated with potential groundwater contamination worse than the migration?) and complete agreement reached with the regulating body.

These two different approaches are illustrated in *Appendix D Vacuum Distribution Diagrams.*

7.4 Gas Transmission

7.4.1 Pressure Losses in Pipework

Pressure loss along a pipe increases with the square of the velocity of the gas, due to friction losses. If the gas velocity is too high, pressure losses will prevent enough suction reaching the far end of the GCS. Pressure loss calculations need to be undertaken to ensure that the gas system being installed has sufficient ability to give the flexibility of gas control at all parts of the gas system as is required. It is best to keep the gas velocity in a pipe below 6 m/s to avoid excessive pressure losses; however velocities of up to 10m/s can be used where systems are designed appropriately. The theoretical pressure loss along a pipe can be calculated from equations governing isothermal flow of a compressible fluid along a pipeline. If the pressure drop is small compared to the absolute pressure the equation pressure loss tables can be used.

If a pipe is not internally debeaded, when connected by butt-fusion, or connected with EF couplers, the turbulence of the flow will be increased. The effect will be to increase the pressure loss in the pipe significantly (by as much as 20%).

Note: Internal debeading is not common practice.

The expected pressure loss along each section of collection pipe can be calculated to derive a total pressure loss from the farthest well back to the gas plant. Fabrications, manifolds, knockout pots, elbows and valves will also add to the pressure losses in a pipe. The exact effect of each is hard to quantify but pressure losses should be kept to a minimum by selecting appropriately sized fabrications. This will allow the correct size of pipe to be selected for the gas main(s) and collecting lines and the correct specification of blower on the gas plant.

At the design stage, any system should be capable of delivering suction in the region of 50 mbar at any wellhead in the collection system (though some wells may operate with suctions much less than this). If the pressure loss in a gas main is excessive, the suction applied to wells close to the gas plant will be difficult to control due to the high suctions in the gas main. In addition, small changes on these wells will have large effect to the suction applied to wells further from the gas plant.

It is crucial that the final design of main distribution carrier mains are of sufficient capacity to cope with complete collection demand during the operational and closed phases of the site. In any design, suitable allowance should be made for error or uncertainty. Under-sizing a main may lead to a requirement for a second line to be installed at a later date.

Where a ring main is to be operational before it is completed, a large diameter pipe will be required.

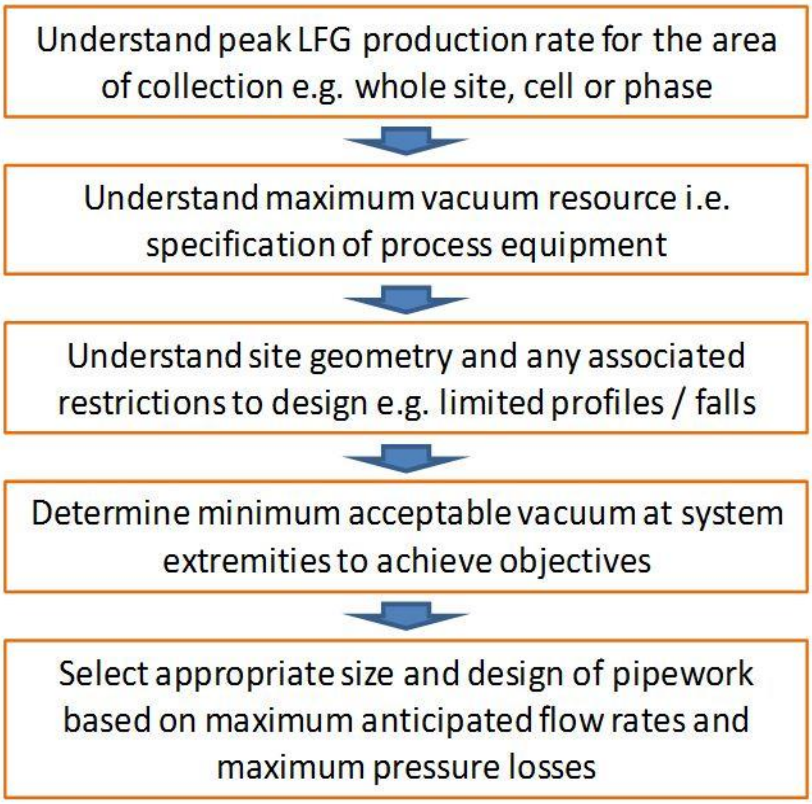


Figure 7.9: The Consideration of Pressure Loss in Gas System Design

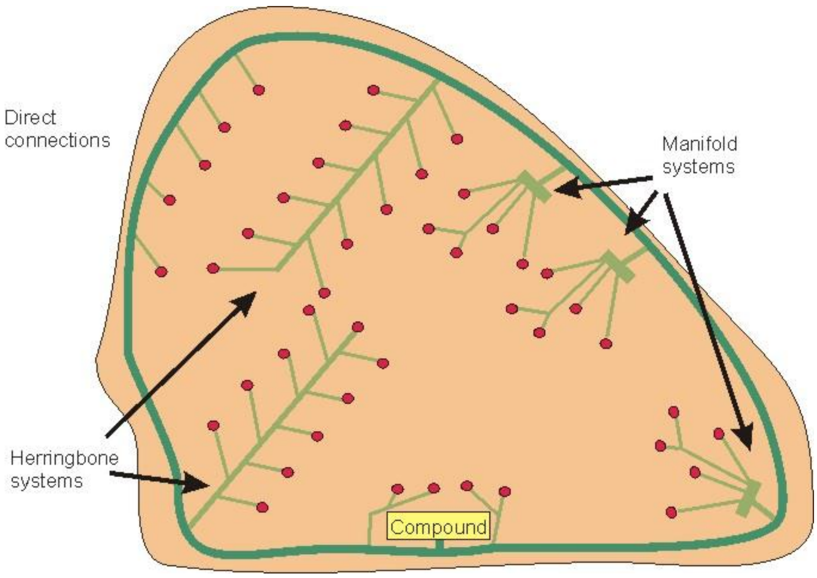
Any capacity calculations will have associated levels of confidence based on the accuracy of historical waste data and future assumptions for the production of LFG. It is the responsibility of the operator to determine appropriate levels of contingency or factor of safety to accommodate this sensitivity.

7.4.2 Gas Carrier and Ring Mains

Gas mains should generally be constructed from 450 mm, 400 mm, 355 mm, 315 mm, 250 mm, 180 mm or 125 mm black MDPE pipe and joined using EF or fully automatic butt welding techniques. Sizing will be based on the predicted peak flow calculations for the site. Ideally, gas mains should be laid in virgin ground to form a ring main around the site. These ring mains may be installed in sections, with extensions being installed as the waste filling progresses. Where gas mains are laid on waste, they should run against contours and minimum gradients should be increased to further facilitate dewatering especially where significant settlement is expected. Installing in virgin ground minimises the potential for damage through settlement or the movement of heavy machinery.

Ideally, in areas that have not yet been restored, gas mains should remain surface laid and held in position using metal pins / staples or wooden stakes to prevent snaking associated with the expansion and contraction of MDPE associated with temperature swings. Even after areas have been restored, consideration should be given to retaining surface laid pipes for ease of maintenance. This will be subject to any appropriate planning conditions.

In areas that have been fully restored, gas mains may have to be buried in the sub-soils dependent on planning conditions or the potential for unwanted interference or vandalism. It is envisaged that a ring main (or multiple ring mains) will be installed on most sites. The pipe should therefore be sized to take half of the expected flow under normal operating conditions, but be capable of taking all the flow under non-routine operation.



Alternative Carrier Connections

Manifold

Figure 7.10: Gas Carrier and Ring Mains

7.4.3 Connecting Pipework

Connecting pipework will generally be constructed from 90 mm, 110 mm or 125 mm black MDPE to SDR 17.6 and joined using EF or fully automatic butt welding techniques, however 50 mm and 63 mm may be used where gas flows are considered to be relatively low. As a guide, 63 mm pipework might be utilised from a gas well if the flow was thought to be less than 35 m^3/hr and 50 mm pipework maybe utilised if the estimated flow rate was less than 20 m^3/hr. Consideration needs to be given to the maximum length of pipe runs to avoid the impact of excessive pressure losses.

Similar advice applies to the positioning, securing and burying of connecting pipework as discussed for main pipework. All connecting pipework should be laid to maximise the fall to the main pipework. Ideally, falls should be 1:50 or greater to facilitate condensate flow. The connection between a wellhead and the carrier pipe should be flexible to allow for the differential settlement. This usually takes the form of a flexible length of reinforced hose between the wellhead and the collection pipe held in place by jubilee clips or similar. The hose needs to be fitted in such a way that there is no stress directly on the ends of the pipe and that there is enough slack in the flexible pipe to take up horizontal and vertical movement. This is usually best achieved by coiling the flexible pipe around the raised wellhead. The flexible pipe should be installed such that no low spots are formed in it as these will be amplified by the weight of condensate.

Figure 7.11: Connecting Pipework

7.4.3.1 Pipework Sizing

Gas mains should be sized to take the predicted peak flows of gas from the site or the discrete areas it is designed to serve. Identifying appropriate sizing at the offset will prevent issues associated with under capacity and the requirement to upgrade at a later date. Care must be taken to understand the phasing of infilling therefore larger pipework may be needed in the early stages, that is, if the gas ring main will not be completed until towards the end of the site's operational life.

Pressure loss and velocity calculations will be made for gas mains and connecting pipework for both normal operating conditions and worst case (non-routine operation). The typical design criterion is to keep the gas velocity below 6 m/s to allow condensate to drain and to prevent excessive pressure losses.

7.4.3.2 Pipework Positioning

For preference, a perimeter gas ring main is laid on either virgin ground or solid ground outside of the waste area to prevent differential settlement and therefore low spots within the main. Permanent gas mains on virgin ground will be installed to falls of typically 1:100 with gas and condensate flow in the same direction. Where gas and condensate flow is in opposite directions, the fall should be at least 1:50. Where the gas main has to be installed on waste the falls should be 1:50 and 1:25 respectively to allow for some degree of differential settlement.

Minimum pipe fall towards drainage point	
Scenario	**Minimum fall**
Pipeline on stable ground, fall and gas flow in same direction	1 in 100
Pipeline on stable ground, fall and gas flow in opposite directions	1 in 50
Pipeline on tipped material, fall and gas flow in same direction	1 in 50
Pipeline on tipped material, fall and gas flow in opposite directions	1 in 25

Table 7-1: Minimum Pipe Fall

Pumped knockout pots will be installed at all low spots in the gas main to collect and aid removal of condensate, (see *7.7 Condensate Management*). Collected condensate will be returned to the waste mass or to the leachate management system in accordance with the site's permit using air driven or electrical pumps. Natural dispersion knockout pots may be utilised to dewater gas collection pipework in temporary sections of the gas collection system within the waste mass.

Connecting pipework should be laid to maximise falls from the well to the main. Where possible, connecting pipes will be laid to provide a fall in the direction of gas flow, but if this is not possible larger diameter pipes should be utilised in order to keep gas velocity down. Pipeline falls should be 1:50 where possible. Some re-profiling of the ground may be required to provide adequate falls.

7.5 Control

Due to the heterogeneous nature of the waste in a landfill site each well will produce gas at a different rate, have a slightly different sphere of influence and require a different level of suction to collect the sustainable gas yield. Because of this, the GCS must be capable of altering the suction applied to each well relative to all the others on the system. This is achieved through the use of valves between the gas mains and each individual well. The principal decision to be made in the design of the GCS is where to locate these valves, that is whether to use valved manifolds to connect the gas wells or connect the wells directly into spur lines with the valve at the wellhead.

The principle of optimum gas extraction is the application of an adequate vacuum throughout the waste mass to prevent as much as practical the uncontrolled release of gas, and to deliver it to a point of disposal without causing excessive air to be drawn in, (which may result in the site becoming aerobic with the resultant overheating or creation of fires). These fires are commonly referred to as 'hotspots' (see *ICoP The Management and Prevention of Sub-surface Fires*).

Maintaining individual monitoring and control facilities associated with each well is essential; however, the location of these facilities can vary according to the type of system, of which there are essentially two approaches:

- manifold systems (primary controls at manifold)
- spur (herringbone) approach

The choice of system (or hybrid of the two) will depend upon the site conditions and the operator's preference.

7.5.1 Manifold Systems

A manifold system connects each well directly into a single valved inlet on a manifold. The suction applied to each well is controlled by a valve on the connecting line. Each inlet on the manifold typically has only a single well connected to it. The advantages of a manifold system are that smaller bore collection pipes can be used, it is much easier and quicker to balance the gas field and there are more useful points of isolation if damage occurs to the gas system or additions need to be made. In addition, if a problem occurs on a well, it has less effect on the remaining wells than a spur approach (where suction may be lost further up the spur line).

Manifolds allow better distribution of suction around a site and better control of suction and flow particularly, for wells with low flow, as there are two points of reduction (at the manifold inlet valve and individual connecting line valve). Small bore pipework is more tolerant to minor condensate blockages where the fall and gas flow are in the same direction, that is, condensate can be pulled through by the gas flow. There is however a risk with manifold systems that the measurements are made remotely from the physical well and so visual inspection of the well is reduced or omitted.

Manifolds are generally installed on the waste and sited at a point of maximum gradient. Manifolds have the advantage of making gas balancing easier and quicker. Any problems with the gas mains and connecting pipes can be quickly isolated and identified using manifold systems. If a problem forms due to settlement of a connecting line, only one gas well will be affected, rather than an entire area of the site.

Each manifold is in turn connected into a gas main, that generally runs around the edge of the site, eventually connecting to the gas plant / flare. Monitoring and access facilities should still be provided at each wellhead in order to periodically assess the condition of the gas wells and connecting pipework.

Manifold in a chamber

Manifold direct on ground
(not recommended for permanent installations)

Figure 7.12: Examples of Manifolds

7.5.2 Spur Systems

A spur approach connects a number of wells into a single line which then connects into the gas main. The line must be larger in diameter but there are fewer of them. Suction is controlled by a valve at each wellhead. The main advantages in this system are the absolute suctions at the wellhead are used for balancing and that any problems with the wellhead can be investigated and acted upon immediately (since the technician has to visit each wellhead to balance the system). The disadvantages are that it is more time consuming to balance and control with only a single valve at the wellhead and, if not designed correctly, condensate problems can block extraction from a whole section of wells.

Variations on these themes will be necessary for connection of sacrificial, temporary and horizontal systems. For these systems, connection to the permanent vertical gas wells should be made via wellheads.

7.6 Wellheads

Wellhead with valve and sample point

Wellhead with electric leachate pump

Wellhead with sample point and air driven leachate pump

Multi-stage wellhead

Pin well

Figure 7.13: Examples of Individual Wellheads

7.6.1 Valves

Valves should be selected that can withstand LFG condensate and usefully modulate the expected gas flow. They should be sized for the expected flows and to suit the size of gas pipe. Generally three different types of valves are available:

Butterfly Valves – cheapest but most control is generally only found over 30 - 40% of the valve range. This design of valve can usually be locked-off for added security.

Ball Valves – reasonable control (50 - 60% of the valve range) and easy to operate remotely (for example, in a manifold using an extension handle)

Linear Control Valves – good control over their entire range, most expensive and not possible to install in every application.

Brass and steel should be avoided due to the aggressive nature of the LFG condensate. Seals should be nitrile rubber or similar where in contact with LFG.

7.6.2 Sampling Points

Sampling points need to be installed to allow the suction and gas concentrations to be measured and to be balanced on the site. A portable gas analyser is used to measure the gas and monitor the suction. Sample points are therefore needed upstream of each valve to allow the valves to be adjusted. Further sample points are also useful for finding problems (for example, on the wellheads and in the gas mains to detect air leaks and line blockages).

Sample points are usually either a self-sealing quick release type socket valve or a ¼” ball valve with hose tail. The choice will depend on the preference of the operator. Both are generally installed by drilling and tapping a ¼” thread into the MDPE pipe.

7.6.3 Wellhead Protection

Where gas wells are to be installed on restored areas or areas liable to public access, they should be protected within wellhead chambers to protect the wellhead against damage. Chambers should be of a robust construction and be sealed with a lockable lid of robust design capable of being easily lifted by one person. The lid should also be designed in such a way that it forms a watertight seal when closed, to prevent the ingress of water into the chamber.

As with individual wellheads, wellhead chambers should be permanently marked with a suitable name tag and ATEX/ DSEAR marking sign, see *ICoP 2, Area Classification for Landfill Gas Extraction, Utilisation and Combustion, edition 1 Nov 2005*.

Figure 7.14: Example of Chamber

7.6.4 Wellhead Connection to Pipework

In general, all above ground wellheads should utilise flexible suction hose in its connection from the well head to the lateral or main pipework. This is designed to allow significant movement of the pipework in relation to the wellhead, for example, by settlement or pipework expansion due to thermal change.

On occasions, it will be more appropriate to utilise EF couplers and pipe instead of flexible suction hose. It would be appropriate to substitute flexible suction hose for EF couplers and pipe if the site has a history of significant settlement quantities, for example, on very deep sites.

Hose tied to outlet. Uphill path could create condensate trap

Well is connected without flexible hose

Hose tied up with air line and forming condensate trap

Flexible hose too short

Figure 7.15: Well Connection - Bad Examples

Multi-stage wells - flexible hose

Flexible hose correct length connections

Figure 7.16: Well Connection - Good Examples

7.7 Condensate Management (Dewatering)

LFG is produced in the landfill at temperatures higher than the ambient air and up to 100% humidity. This means that as it cools in the collection system, water condenses out of the gas and collects in the pipes. If there are any low spots in the gas system, condensate will form that could block the passage of gas and cause slugging. Slugging is the effect of condensate sloshing backwards and forwards as differential pressure builds across the liquid blockage, allowing gas to pass through only intermittently. This will manifest itself with variable suction and flow on the gas system. At worst, it will completely prevent extraction. It is therefore vital when designing a GCS that any low spots should be designed out and any that cannot be avoided should have a method of dewatering installed. Standing condensate can also form where the gas and condensate flow is in opposite directions. Pipe falls should be steeper where gas and condensate flow is opposite and gas velocities are elevated.

Landfill sites are also subject to large amounts of general and differential settlement. The GCS design should be such that it can cope with major settlement or is easy to modify when subject to it. In practice, the collection pipes should be laid to exaggerated falls to take into account the possibility of settlement. The falls should be greatest where the gas and condensate flow are in different directions and gas velocities are high. As a rule of thumb, a gas main installed on virgin ground should be laid to falls of at least 1:100. Collection pipes on the waste should aim to have falls of 1:25 to 1:50, depending on the direction of the gas flow. Where pipe is surface laid, falls may be lower, as it is easier to rectify any dips in the pipeline caused by settlement.

7.7.1 Dewatering at the Wellhead

Self or back dewatering wellheads (that is, where condensate flows back to the well) can be used where manifold or carrier main dewatering is impossible or in areas of dry waste, where conservation of moisture within the waste mass is essential. The wellheads generally incorporate a 3m - 6m section of pipe from the wellhead where the internal diameter is greater than the remainder of the well pipe. The increase in diameter locally decreases the velocity of the gas within the pipe allowing the condensate to fall back against the direction of flow into the well casing. If the connecting line falls away from the well the relative rise in the wellhead will accentuate the falls on the pipe.

Certain designs of in-line dewatering wellhead overcome this by removing a physical connection between the wellhead and the well casing. These incorporate a condensate trap and reservoir in the wellhead and also allow a carrier pipe to connect into and out of the wellhead. This style of wellhead is suited to sites where the landfill restoration contours are flat or undulating as they reduce the need for multiple additional dewatering points.

Where necessary, an ATEX rated pump (electric or air) can be incorporated into the well. The resulting condensate can be returned to the landfill by piping to a convenient leachate drain or the leachate drainage system.

Figure 7.17: Electric Pumped Wellhead

Figure 7.18: Air Pumped Wellhead

7.7.2 Condensate Drain Legs

These can be installed in carrier pipes and gas mains. They allow condensate to drain into the surrounding waste mass by gravity. Usually, they will also encourage water to drop out of the gas stream due to changes in gas velocity or direction. They have a condensate trap that will hold water against the maximum suction that can be applied. Usually they take the form of an upper and lower chamber with holes in the lower chamber to allow condensate to drain into the waste. They can only be installed in waste and the hole needs to be sealed with bentonite to stop surface water entering the waste mass. They are prone to problems caused by the surrounding waste becoming saturated with water and flooding the pot. Commonly, the seal is difficult to achieve and they tend to flood during periods of wet weather causing bio-fouling.

Where the wellhead is designed to allow condensate to flow back into the well, the design must allow for settlement.

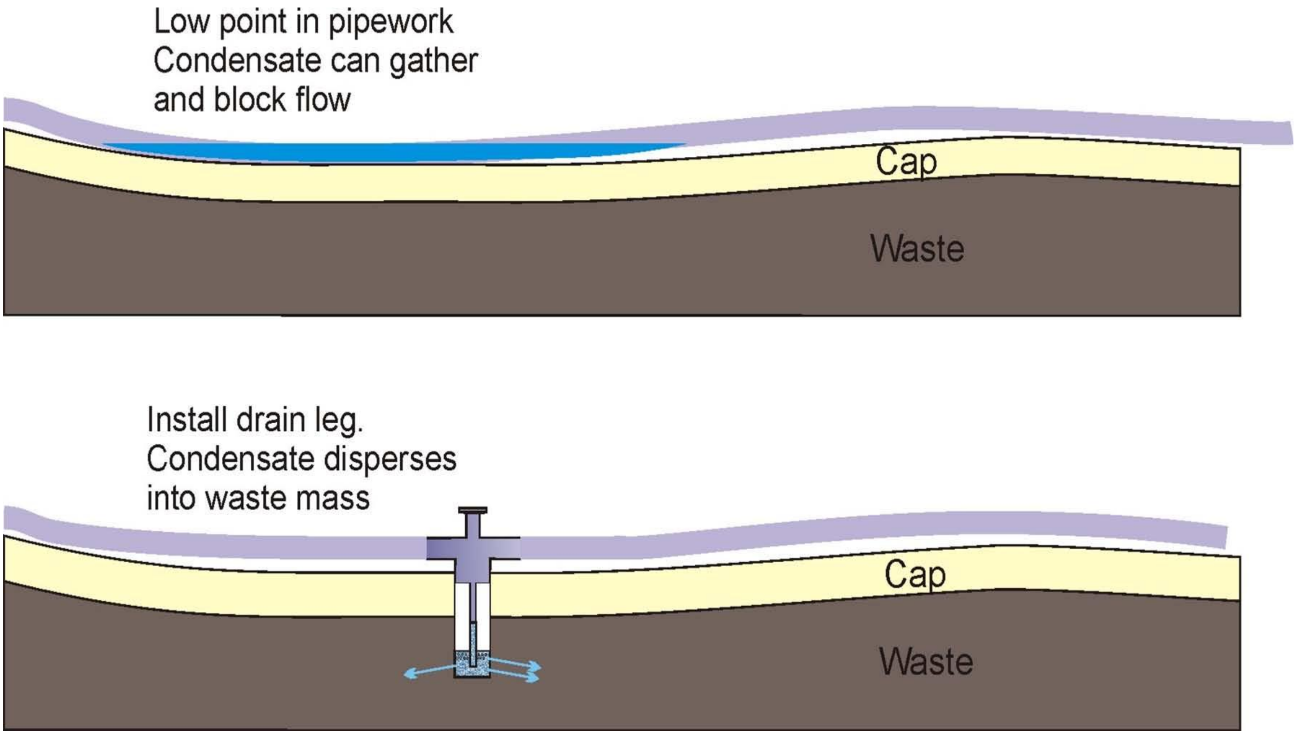


Figure 7.19: Drain Leg at Low Point

7.7.3 Pumped Condensate Knockout Pot

These can be installed in carrier pipes but most commonly in gas mains due to the high cost of the pot and pump. They comprise of one or more chambers with a pump installed to automatically remove any condensate collected. One of the most maintenance friendly designs has an inner chamber for the pump sealed from the outer gas chamber by a liquid seal. This allows the pump to be removed without having to isolate the knockout pot from the gas field. The pump can be electric or air driven or even mounted outside the knockout pot. Condensate may be returned to the landfill site via a gas well or into the leachate treatment system on site and it is good practice to monitor volumes of condensate returned to the landfill if this system is employed. The pump discharge line would normally be installed in MDPE pipe. It should be appropriately identifiable on site, rated for the required pressure and sized for the flow expected. Condensate lines may freeze in a severe winter therefore need to be protected from the cold through burying, lagging or the installation of trace heating systems.

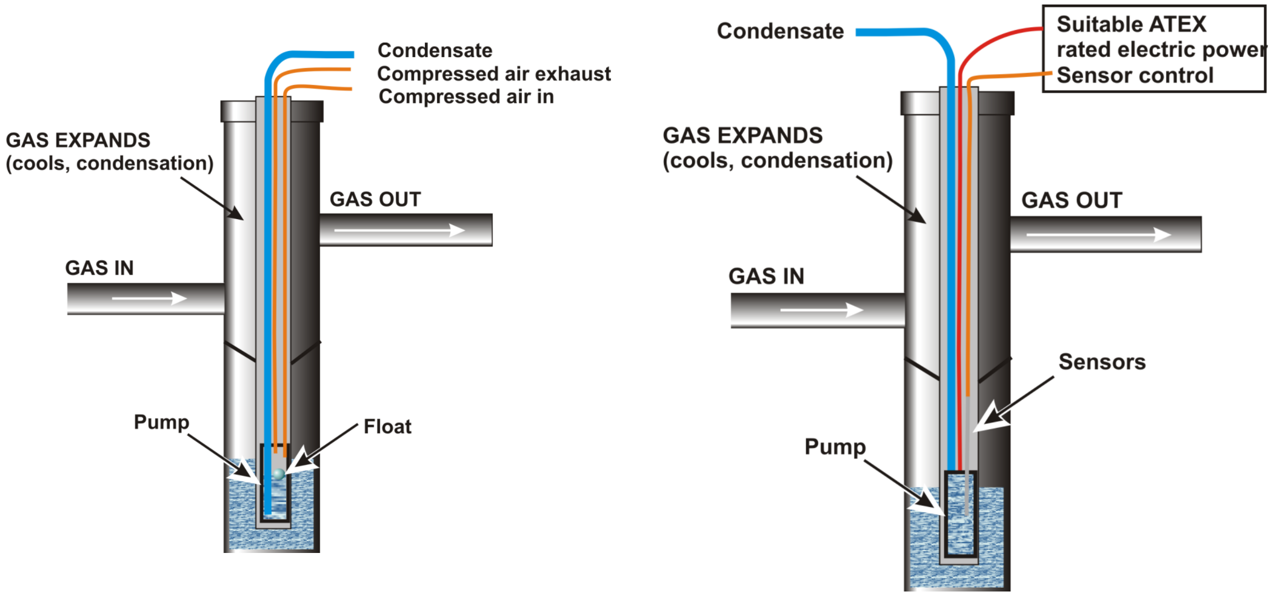


Figure 7.20: Examples of Pumped Knockout Pots

Passive condensate removal techniques, such as dewatering legs and draining to gas wells, are limited to the waste mass and may lead to bio-fouling and reduced porosity of the waste and, in the worst conditions, in very wet winters, even failure of the GCS.

As with gas wellheads, a flanged access / inspection port should be installed and designed to facilitate access into the system for maintenance (for example, pump servicing) while the remainder of the system remains live. The top blanking flange should also include LFG monitoring facilities and DSEAR signage as discussed in *7.5 Control*.

Condensate will drain into the external chamber because of the falls on either side of the knockout pot and by virtue of a decrease in velocity through the pot. The condensate will be removed by means of a pneumatic or electric pump.

Knockout pots should be located in a drilled or excavated sump to a depth to suit the installation and backfilled with a suitable bedding material. Similar to wellheads, knockout pots maybe protected by a chamber of a robust construction that is able to protect the pot against damage and unwanted access.

7.7.4 Condensate Discharge Lines

Condensate discharge lines are often constructed from 32 mm, 50 mm, 63 mm or 90 mm blue MDPE SDR11 (or other for similar pressure duty). As with collection mains, the pipework is normally joined using EF or fully automatic butt welding techniques. Joints should be kept to a minimum. Discharge lines will be routed from the pumped knockout pots to the chosen point of disposal, usually the nearest leachate sump, appropriate well or soak-away. In most instances, the condensate is returned to the waste mass in a controlled manner. If lines are surface laid, it is advisable to provide appropriate insulation to prevent freezing of the lines, which would prevent the system from operating effectively.

7.7.5 Air Compressor

Compressors to supply the pneumatic system with air are usually rotary vane or screw type fitted with a pressure regulator, an isolation valve and an hour's run meter. An isolation valve immediately downstream of the dryer is advisable.

Provision of a refrigerant dryer reduces the dew point of the compressed air to actively remove entrained liquid and provides the system with extra reliability. Inclusion of an air fuse to isolate the compressed air supply in the event of a sudden drop in pressure (for example, pipe failure) will prevent unnecessary operation.

Pressure systems must comply with the Pressure Systems Safety Regulations 2000.

It is preferable to have a separate air system for leachate and condensate from the system used for normal site operations.

Figure 7.21: Air Compressor with Refrigerant Dryer

7.8 Construction Quality Assurance (CQA)

To ensure that GCSs are installed as designed and specified, development of a CQA Plan in line with LFTGN03 is necessary. The requirements of the CQA Plan should be followed for all future GCS works (unless otherwise agreed with the regulator).

Construction activities should be monitored by a qualified supervisor, who should record evidence of conformance (for example, photographs, written logs). Third party CQA is considered mandatory by the Environment Agency when drilling or installing permanent sections of the gas collection system near to or through, or when welding to, an engineered cap. Similarly, when drilling within a reduced stand-off from the basal liner. Internal CQA is considered appropriate when installing or maintaining temporary or permanent gas control systems, where there is no potential for damage to the lining or capping systems.

The necessary detail contained within a CQA Plan will depend on the type of installation but should consider the following:

- Gas wells
- Materials
- Drill depth
- Pipe jointing
- Installation of pipe, gravel pack and seal
- Ring mains and collection pipework
- Positioning
- Jointing
- Gradients
- Leak testing
- Fabrications (for example, manifolds, knockout pots)
- Pressure test
- Completion file / Validation report
- Full or part-time CQA supervision on site for the duration of the works

7.8.1 The Different Types of Gas Collection System

System type	Definition
Sacrificial	Has an indefinable, but limited life expectancy (for example, installation in operational area)
	Will not involve intrusive installation work or be installed sub-surface
	May be constructed of temporary pipework and connections (for example, flexi-pipe and flex seal couplers)
Temporary	Is expected to be installed and removed within 6 months (for example, temporary solution during over tip or capping)
	Will not involve intrusive installation work or be installed sub-surface
	May be constructed of temporary pipework and connections (for example, flexi-pipe and flex seal couplers)
Semi-Permanent	Is anticipated to be an intermediate solution for periods > 6 months (for example, pre-permanent capping or restoration)
	Will potentially involve intrusive installation work (> 1 month) i.e. knockout pots, but pipework will be predominantly surface laid
	May not be constructed of temporary pipework or connections (for example, flexi-pipe and flex seal couplers) and must be constructed using polyethylene (PE) pipework and associated butt or EF welding techniques
Permanent	Is anticipated to be a long term installation (for example, years) and will be installed post final capping or restoration
	Will potentially involve intrusive installation work (> 1 month) for example, knockout pots, but pipework will be predominantly surface laid
	May not be constructed of temporary pipework or connections (for example, flexi-pipe and flex seal couplers) and must be constructed using polyethylene (PE) pipework and associated butt or EF welding techniques

Table 7-2 Different Types of Gas Collection System

7.8.2 CQA Validation

A report containing the relevant paperwork from the works should be issued post completion. Depending on the type of installation, this may include, but not be limited to, the following:

- drilling Logs
- CQA information including: dipped well depths, butt-fusion log sheets, EF log sheets, failed joint log sheets, pressure test certificates for fabrications, gas system, and air main
- as built drawings
- pressure test certificates (if undertaken)
- a takeover certificate
- relevant instruction / maintenance manuals (for example, air pumps)

The contractor will be required to carry out a full survey of any completed scheme. All pipeline routes, gas wells and other fabrications should be located and levels calculated. The survey should be referenced to the OS grid and datum.

The following drawings should be produced at a recognised scale to show the required information clearly.

- scheme layout showing the existing site survey and the general scheme layout
- gas scheme (as built), showing the scheme in its entirety, including all wellhead references and pipe sizes - differing pipe sizes should be indicated by different line styles or colours
- sections should be produced along all gas line routes showing ground level, pipe level, joint numbers, chainage, location of junctions and schematic details of wellheads and knockout pots
- accurate drawings should be produced for all individual fabricated components such as wellheads, manifolds, condensate dewatering legs, pumped condensate knockout pots and chambers. A separate drawing should be produced for each component stating the component reference number for identification

7.8.3 Commissioning

The CQA Plan should contain the commissioning plan for the GCS. The tests on commissioning will include, but not be limited to, the following:

- pressure or leak test of gas main
- pressure test of air system and condensate lines
- leak test of connecting lines
- dipping of gas wells

The majority of GCS construction will involve the extension of existing systems.

A copy of the complete commissioning forms should be included in the CQA Validation Report for the works.

7.8.4 Decommissioning

Accurate records of the temporary disconnection / removal must be maintained to ensure that balancing data is maintained appropriately.

7.8.5 Physical Decommissioning

The physical infrastructure, such as disused wells, must be maintained in the same way as an operational well.

Alternatively, it may be necessary to permanently decommission sections of the site's gas control system and/or replace gas extraction wells. This maybe as a result of an item reaching the end of its useful working life, or it may have become damaged and unserviceable or as a result of engineering works at the site. In all cases, it is essential that the elements to be decommissioned are done such that they cannot provide a migration pathway to allow gas to escape to atmosphere or leachate to leave the site or air to enter the waste mass (prevention of hot spots).

The steps listed below describe a method to ensure GCS decommissioning is carried out to the highest standards.

7.8.5.1 Pipework Decommissioning

Prior to the decommissioning of any part of the GCS, the section to be decommissioned needs to be correctly and clearly identified and completely isolated from the active gas extraction system. This can be achieved by isolation valves or temporary squeeze off followed by permanent EF end caps, where appropriate.

7.8.5.2 Squeeze off

- use a squeeze off tool to clamp the pipe or operate an isolation valve
- cut the pipework and install an EF end cap on the extraction system, see CQA Plan (if required)
- release the squeeze off tool once the EF weld has cooled for the correct amount of time
- remove the obsolete extraction pipework from the system

If the pipework cannot be completely removed (because it has been buried or over tipped) seal the projection from the surface with an EF end cap.

7.8.5.3 Gas Well Decommissioning / Replacement

Prior to the decommissioning of any part of the GCS, the section to be decommissioned needs to be correctly and clearly identified and completely isolated from the active gas extraction system. This can be achieved by isolation valves or temporary squeeze off followed by permanent EF end caps, where appropriate.

1. remove the well head
2. where possible, the well casing should be extracted using an excavator
3. backfill the void / well casing with sand (or similar free flowing material) to 3 metres below ground level
4. install a bentonite seal as follows:
    - pour a bag of dry bentonite to form a dry layer on top of the backfill
    - gradually fill the annulus with water (from a bowser or standpipe) and empty the remaining bentonite into this standing water until the annulus is full

Note: If it is not possible to remove the well casing, it should be cut down to ground level and an EF end cap fused onto the well casing.

Note: If a well has been over tipped and will be located below the level of the capping, no sealing actions are required.

7.8.5.4 Replacement Well

A replacement well should not be commissioned until the existing well has been decommissioned, in order to prevent air ingress through the waste and into the gas extraction system.

On completion, the DSEAR register will need to be updated and the well number altered on the drawings to identify that the gas well has been replaced.

7.9 Temporary GCS

Temporary GCSs will generally be used in large cells to provide gas control prior to the permanent system being installed, they may also be used for odour and migration control. Temporary systems will be installed to largely the same specification as permanent systems, however they will often utilise different types of abstraction well.

Selection of the type of temporary system will strongly depend upon the type of problem expected or encountered, layout of the area to be extracted, length of time the system will be required and length of time that the area will be uncapped or left until surcharging. Table 7-3 summarises the selection of the correct temporary system to be used in a number of circumstances.

Problem Area	Timescale Suggested	Temporary System
Greenhouse gas emissions	Active cell while still tipping	Horizontal Wells
Odour	Active cell while still tipping	Horizontal Wells
Odour	Active or completed cell. To be surcharged or capped in < 2 years	Push Wells
Odour	Active or completed cell. To be surcharged or capped in > 2 years	Temporary Gas Wells
Shallow seated migration	Active or completed cell.	Buried Push Wells
Shallow seated migration	Active or completed cell. To be surcharged or capped in < 2 years	Surface Push Wells
Shallow seated migration	Active or completed cell. To be surcharged or capped in > 2 years	Temporary Gas Wells
Migration at depth	Active or completed cell < 20 metres deep Any time period	Temporary Gas Wells

Table 7-3 Selection of Temporary LFG Control Measures

7.9.1 Settlement

Settlement occurs through the degradation and consolidation of waste. Waste is usually compacted by mechanical means when it is deposited in a landfill site. It will however settle further. The amount and rate at which it settles is affected by a number of factors.

Settlement occurs:

- as a function of waste depth, rate of fill and time
- due to the breakdown of waste through degradation
- following the production and removal of gas
- as a result of the removal of leachate through pumping
- as a result of subterranean fires

The above factors give rise to general and differential settlement at differing rates particularly within the first ten years after landfill. Historically, settlement was frequently under estimated. Differential settlement causes low spots to form in the collection pipe work, which then block with condensate. Condensate in pipes can cause wild pressure swings (called slugging) and therefore require remediation.

7.10 Historical Infrastructure

Landfill sites are likely to include both old and new infrastructure. Older installations may not have been installed to meet current guidance. (This may also include Gas Utilisation Plant.)

Where sections of the system fall significantly below best practice, they should be systematically upgraded. A risk based approach is sensible, balancing the cost of replacing infrastructure against the likely environmental consequences of leaving older infrastructure in place.

All future systems will be installed in line with best practice and in line with this and other LFG ICoPs, endorsed by the Environmental Services Association (ESA) and the regulatory bodies.

7.11 Timing of Installation

The timing for the installation of new sections of the GCS will largely depend on the specific design and geometry of the cell and the waste going into it. Generally, where a cell is to remain open for greater than six months, a temporary GCS will be installed. Timing of installation will depend on waste composition but will be as soon as necessary to control LFG as it is produced; this could be within the first few months. A permanent system will be installed as soon as practicable. Dividing a site into phases, and the phases into cells, can facilitate / expedite the installation of a temporary or permanent GCS.

8 Gas System Operation and Maintenance

Due to the heterogeneous nature of the waste in a landfill site, each well will produce gas at a different rate. Effective landfill gas (LFG) management can only be achieved if LFG is extracted at the optimum sustainable rate from the waste mass. This achieves two aims, to:

- minimise fugitive emissions and lateral migration
- maximise utilisation

A ‘flare led’ extraction philosophy, where the amount of gas extracted matches the generation rate and remains constant regardless of the level of utilisation (that is, the flare will operate to burn excess gas should an engine trip or de-rate) is the most effective way of achieving these aims.

An effective operating philosophy will have the following primary objectives:

- the stable operation of the gas extraction systems
- the reduction of incidence of over extraction and the potential for subterranean landfill fires
- the continuous measurement of the sustainable surplus gas available for utilisation
- the continuous evaluation of actual extraction rates versus predicted rates from modelling, (see *5 The Principles of Landfill Gas Modelling*).
- the ability to undertake LFG mass balance calculations for each site
- the optimisation of utilisation plant to ensure maximum availability and output whilst operating within specified emissions limits

8.1 Fundamental Principles of Balancing

In order to control LFG and prevent its release to atmosphere, LFG is positively abstracted from the landfill site by pulling it into a GCS under vacuum. This alters the composition of the gas as the gas abstracted under vacuum will contain differing levels of nitrogen and oxygen which come from air drawn into the site or collection system. Air is approximately 80% nitrogen (N_2) and 20% oxygen (O_2). The typical composition of LFG (under extraction) from a well-balanced gas system would comprise:

Gas	Typical% LFG
Methane	40 - 50%
Carbon Dioxide	30 - 40%
Nitrogen	< 20%
Oxygen	< 5%

Table 8-1: Typical LFG Composition

LFG is produced at different rates through the waste mass because waste is not homogeneous. LFG abstraction wells within the landfill site must be individually set up and operated (balanced) to maximise the sustainable quantity of gas abstracted from the site. Excessive suction applied to a gas well can draw excessive air in through the cap, infrastructure or sides of the site. The oxygen from this air is then used by aerobic microbes to produce carbon dioxide in preference to methane therefore reducing the calorific value of the gas and potentially turning the waste aerobic which can lead to subterranean landfill fires, (see *LFG ICoP: Management and Prevention of Sub-surface Fires*).

There are many misconceptions about LFG management and how balancing works. The diagrams in *Appendix C Balancing Examples* provide a simple guide to the fundamental principle of good gas management, which being the sustainable extraction of the LFG being produced.

8.2 Balancing Drivers

The following techniques are adopted by the industry in order to help achieve optimum levels of extraction at a gas well level. It is good practice to establish some operating parameters for the key balancing parameters (for example. bulk gases, key trace components and pressures). This provides some common guidance for the monitoring personnel and assists in the balancing decision process by providing a window of acceptable operation. An identified breach of these trigger levels will initiate a standard reaction such as opening or closing the well, or instigating further analysis.

8.2.1 Free Nitrogen

The balance gases are what make up the gas other than the major components of CH_4, CO_2 and O_2. In order to prevent fugitive LFG emissions from the site, it is necessary to maintain the site under negative pressure (vacuum/suction). It is therefore accepted that some air will be drawn into the site. Air comprises essentially 80% nitrogen and 20% oxygen (with other trace gases). Free nitrogen is an indication of how much air is being drawn directly into the waste mass, as it measures the level of oxygen being consumed by calculating the nitrogen left behind, that is ‘free’ of the oxygen it was with when it was air. The level of free nitrogen is calculated as follows:

%Free Nitrogen = %Balance – (4 x %Oxygen)

where

% Balance = 100% - (%Methane + %Carbon Dioxide + %Oxygen)

This gives an indication of excessive air ingress to the site through excessive vacuum. On a capped site, with good gas control, the level of free nitrogen would be expected to be below 20% (15% is often used as a control level). On a site with high or excessive air ingress the free nitrogen level could exceed 20% (this could pose a risk of sub-surface fire). On a site with extremely low air ingress (or insufficient suction) the free nitrogen would be less than 7.5%. To optimise LFG abstraction levels free nitrogen levels should be between 7.5% and 20% (or 15%).

However, where wells are being used for other purposes, such as odour or migration control or in reaction to a sub-surface fire, site specific control levels may be agreed and imposed. In the early stages of gas production, (from a new phase or cell) lower levels are used. Similarly, after site closure, alternative levels may also be set.

8.2.2 Ratios

If an area of the site has not reached stable methanogenic conditions or has been turned aerobic due to the over extraction of gas (and corresponding influx of air) the concentration of methane will drop below that of carbon dioxide. If this occurs, it would be expected that temperatures would rise (aerobic activity generating higher heat energy than anaerobic) which, in the presence of the oxygen, could create the correct conditions for combustion of some elements of the waste. Details of the causes, detection and control of sub-surface fires can be found in the *DSEAR ICoPs* and *LFG ICoP: Management and Prevention of Sub-surface Fires*

The normal ratio of CH_4 to CO_2 at point of production is 60/40 (expressed as 1.5:1) and this ratio is only changed with the introduction of atmospheric gases as a result of active extraction. If the ratio of CH_4 to CO_2 drops below 1:1 (that is, there is less CH_4 than CO_2) it is an indication that aerobic conditions are becoming prevalent in an area. Vacuum should be reduced immediately on a well approaching this ratio (if it had previously been anaerobic). Wells installed in fresh waste may show an elevated CO_2 ratio, as this is normal for the early stages of degradation. Care should be taken in these instances not to elevate free nitrogen levels.

8.2.3 Elevated Oxygen

An air leak into the collection system will be indicated by elevated levels of oxygen. Many LFG operators use a trigger level of 5% (or lower depending on the site requirements) at the gas well, where the technician would make a physical check of the system. If a minor problem is found, the technician should initiate a repair and re-check the reading. Where a defect is found that cannot be rectified at the time, the Defect Management System should be used, (*see 8.3 Defect Identification and Maintenance*). Very high levels of oxygen are to be avoided as oxygen and methane are explosive when mixed in the ratios of between one and four parts oxygen to one part methane (as measured by volume).

A high level of oxygen observed whilst balancing generally indicates that air is directly entering the GCS at the wellhead (or very close to it) or in the connecting pipework to a manifold. Other causes can be faulty sampling valves or tubes giving spurious readings.

Consideration must be given to the age of the waste and its potential to produce gas. Very old sites may be associated with very low levels of gas production and therefore high levels of oxygen. The following diagram identifies a process flow for the identification of oxygen ingress.

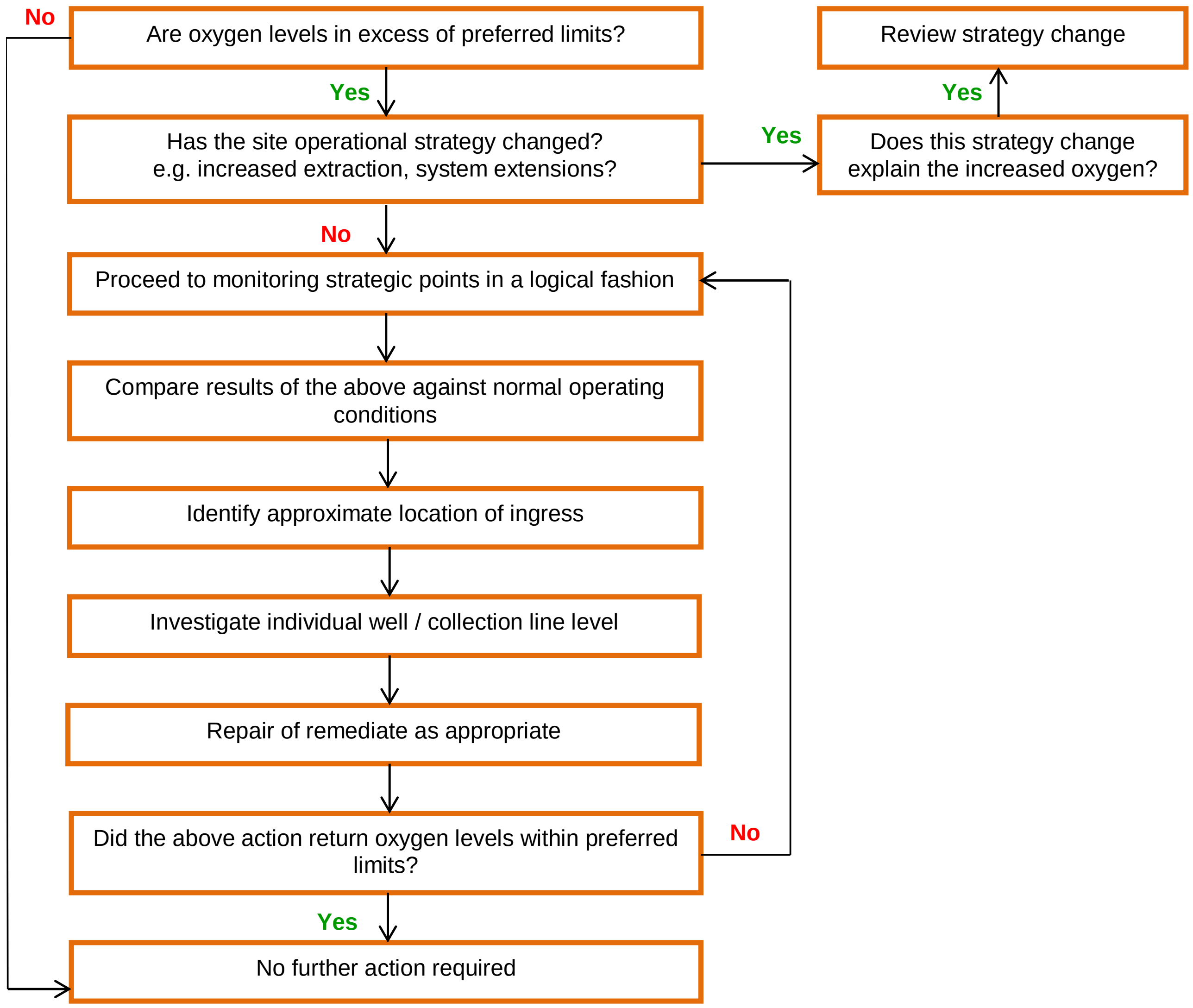


Figure 8.1: Identifying, Locating and Remedying Excessive Air Ingress

8.2.4 Elevated Carbon Monoxide

Carbon monoxide (CO) can be monitored in the LFG at individual gas wells during the gas balancing regime. CO is a gas produced as a by product of incomplete, or poor, combustion and is not thought to be produced as a result of chemical reactions within a landfill site during the degradation process. As such, elevated levels are normally attributed to thermal activity deep within the waste mass (commonly referred to as sub-surface fires), however as it is hard to determine whether or not low levels of CO monitored are residual from waste that was thermally active before disposal, or potential instrument error (high levels of hydrogen and hydrogen sulphide are known to affect the CO cell) a trigger limit of 100 ppm is often used.

Operators should adhere to the management techniques laid out in the ICoP ‘The Management and Prevention of Sub-surface Fires’ published in 2008 and endorsed by the Environment Agency.

If levels of CO exceed 100 ppm further investigation should be initiated which may require the suction to the gas well to be reduced, however if levels are recorded above 1,000 ppm the gas well should be turned off immediately. These readings should be confirmed by laboratory analysis.

8.2.5 Temperature

Temperature in a well can give an indication of anaerobic and aerobic activity. Low temperatures indicate little activity, perhaps, due to inert waste. Temperatures of 40 - 70 ^{o}C indicate normal anaerobic activity. Higher temperatures can indicate aerobic activity while extreme temperatures (over 80^{o}C) could indicate sub-surface fires. In rare circumstances, certain waste streams or the interaction of certain wastes can give rise to chemical reactions resulting in higher temperatures.

Temperature can be measured using a temperature dip meter. The temperature is measured at regular depth intervals, for example on a 50 metre well the temperature could be measured at 5 metre intervals. By combining readings from several adjacent wells, the data can be plotted to give a 3D profile of that section of the landfill.

8.2.6 Deviation from Standard Balancing

Occasionally, maintaining these parameters will not be achievable and in order to ensure the LFG is effectively controlled, conscious exceptions maybe adopted. Due to the potential consequences of breaches of certain parameters, extra vigilance should be maintained in the following circumstances:

- migration control
- odour control management of sub-surface fires
- migration and odour control may require extraction to be increased so that a number of these balancing drivers are temporarily over-ridden
- management of sub-surface fires may require extraction to be decreased or suspended

8.3 Defect Identification and Maintenance

A defect is defined as a failure or weakness in the containment or extraction systems that allows the passage of volumes of gas, air or water into or out of the system and therefore affects the systems performance. Defects can occur during the build process, through design issues (these should be picked up during the commissioning stage), through unplanned or differential settlement or through post-installation impact damage. Good design, installation, CQA and operational practice will minimise the potential for defects to occur.

Defect identification can occur through the following processes:

- visual observation
- odour identification
- measurement of gas escape with appropriate equipment
- identification from balancing data analysis

Defects can occur at any time during the operation of the site, therefore defect identification and repair is a continual and on-going process. The more frequent the defect sweeps and more rapid the defect repairs, then the better will be the gas management and therefore gas collection. It is good practice to have a Defect Management System.

Provided that defects are sought, detected and repaired on an on-going basis, significant losses of methane through the cap are unlikely. The same application of good gas management should enable a similar process to apply for most instances of lateral migration. It is possible to use methane entrained in the leachate to calculate losses in that route and in a similar manner the slippage through utilisation. Using all this easily measured and calculated data, under the auspices of good gas management and the 'whole gas' approach, should enable a good assessment of total gas capture to be generated for each site.

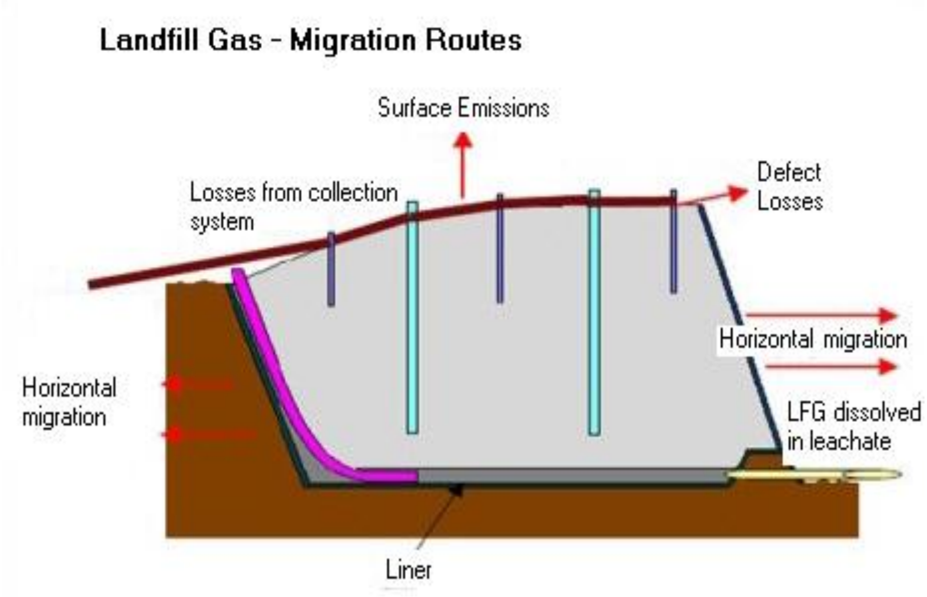


Figure 8.2: Migration Routes from a Landfill

8.4 Maintenance of Infrastructure

A landfill site is a hostile environment and regular inspection, maintenance or replacement of infrastructure is essential to ensure the safety and environmental compliance and efficiency of the site.

A risk based maintenance programme should be devised for each site taking into account the age, design and location of infrastructure. More sensitive sites may need more regular inspection.

This may be achieved by a desk based assessment of performance or by physical inspection, as appropriate.

8.4.1 Gas Well Condition Survey (GWCS)

Ideally, every well should be inspected every 12 months, to assure its physical integrity. Where wellheads are buried or inaccessible regular inspection may not be possible and inspection need only occur where evidence suggests a problem exists. Where it is known or expected that gas wells may have a limited life expectancy, the frequency of inspection should be increased. Where a desk based assessment has not highlighted any problems the inspection interval may be decreased.

8.4.1.1 Fixed Parameters

Each well will have a set of fixed parameters such as:

- installed date - the date the well was commissioned
- installation depth - the depth of the well when it was first installed
- depth of plain casing (as installed)
- depth of slotted casing. The length of the well from perforations to base
- x co-ordinate - the latitudinal geo co-ordinate
- y co-ordinate - the longitudinal geo co-ordinate
- z co-ordinate - the height above sea level
- stand-off from base - the distance between the base of the well and the base of the site

8.4.1.2 Regular Inspection

Where required, each well should be inspected, to assure its physical integrity. The following parameters should be recorded:

- condition of headworks
- connected - is the well connected to the gas main?
- dip to base - how deep the well is (this may change due to settlement or well collapse)
- dip to liquid - depth from top of well to liquid level
- depth of plain casing

8.4.1.3 Condition Analysis Report

Comparing the values from the Fixed Parameters and the Variable Parameters gives a Condition Analysis Report:

Well ID	Dip to base	% Original drilled depth	Dip to liquid	Effective slotted depth	% Original effective slotted depth	% Slotted below liquid level	Slotted depth vs installed depth	Comment / action taken
Unit	m	%	m	m	%	%	%	
ARPRL063	14.3	104.9%	7.3	-	-	-	-	
ARPRL151	14.9	104.3%	7.3	-	-	-	-	
ARPRL156	15.5	103.7%	8.0	-	-	-	-	Disconnected
ARPRL161	16.7	101.3%	8.6	-	-	-	-	Broken valve
ARPRL163	17.7	99.6%	8.9	-	-	-	-	
ARPRL164	16.2	97.4%	10.4	-	-	-	-	
ARPRL169	17.8	106.8%	11.4	-	-	-	-	
ARPRL170	15.6	98.1%	8.3	-	-	-	-	
ARPRL171	18.3	104.6%	8.8	-	-	-	-	
ARPRL183	18.1	104.6%	9.0	-	-	-	-	

Figure 8.3: Condition Analysis Report

8.4.1.4 Infrastructure Development

Record any activity that has taken place during the reporting period:

- number of wells drilled in period
- number of wells operational in period
- number of wells inactive in period
- number of wells decommissioned in period
- number of wells damaged by site activity
- number of wells disconnected as a result of site activity

8.4.1.5 Consequential Actions Plan

It is important to take action as a result of the survey for example, the following Action Plan is taken from a Gas Well Condition Survey:

1. Well replacement proposals. Well performance is under constant review, a proposal for well replacement will be submitted for completion Qtr 2/3 2010.
2. Well maintenance proposals. Well maintenance is on going and issues are dealt with as and when they arise by the technician on site or by a contractor under instruction. All wells with bentonite seals will undergo rehydration during Qtr 2 2010.
3. Leachate removal proposals. There are currently no new leachate removal proposals.
Other notes:
The integrity of the cap liner has been compromised around a gas well on Line D in association with a hotspot. We have installed 160 mm pods for liquid recirculation. The system will be connected and commissioned after the completion of the current soil works. Re-drilling will take place on identified gas wells in Qtr 2/3 2010; these wells will be confirmed following the 1st Qtr dipping programme and data analysis and a proposal submitted.

8.4.2 Staged Approach

In order to spread the workload over a longer period it may be possible to survey each phase of a landfill separately. However, this can mask the causes of problems, where one phase is influencing the results of another.

8.4.3 Asset Management (Planned Maintenance)

In order to ensure gas field infrastructure is regularly maintained, it is useful to keep a record of each asset and its parameters and service history. A computerised system gives flexibility and allows for better planning and control than a paper based system. It is easier to analyse the results and to spot historical trends.

8.4.4 General Inspections

Regular observation of the site can indicate potential issues such as settlement. Each well should be physically inspected by casual observation while traversing a site even if that well is not the subject of specific inspection.

A general inspection should be made each time a reading or balancing action occurs.

- look for damage to joints, flexible hoses and leachate lines
- listen for continuous running pumps and air leaks
- inspect joints
- clear vegetation
- look for evidence of settlement, for example a flexible hose that no longer reaches the ground

8.4.4.1 Internal Inspections

Above ground inspections can only tell part of the story. Dipping can determine the depth of the well and the level of liquid. Measuring the depth of the well can give an indication of sub-surface damage such a shearing (where a well collapses due to lateral movement of the waste mass).

Dipping diagram **Dipping - dip tape**

Figure 8.4: Dipping

8.4.4.2 Camera Surveys

Where the original depth of a well, or the start of the perforated section is unknown, a camera survey can help. A camera survey can also tell what has happened where the dipping gives a lesser depth than original installation records.

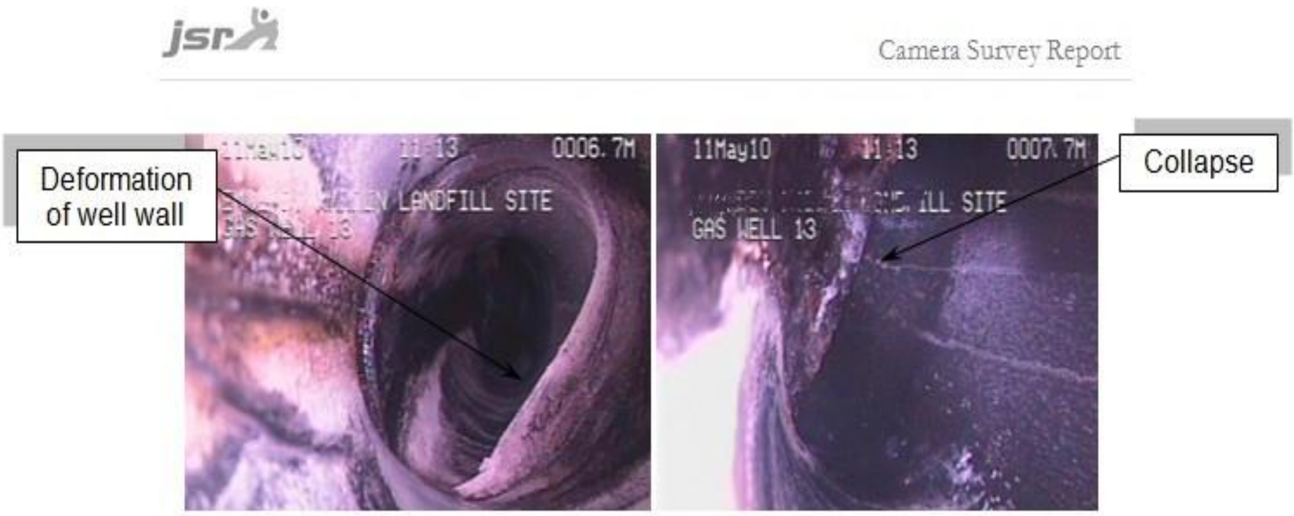


Figure 8.5: Camera Survey

8.4.4.3 De-silting

Where a well has become silted, it may be possible to use a slurry pump to flush the silt. Where leachate levels are not high enough, additional water may be required to flush the well. In any event, it is essential that the resulting spoil is treated with care and must not be allowed to come into contact with the cap (or personnel).

8.4.4.4 Bentonite Rehydration

In most cases, rainfall will ensure that bentonite seals remain hydrated. Where rainfall is low, (particularly during summer months) artificial hydration maybe required. Liquid may not be easily available on site. Where carried, water from drums or bowsers can be poured. Where not available, alternative natural sources can be used.

Bentonite seals can also be repaired by injecting slurry under pressure using an injection rig.

8.4.4.5 Boot Seals

In some cases a 'boot' or 'top hat' is installed around the well. This is a way of raising the cap membrane up around the well to provide a watertight seal. The seal should not be welded to the gas well, as movement must be allowed for. It is very difficult to achieve a gas tight seal and the main use is to prevent liquid ingress.

Boot seals should not be used as an alternative to bentonite seals. These seals can become damaged due to surface movement and general weathering.

Figure 8.6: Damaged Boot Seals

Repair can be achieved by installing concrete rings and sealing with bentonite or by excavating to below the cap and resealing with hydrated bentonite.

8.4.5 Pipework

Surface laid pipework is easier to inspect and maintain. Provided black MDPE pipe is used, the degradation from sunlight should be minimal. However, considerable expansion can be expected as temperature varies, and allowance must be made. The pipework must have adequate fall and dewatering pots installed at any low point.

Planning conditions may require that pipework is buried. In this case suitable trenching should be excavated, ensuring adequate falls are incorporated. The pipe will normally be buried at a depth to top of pipe of 300 mm to 500 mm. All buried permanent pipework should be surveyed and recorded. Tracer points may be installed so the route of the pipe can be seen above ground.

8.4.6 Re-profiling

Re-profiling of the carrier pipework maybe required where settlement or other landfill operations have occurred. The pipework should be reassessed to ensure sufficient fall and avoid low points. Where low points cannot be avoided, additional dewatering pots may be required.

8.4.7 Pressure Drop Analysis

By measuring the pressure at various points in the GCS you can detect blockages, condensate traps or collapsed pipework. The pressure drop should be small and consistent with the theoretical pressure drop calculations.

8.4.8 Trigger Breach Protocols

All sites should have a protocol for incidences where a site parameter is breached and what action to take depending on the severity of the breach (in terms of quality and quantity and length of time of breach). Where a measurement is made that exceeds the site parameter, the agreed protocol must be followed. This could mean reducing vacuum or turning off a well, while further investigation is made.

8.4.9 Electrical Resistivity Imaging

Electrical Resistivity Imaging (ERI) can be used to investigate the degree of saturation of the fill material and level of leachate within a landfill site. This enables the general characteristics of the cell to be determined to optimise leachate recirculation to enhance gas production and recovery.

ERI can be used to determine a suitable drilling strategy for the site. Electrical properties are among the most useful geophysical parameters in characterising earth materials.

Variations in electrical resistivity (or conductivity) typically correlate with variations in soil type, water saturation, fluid conductivity, porosity and permeability. ERI may be limited by a Linear Low Density Polyethylene (LLDPE) or HDPE cap.

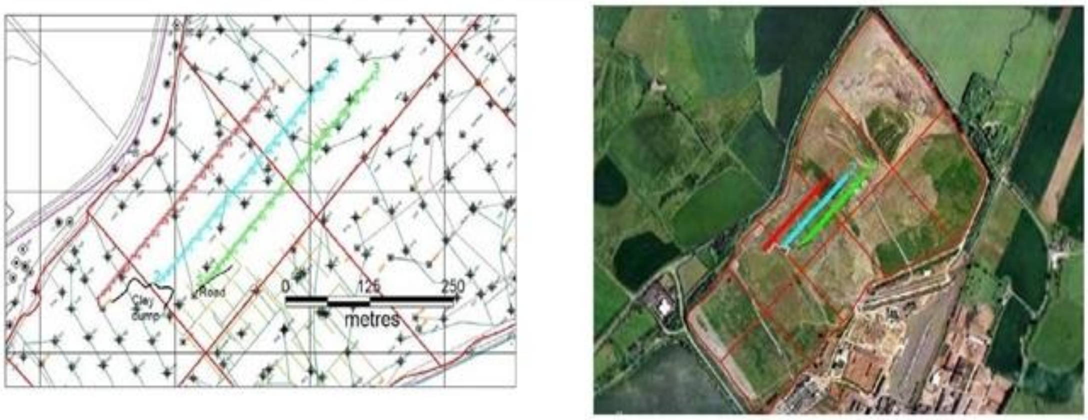


Figure 8.7: Line Plan

The modelled image is calculated by software and presented as colour scaled contour plots of changes in subsurface resistivity with depth.

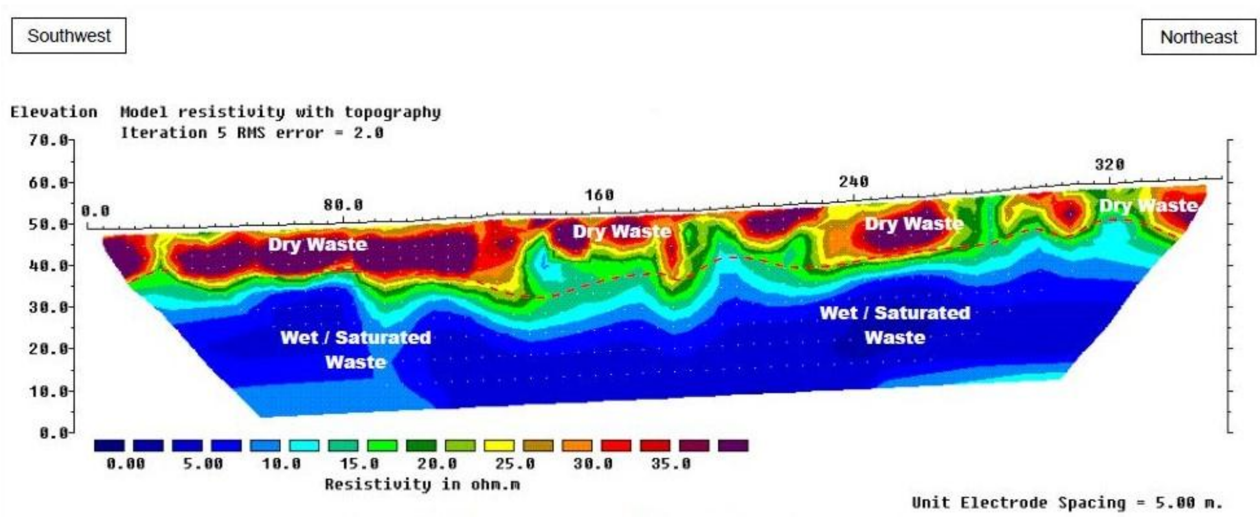


Figure 8.8: Resistivity Modelling

9 Data Collection, Management & Analysis

To fully determine a site's performance and to assist with fault identification and resolution, it is important that relevant data is collected accurately, stored securely and is readily available for analysis and reporting.

A fundamental requirement of good gas management is not only having the ability to collect the data but also to interpret it and draw appropriate conclusions. In its most simplistic form, you cannot react to lateral LFG migration unless you have measured such an incidence in a correctly located and installed monitoring borehole. However, simple possession of the data neither manages nor removes the risk. Identifying the source of the potential leak and then installing repairs or control measures to minimise its impact is the correct response. In the same manner, it is no good collecting gas balancing data if you don't interpret the results and then act upon the conclusions of that interpretation.

A monitoring and sampling plan will define what data is collected, the frequency, and sets out who is responsible and how it should be carried out. Accurate collection and interpretation of data is essential to demonstrate that the site's control measures are functioning correctly and are adequate and compliant with the site's permit. It also enables the site's conceptual gas production model to be verified and if necessary recalibrated.

9.1 Data Collection

Data from appropriate parameters should be collected on a regular basis and use a consistent approach and methodology. This will ensure that valuable information is collected and assist in overcoming any potential 'noise' associated with gathering data in the field. It is accepted that there are various degrees of accuracy attributed to various instruments, but identifying change or 'abnormal' operating_conditions allows for more thorough or reliable monitoring to be performed.

9.1.1 Gas Collection System Monitoring Requirements

The gas collection system (GCS) is the primary means of landfill gas control on the site. In order to ensure that gas abstraction is carried out in line with best practice, it is advised that the following requirements are carried out:

Location	Parameter	Frequency
Gas Plant inlet lines	CH_4, CO_2 , O_2, (balance gas), CO, suction, flow	Weekly
Manifold overall mix (composite)	CH_4, CO_2, O_2, (balance gas), CO, suction	Fortnightly
Gas Wells (at wellhead or manifold)	CH_4, CO_2, O_2, (balance gas), CO, suction	Monthly
Leachate Wells	CH_4, CO_2, O_2, (balance gas), CO, suction	Monthly
Gas Wells (at wellhead or manifold)	H_2S (using dedicated H_2S meter)	Six monthly
Gas Plant inlet lines	Trace Gas Analysis	Annually (unless stated otherwise in the Permit)

Table 9-1: Typical GCS Monitoring Requirements

It should be noted that the above frequencies and determinants may be above those specified in the site's permit.

Deviation from the suggested frequencies may be justified dependent on system design. Due to the difficulties in obtaining accurate and meaningful data, temperature and flow will not routinely be measured; however it may be measured in response to a suspected sub-surface landfill fire.

9.1.2 In-Waste Monitoring Points

In-waste monitoring points are not required in a well-managed landfill site and certainly not within the influence of operational gas wells as they increased the risk of sub-surface combustion resulting from potential air ingress. The detection of waste becoming anaerobic and therefore producing LFG in a new cell or in new waste can be carried out using leachate wells or FID (flame ionisation detector) walk over surveys.

In-waste boreholes (or leachate chambers where installed) may however be used to determine when or if LFG extraction should be installed in certain areas of the landfill. In this instance, if LFG is found in sufficient quantities and qualities, an LFG extraction system would be installed and the in-waste monitoring boreholes converted to extraction wells.

In-waste boreholes might also be used by an operator to confirm cross suction between wells, where it is not possible to prove cross suction through normal testing methods. If an in-waste borehole is installed, and gas is found, the well would generally be adopted into the LFG extraction system. If no gas is found and/or cross suction is proven, the well is in effect redundant and can be retained or removed as determined by the operator.

9.1.3 Perimeter Borehole Monitoring

In order to ensure that the GCS is adequately controlling the lateral migration of LFG from the site, the requirements detailed in the following table are suggested as a minimum for normal circumstances. Individual sites may require substantially different controls depending on the risk and the nature of receptor.

Location	Parameter	Frequency
Perimeter Borehole	Methane (CH_4)	Monthly
	Carbon Dioxide (CO_2)	Monthly
	Oxygen (O_2)	Monthly
	Differential Pressure	Monthly
	Atmospheric Pressure	Monthly

Table 9-2: Typical Perimeter Borehole Monitoring Requirements

9.1.4 Hydrogen Sulphide

Regular hydrogen sulphide (H_2S) sampling should be carried out in addition to routine balancing. The frequency of analysis will be determined by the site conditions. H_2S monitoring is required in order to identify any H_2S 'hotspots' from a health and safety perspective. A separate monitoring sweep using a dedicated H_2S meter, may be required as H_2S is often deliberately scrubbed out (using a filter) during normal GCS monitoring in order to eliminate any interference with the identification of other key parameters (for example, carbon monoxide).

9.1.5 Trace Gas Analysis

Trace gas analysis should be carried out annually from the overall gas mix coming from the landfill site. Other locations may also be required if specified in the site's permit or where there is a specific requirement. The trace gas analysis will be used in future reviews of the LFGRA for the site and to identify specific trends that may impact the operation or performance of the system (for example, generator performance).

Additional periodic trace gas analysis maybe required for operational reasons for the generator and should be stored and reused in any site analysis, see *LFTGN04*.

9.1.6 Carbon Monoxide Monitoring

When using handheld field analysers, operators should be aware of possible cross gas interference, (the presence of H_2S and hydrogen (H_2) can give erroneous CO readings). It is common place to use an H_2S filter during routine monitoring (see *8.2.4 Elevated Carbon Monoxide*).

9.1.7 Odour Monitoring

For some sites, odour monitoring may be required. This may be due to high levels of odorous compounds in the LFG and / or proximity to receptors. If required, this would be carried out as indicated in the site's Operations Plan or Working Plan. Where a higher level Odour Management Plan has been implemented it will supersede the Operations Plan.

9.1.8 Compound Readings

The treatment measures for the site are the primary means of LFG disposal, (see *11 Gas Treatment*). The requirements detailed in the following tables should be carried out as a minimum to ensure that the Gas Utilisation Plant is operated in line with its aims and objectives and that general good maintenance is being practised.

Parameter / Control system	Frequency	Units
Booster Hrs	Weekly	Hrs
Flare Hrs	Weekly	Hrs
Flare Operating Temperature (not recorded)	Continuous	Celsius
Flare Operating Temperature (recorded)	Weekly	Celsius
Methane (CH_4)	Weekly	% by vol
Carbon Dioxide (CO_2)	Weekly	% by vol
Oxygen (O_2)	Weekly	% by vol
Suction / Delivery Pressure	Weekly	mbar
Flow Rate	Weekly	m^3/hr
Valve Positions	Weekly	% open

Table 9-3: Typical Monitoring Frequencies and Parameters for the Gas Plant/Flare

Parameter / Control system	Frequency	Units
Output (recorded)	Weekly	kWh
Output (not recorded)	Weekly	kWh
Cumulative Output	Continuous	kWh
Hours Run	Weekly	Hrs

Delivery Pressure	Weekly	mbar
Flow Rate (where possible)	Weekly	m^3/hr
Gas Temperature (where possible)	Weekly	Celsius

Table 9-4: Typical Monitoring Frequencies and Parameters for Generators

9.1.9 Combustion Emission Monitoring

Emissions monitoring of the generator exhaust gases and flare emissions must be undertaken in accordance with the requirements of the site's permit and the regulatory applicable guidance. Should a gas plant / flare or generator fail an element of its annual (or quarterly) emissions test, a notification should be made to the regulator (in accordance with the site's permit) and a repeat test be carried out within six months. If it fails its repeat tests, it should be reviewed against the details within the site's LFGRA to assess whether or not they could cause excessive levels at any of the local receptors. Site specific monitoring to verify results may be advised to identify the true nature of any modelled excess.

9.1.10 Surface Emission Monitoring

Surface emissions monitoring is carried out to quantify methane emissions from restored or temporarily restored landfills to demonstrate appropriate management of LFG within the site and measure the integrity and performance of a capped area. The current *Environment Agency guidance (Landfill Technical Guidance Note 07 (LFTGN07))*, recommends monitoring methods to quantify these emissions via a two stage process. Requirements to monitor these emissions are set out within the site's permit.

Practical application of the monitoring required is dependent on the site development and restoration process and may lead to differences in approach from the idealised standards / approach currently set out in *LFTGN07*. While the guidance states that permanently capped areas should be monitored within 12 months of completion, changes at a site level in operational techniques (for example to control odour or minimise water ingress) may result in smaller areas of waste being capped at higher frequencies, rather than whole cells being capped in one event. This reflects the dynamic environment of a landfill surface, which changes with time until the site (or cell) fully enters its aftercare state. In such cases, it is often not practical to carry out meaningful surface emissions monitoring where the site is being actively and progressively restored. On a practical note, while stage 1 monitoring has benefit in confirming appropriate operation of the GCS and cap integrity, stage 2 flux box monitoring should be carried out on completion of the permanent capping for the phase as a whole.

Many landfill sites in the UK have been developed with a number of different engineering methods, from dilute and disperse to fully modern engineering techniques. Cap designs have equally evolved over time and are a key consideration when trying to quantify methane emissions. Sites containing a mix of cap designs will need to have limits assessed individually. Vegetation cover will also vary significantly from site to site, depending on the restoration requirements (regulated by local planning requirements) and the maturity of the area, which in itself may prohibit access.

In recognising the high standards of quality control and design of contemporary capping systems, it is proposed that once the initial stage 1 and 2 monitoring has been completed, the frequency of further monitoring maybe reduced to annually for stage 1 monitoring, with stage 2 verification monitoring being undertaken every 4 years thereafter.

For sites that closed under the permitting regime (PPC or EP regulations) and areas of capping that fall outside of the ‘modern engineering techniques’ but are within the modern permit site boundary, guidance set out within *LFTGN07* requires the operator to produce a LFG emissions review. This review requires a conceptual model to be drawn up and should identify relevant performance criteria against the risks they present. Each model should take into account the ‘as built’ cap design at the time of construction, the management techniques in the site to control the source term of LFG and the wider environmental impacts from a fully restored and often well established area. While assessment of the emissions performance of restored areas of a closed site is desirable, the practicalities of accessing and deploying surface techniques across a restored site surface (for example, resulting in the disturbance of well-established habitats) must be considered prior to undertaking any survey programme.

9.1.11 Other Environmental Monitoring

To ensure the GCS is operating and being operated correctly, various forms of monitoring will be undertaken at the perimeter of the site. This will include monitoring of perimeter boreholes and a general odour survey, but may also include routine FID monitoring, Jerome monitoring (H_2S), flux box surveys and diffusion tube monitoring.

9.2 Data Collection Quality Assurance (QA)

9.2.1 Handheld Instruments

Handheld equipment must be serviced and calibrated in line with the manufacturer’s recommendations to ensure that the data collected is accurate. It is also important that robust procedures are developed and that suitable training is given to employees regarding the calibration and use of field equipment.

Most analysers now used in the field have a built in memory to store the reading taken. It is important that this function is developed and used rigorously to cut down on human error. The manufacturers’ provide extensive training on the optimisation of such systems.

9.2.2 UKAS (United Kingdom Accreditation Service)

The UKAS is the sole national accreditation body recognised by the UK government to assess, against internationally agreed standards, organisations that provide certification, testing, inspection and calibration services.

Accreditation by UKAS demonstrates the competence, impartiality and performance capability of these evaluators. UKAS is a non-profit-distributing private company, limited by guarantee. UKAS is independent of government but is appointed as the national accreditation body by the Accreditation Regulations 2009 (SI No 3155/2009) and operates under a Memorandum of Understanding with the Government through the Secretary of State for Business, Innovation and Skills.

9.2.3 MCERTS

When selecting a company to carry out certain monitoring work, for example, combustion emission monitoring, it is important to ensure that the company, their personnel and equipment are all MCERTS accredited. MCERTS is the Environment Agency's Monitoring Certification Scheme. The scheme provides a framework within which environmental measurements can be made in accordance with the Environment Agency's quality requirements.

The scheme covers a range of monitoring, sampling and inspection activities including engine and flare emissions modelling. MCERTS promotes public confidence in monitoring data and provides industry with a proven framework for choosing monitoring systems and services that meet the Environment Agency's performance requirements.

MCERTS is operated on behalf of the Environment Agency by Sira. UKAS accredits Sira to undertake the product and personnel certification activities which underpin the MCERTS scheme.

9.3 Management

Good environmental data management is a critical element of the management of a site. Data needs to be readily available for both reporting to the regulator and detail analysis and trending. Data should therefore be stored such that it is:

- accurate – the data must relate clearly to the monitoring locations
- secure – daily back ups, duplicate records etc.
- accessible – by all who may need it
- healthy – data must be validated to check for corruption, duplication

9.3.1 Storage

The most common means of data storage is a database. These can be either off the shelf environmental databases, such as MonitorPro, or bespoke systems developed by the operator. Storage systems should allow data to be stored securely but yet provide unhindered access. Data should be on a central server which is automatically backed up on a daily basis to a remote system.

Paper based records are acceptable where the process is rigorous. Originals should be retained for the lifetime of a site and copies held off-site. Automatic scanning of paper records into a database can help prevent data transcription errors.

9.3.2 Systems

Systems should be developed to ensure that data is imported into the database from the field equipment automatically to avoid the need for manual data entry as this can add further potential for human error. A system of manual / automatic data screening tools should be used at the imputing stage to provide a ‘first pass’ screen of the data, primarily to detect errors, but also as a management tool to provide feedback to the monitoring personnel and management regarding issues such as over extraction, high CO etc.

9.3.3 Quality Assurance of Stored Data

Exception analysis software can highlight anomalies and operators should consider reacting where data suggests a spike in an otherwise smooth trend. Where databases are used many complex data checks can be undertaken as part of a validation exercise. Such programmes can be written to look for duplicate data, corruption, etc.

It is suggested that such exercises are undertaken regularly to avoid incorrect data being reported to the regulating body.

9.3.4 Key Performance Indicators (KPI)

With such a vast amount of data being stored it is possible to use certain parameters as KPIs to drive the performance of the team managing the LFG on the site.

9.4 Trending and Analysis

The analysis of LFG and other site data (for example, leachate) needs to be undertaken both proactively and reactively. Proactive data analysis should be a priority and should be scheduled as a specific and regular task for completion. Routine analysis of data provides an understanding of the condition of the site and more particularly of the waste mass. Carefully monitoring key LFG parameters such as bulk gas components, liquid levels and the condition of the gas collection infrastructure (wells and pipework), and more specifically tracking changes that may or may not be occurring, can help define a strategy for maximising gas capture for environmental control and utilisation. It will also help determine appropriate maintenance strategies for the site.

It is recognised that different organisations and individuals will have different analysis capabilities, but this should not prevent it from being carried out. The depth of analysis can vary greatly depending on the objective. It can be completed while out on the gas field at a gas well level, at strategic locations around the field or it can be applied through the use of statistics, specialist modelling tools or data analysis software. It is important that effective training is delivered to the people expected to undertake the analysis. It is also important that appropriate tools are provided to make analysis and the interpretation of results as easy and as efficient as possible.

In an ideal world, proactive analysis would be sufficient to inform the operator of the condition of its infrastructure. Hypothetically, ensuring the uninterrupted and optimal operation of an ‘ideal gas system’ should in turn prevent the uncontrolled release of emissions.

However, the reality of the landfill environment dictates that the installation and operation of a perfect LFG extraction system is impossible. Performance is affected by site engineering, compaction rates, liquids, site operations, settlement and many other factors within and outside the control of the operator. All of these aspects are dynamic, and this influences the extent of their impact on gas production and gas management. By creating an understanding of the site through routine analysis, any deviation from the ‘norm’ can be investigated and in many cases anticipated. Analysis undertaken on a purely reactive basis leaves the operator vulnerable. When an emergency situation requires a swift resolution, the lack of historical analysis can hinder a timely identification of a suitable solution.

Despite best efforts of many operators in completing proactive analysis, most will have experienced situations that dictate the need for reactive analysis especially in emergency or high risk situations. It is therefore important that operators of LFG systems are prepared for such events.

To assist with analysis, operators of gas systems should be familiar with the various approaches and tools that are commonly used. Below is a non-exhaustive list of the techniques and tools commonly used by the industry to inform of system condition and to problem solve in the field.

9.4.1 Gas Production Rates vs. Gas Models

This is a very high level approach to analysis. Despite the limitations associated with gas modelling, (see *5 The Principles of Landfill Gas Modelling*), it is good practice to compare actual extraction rates against those predicted in a LFG forecast model (for example, GasSim). Any major discrepancy should be investigated and understood. Certain models can be readily broken down into component areas of site and comparison undertaken on a cell by cell / phase by phase basis.

The results obtained from this comparison will often drive further more informed analysis at a more micro level.

9.4.2 Trending

Trending of LFG data can provide an early warning of impending problems, such as blockages as well as inform of opportunity. The obvious parameters to trend are the bulk LFG components such as methane and oxygen as well as other key operating parameters such as flow or vacuum. Regular collection of data and its effective storage, for example in an online database, is critical to allow meaningful trending to be achieved. Large amounts of data taken over long periods are likely to provide more accurate trends. There are many aspects of both the natural environment (such as seasonal trends) and aspects of landfill management (such as capping and leachate management) that can influence LFG production and collection rates. It is therefore important to understand the possible impact of these factors on any trends. This type of analysis can be easily achieved using spreadsheets or similar software. Often databases have in built trending tools.

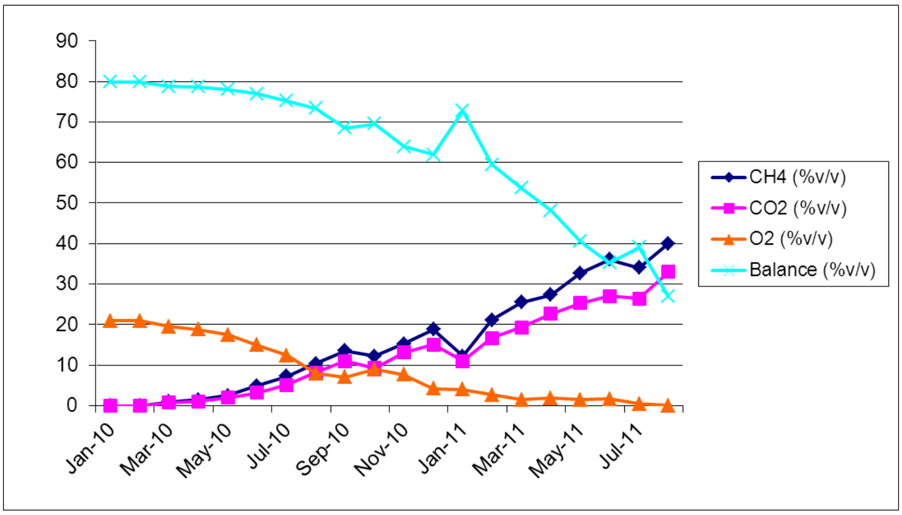


Figure 9.1: Example of Bulk Operating Parameters over an Extended Period (2 years)

9.4.3 Database Tools

Most computer databases have in built analysis tools or the facility to easily export data into other packages (such as Excel). There are numerous ‘off the shelf’ products that are marketed by environmental specialists and are aimed specifically at the LFG market. Alternatively, there are other products that can be adapted to the market and it is not uncommon for businesses to develop their own database that can grow around the specific needs or preferences of the business. Computer databases can also track site monitoring activity to ensure that minimum requirements, as prescribed by either the regulator or the operator, are undertaken.

9.4.4 Filtering

Most databases have the facility to filter data to make it easy to identify certain outliers or exceedances such as elevated oxygen or high vacuum. More advanced examples of filtering incorporate the use of Pivot tables that can help indicate how wells or parts of sites behave under certain influences.

9.4.5 Image Mapping

Image maps are becoming an increasingly common tool available in many specialist LFG databases. The images are produced by allocating data to specific co-ordinates across a site, for example, the level of methane at a gas well. By inputting data collected, for example, during a single monitoring session, the image mapping software can provide a picture of the condition of the site. This very visual tool makes interpretation of data very easy.

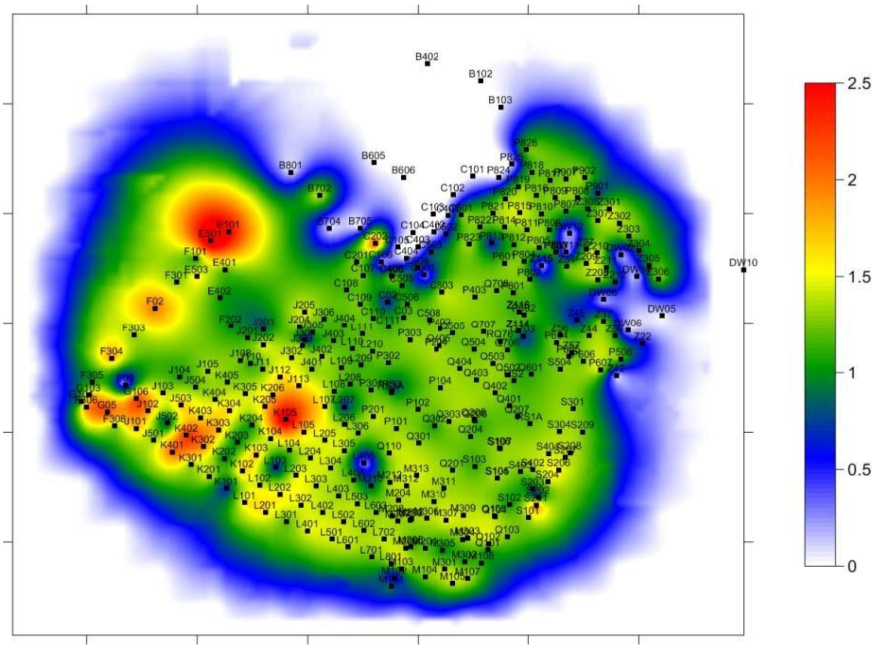


Figure 9.2: Example of Image Map Showing Ratio of CH_4:CO_2 across a Site

9.4.6 Site Plans in Analysis

Maintaining up-to-date site plans of the GCS is critical in allowing effective analysis. Site plans should include details of pipework and well location and sizing along with the position of key fabrications such as knockout pots and manifolds. Inclusion of this level of detail allows completion of Zone of Influence (ZOI) surveys and pressure drop reviews. ZOI drawings use assumptions on the radial influence of vacuum of different types and sizes of well. From these drawings analysis can be undertaken to identify any gaps in the system. Where gaps are identified on the plan, these need to either be justified or addressed. It should be remembered that this type of analysis is based on hypothetical performances relating to the influence of wells, and consideration needs to be given to specific site conditions and requirements. The approach, however, does demonstrate the application of good practice.

Figure 9.3: Example of Zone of Influence Drawing

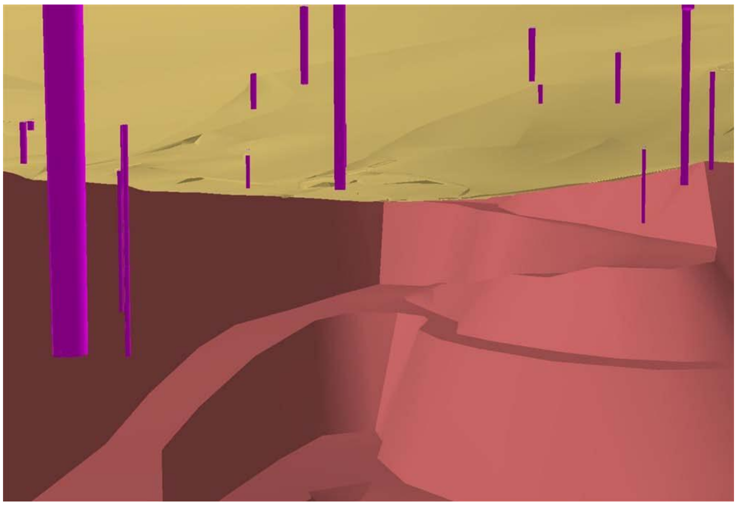


Figure 9.4: Example of 3D Modelling Output

The availability of an up-to-date LFG system plan also allows pressure drop reviews to be undertaken, where theoretical system performance can be checked against measured results. Improvements in IT and the availability of software also now allows for 3D modelling of sites to be readily completed and this will provide a clearer picture not only of lateral gas wells coverage, but an idea of the vertical effective depth and leachate levels.

9.4.7 Gas Well Condition Surveys

As the effectiveness of any gas well installed in waste is known to deteriorate over time (due to silting, flooding, collapse etc.) it is important that the internal condition of the well is inspected at regular intervals. Where wells can be easily accessed, this can be achieved through dipping with a dip meter, rodding with drain rods or increasingly through the use of specialist cameras. The condition should then be compared against the original installation details and depending on the drivers (for example, is there migration or unacceptable gas release?) a decision should be made as to whether any action is appropriate. This could be in the form of de-silting, installation of a down well pump or replacement of the well.

9.4.8 Reporting

The reporting requirements for LFG management data, including performance data obtained from engines and flares is set out in the Environment Agency's *Technical Guidance Notes LFTGN03 - LFTGN08*. The key reporting tasks are broken down into the following types of reporting:

- notification / exception reports
- routine data reports
- compliance reports
- assessment / analytical reports

9.4.9 Notification/Exception Reports

Notification or exception reports are the primary means by which action requirements are identified to interested parties such as field engineers, site operating personnel or the Environment Agency. This would typically be an exceedance of a predefined control or trigger limit within the data being obtained. An example of this would be the common practice of establishing the normal operating parameters for gas field balancing.

Exceedance of these predefined limits will trigger an investigation or response as set out in the gas management plan, and depending on the severity, require further reporting, notifications, or activities to the regulator.

Key information within the notification reports should include

- date and time of report issue, together with date and time of the exceedance
- names and contact details
- actions required or implemented
- tabulated and or time series data
- any other relevant information

Where longer term action strategies are implemented or agreed, it may be necessary to develop alternative on going reporting of issues

9.4.10 Routine Data Reporting

Routine data reports should enable the data to be viewed and transferred both internally and externally and may include raw data, data summaries, quality control checks, notification requirements and remedial actions taken or required.

These reports range from simple notebook records, through to data logging reports to export reports from databases and spreadsheets. Due to the risk of transcription errors, it is best practice to record as much data as physically possible using electronic logging equipment that is integrated into most modern field equipment.

9.4.11 Compliance Reports

There are a variety of compliance reports which may be required by the regulator which are set out within the site's permit, and will be dependent upon the risk category for the site. These include monthly data submissions and quarterly or annual interpretive reports.

9.4.12 Assessment / Analytical Reports

The performance of the system needs to be compared periodically to the assumptions made in both the system designs and any computer models, in order that variations can be identified and addressed.

10 Whole Site Gas Collection Efficiency

Section 5.7, Limitations of Modelling, describes the importance of measuring actual LFG collection and using the data collected to refine and verify gas prediction models. This ensures that the inherent uncertainties in any gas model are reduced and minimised as far as is practicable through the use of real data and continual fine tuning. This section describes the principle of Whole Site Gas Collection Efficiency (WSGCE) and illustrates how it can be easily calculated, major sources of loss of collection can be identified and model verifications can be undertaken. WSGCE cannot directly predict the volume of gas lost through cap permeation or open area venting, however in many instances it can be used to show losses through activities and stability of collection, both of which are fundamental in understanding if gas collection is being optimised.

Based on the above, with simple measurement and operational data, it is possible to construct simple models that show trends and features which are directly attributed to the activities on the site and the success in maximising LFG collection.

10.1 Pathways of Gas Release

LFG is generated from the decomposition of waste in the absence of oxygen the detail of which is discussed elsewhere in this ICoP. Where LFG is not efficiently collected, its residence time in the waste mass will generally be short, before it finds the easiest routes of escape. These escape routes will comprise;

- Permeation through capped or temporary capped areas,
- Venting from uncapped areas or cap defects, and
- Lateral migration.

LFG emerging to and through any oxygenated surface will be to some extent oxidised and for the purposes of this method of collection efficiency, are grouped in the permeation, migration and venting routes described above. If WSGCE is high, permeation and venting losses will be effectively minimised, but, if necessary, can be measured through surface emission and perimeter borehole quality and quantity monitoring.

10.2 Underpinning Assumptions

For WSGCE to be used as an effective method of measurement of success in gas collection, a number of assumptions of operational practice and standards need to be understood and applied. These are:

- Capping and temporary capping systems regularly swept for defects (for example, using a FID) and all significant defects are identified and repaired as soon as reasonably practicable
- Gas collection systems are generally airtight and are maintained as such, (see *8.3 Defect Identification and Maintenance*)
- Activities on the site that directly impact on the gas collection system (such as damage from moving vehicles, temporary well decommissioning for capping etc.) are recorded and data collection frequency and components is sufficient to show before and after LFG flows and concentrations

- LFG field balancing includes flow and LFG component concentrations (CH_4, CO_2, O_2 at least) at the main feeds into the treatment infrastructure prior to the balancing event and post the balancing event. Other quality and quantity measurements can be undertaken at the wellhead, branch or manifold, which can be used to understand the performance of elements of a gas field and could be useful in tracking down priority areas of underperformance
- Other elements of good gas management balancing are undertaken as defined in this document
- LFG flows are normalised to a consistent methane concentration in any analysis
- Combustion or destruction infrastructure for the collected gas is not a limitation on the ability to extract gas from the gas collection system. If it is, then any analysis would need to account for these other impacts.

10.3 Principles of the Application of WSGCE

WSGCE is seeking to establish, by the simple analysis of data collected in the field, where gas collection losses are occurring. Simple theoretical examples are set out below; these real examples are presented and analysed to show how the various elements might be identified. For example, WSGCE might identify loss of collection through wells being turned off to allow capping.

Figure 10.1 below shows a simple example showing actual gas collected and identifies where the volume of gas collection is climbing over the period 1 to 7, then declines and recovers through week 8 to 12 and then continues to show increased LFG capture thereafter. WSGCE is interested in two aspects, the rate of increase in gas collection and the 'event losses'.

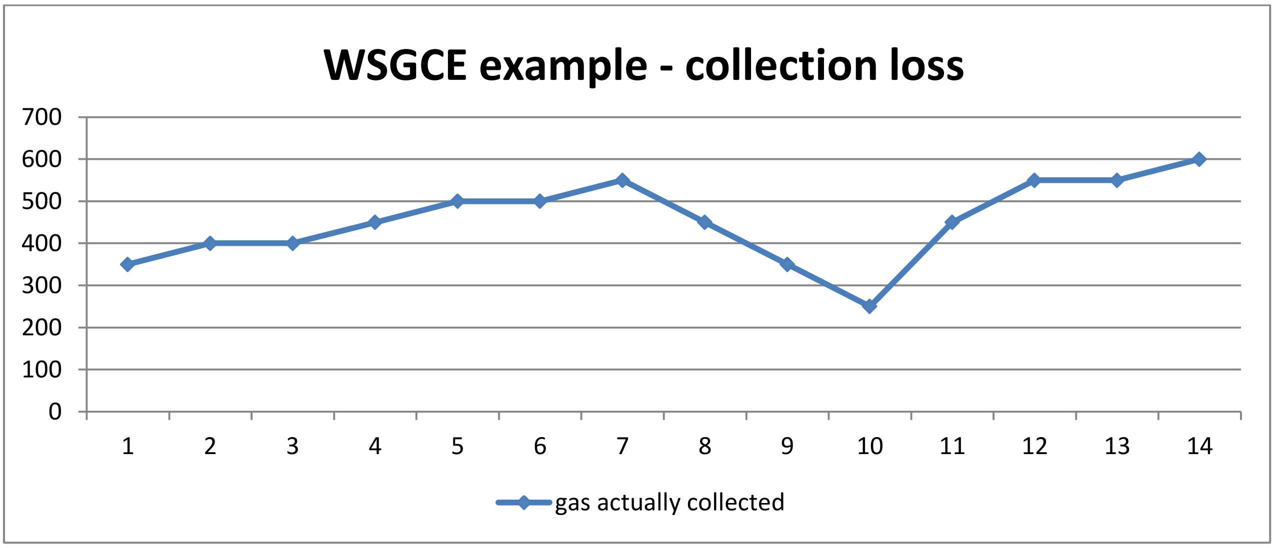


Figure 10.1: Example of Collection Loss

Considering the 'event' shown in the graph, it is quite clear that prior to the event gas capture was 550 m^3/hr, after the event recovered to 550m^3/hr and then 600m^3/hr. It is very unlikely that the site reduced its production of LFG in a manner that would reflect the above graph and if, for instance, part of the site had become aerobic and methane concentrations had reduced, then the LFG quality measurement would clearly identify the area of the site and the period and extent of any aerobic process. It is more likely that an event took place, such as:

- disconnection of part of the gas system to allow for capping operations, or
- damage to a main gas pipe through impact or settlement, or
- major gas field maintenance requiring system isolation.

If such an event could be avoided, the gas capture curve would look like the red line shown in Figure 10.2.

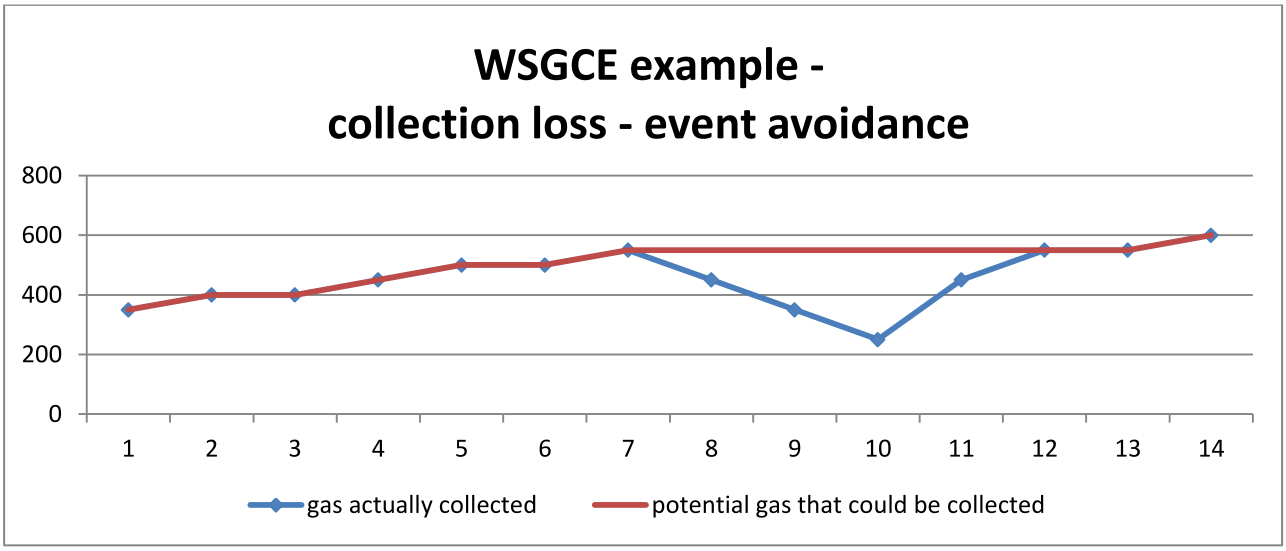


Figure 10.2: Example of Collection Loss - Avoidance

If the event could be avoided in the manner shown, the area of the graph trapped between the two lines would be directly proportional to the volume of LFG that would be not have been lost during the period. If the periods represented weeks, then simply adding up the hours of operation at each flow rate between the curves would provide a reasonable estimate of the potential LFG loss, for example, Week 7-8 (168 hours) by a gas collection difference of 50m^3/hr on average, would give 8,400 m^3 of LFG lost from collection in that period. If the event had been completely avoided, the volume of gas lost to collection would amount to 126,000 m^3 of LFG, or 63,000 m^3 of methane (assuming LFG is 50% methane).

Understanding this allows the operator to better plan and design its systems and response processes to prevent or minimise the impact of such operations. Where such events are expected and cannot be avoided, it would therefore be possible to advise regulators in advance of the likely impact of the event and the expected loss of gas from collection.

Considering the other potential scenario (an increase in the amount of gas collected), the question arises: is the collection increase a result of an increase in the production of gas or an increase in gas collection efficiency? If the former, the operator would seek to increase efforts to collect gas whilst carefully monitoring the gas concentrations. If gas concentrations indicate gas resource depletion then the rate of extraction would be reduced until stable collection is achieved. If however methane levels do not decline below acceptable levels as the rate of gas collected increases, then it is most likely that the collection efficiency was too low. It is likely in this second instance that the methane concentrations would be elevated beyond those normally expected for active gas extraction. An example of a gas curve that might indicate the above example is shown in Figure 10.3.

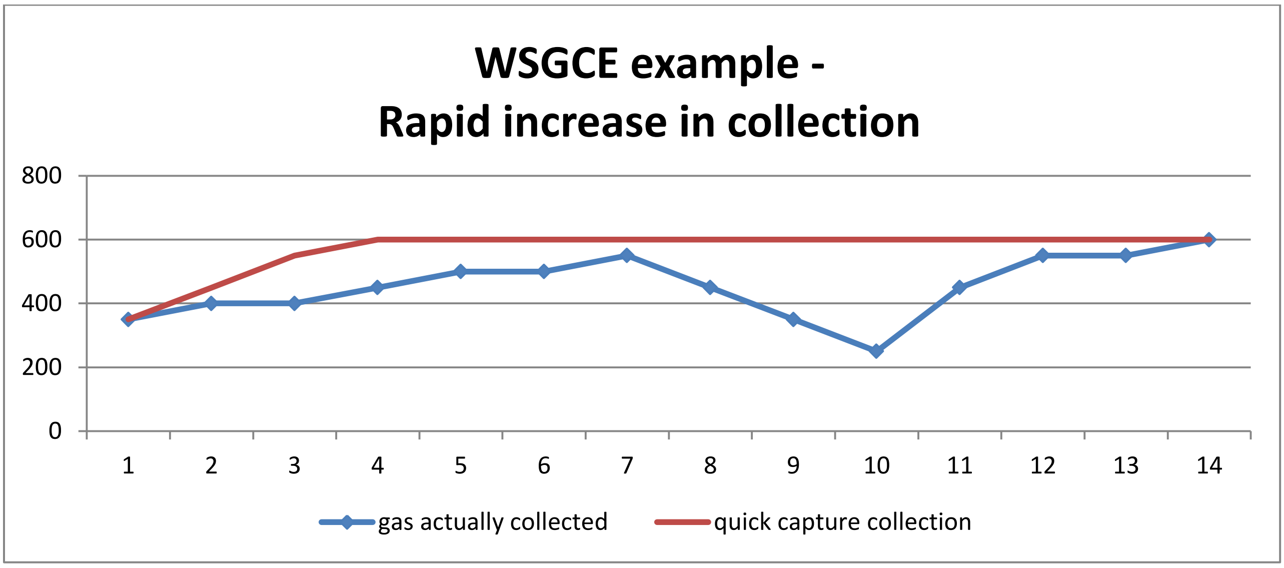


Figure 10.3: Example of Rapid Increase in Collection

Again, LFG collection losses would be estimated through the area of the graph between the two curves and the operator can improve their procedures and systems such as to try to achieve the brown line.

Another example of potential loss of collection is 'flutter' in the volumes of LFG collection which may be indicative of poor collection methodology or poor system and containment design. In the example below (*Figure 10.4*) it is clear that the rate of collection of LFG shown in the blue line flutters high and low whereas a more 'stable' gas system would have fewer swings between the periodic balancing events.

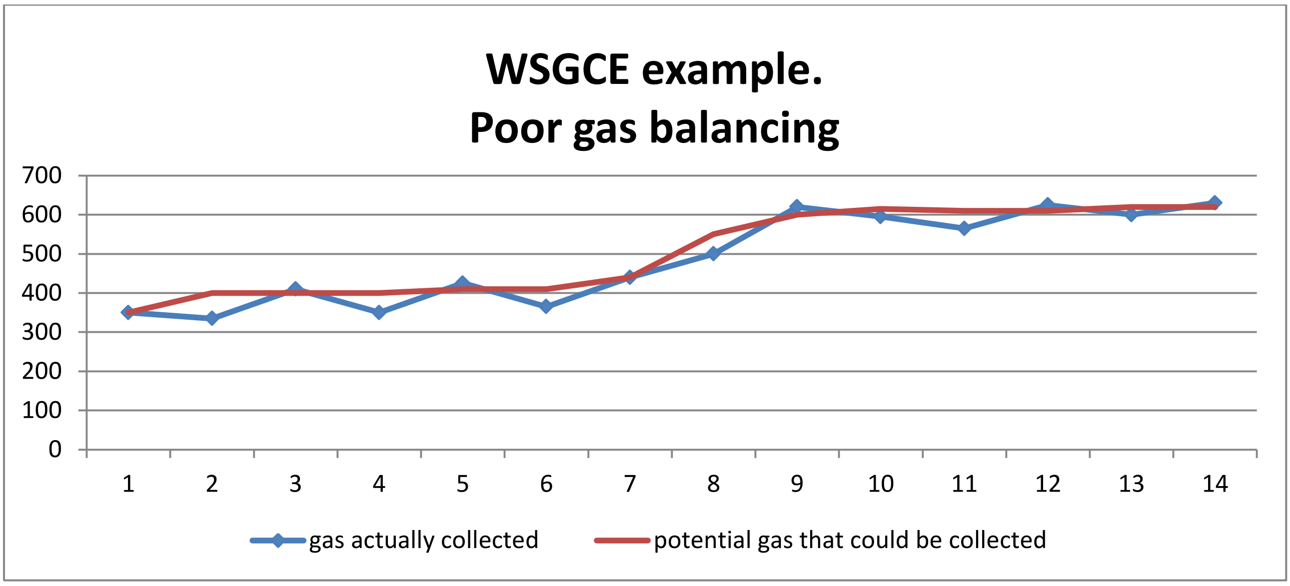


Figure 10.4: Example of Poor Gas Balancing

In this instance, the LFG collected may be less than ideal (ideal being suggested by the red line) which leads to loss of gas collected. A real example of this is shown in *Figure 10.5* and *Figure 10.6*.

10.3.1 Example Site 1 (Real Data from a Real Site)

There is uplift in gross LFG collected at point 'A' without a resultant drop in methane and carbon dioxide concentration. This would indicate that LFG was not being removed at a rate from the landfill site at an equivalent to its natural production, leading to an enrichment of the methane concentrations (50-55%).

At point B there is a reduction in the methane concentration to around 45% by volume and CO_2 levels are relatively constant. Extraction volumes at point B are steady, suggesting that during the period between point A and point B sufficient LFG has been extracted to remove any temporary reservoir of LFG and that after point B, with relatively consistent methane, collection is more closely matching production. As there is a drop in methane concentration and volume, it is also likely that proportions of other gases may have increased and monitoring of gas concentrations will provide any evidence of this. If oxygen concentrations had increased, it may be necessary to repair or remove the source of this additional ingress, to prevent oxygen being drawn into the landfill.

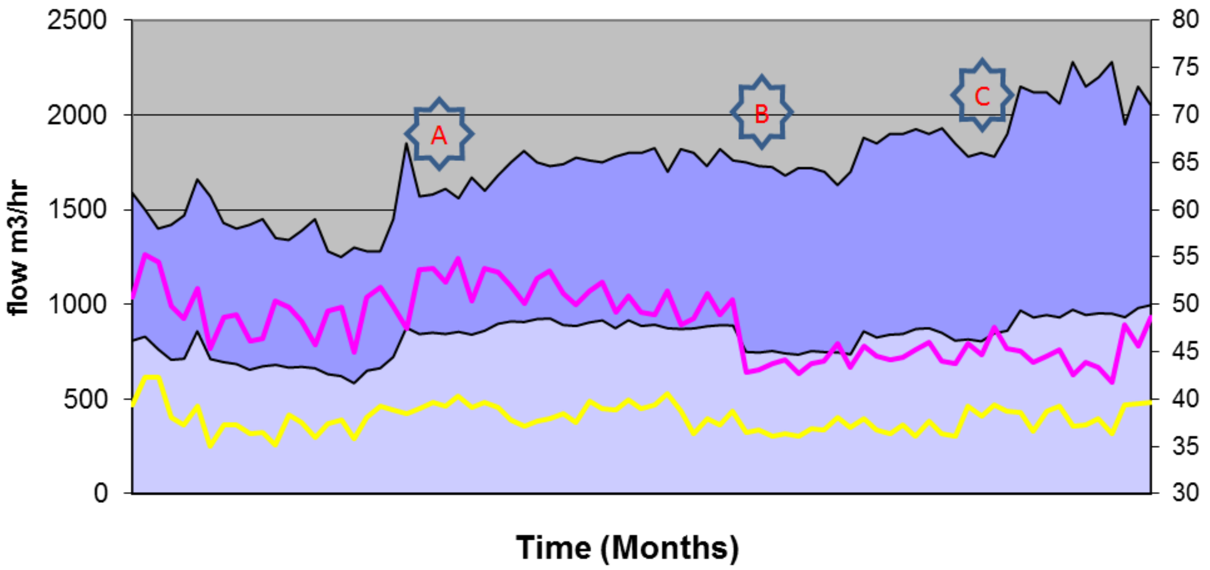


Figure 10.5: Example Site 1

After point B, collection volumes climb to over 2000 m^3/hr, with methane and carbon dioxide levels relatively stable suggesting more LFG availability. In actual fact a new extension to the LFG collection system was installed at point C. The dip in gas collection shown beforehand was due to disruption to the existing grid collection system, to allow the new system to be connected.

10.3.2 Example Site 2 - Impaired gas balancing or system design example.

The example in Figure 10.6, shows that the site is subject to high and fluctuating leachate levels, difficult site gradients and a surface laid gas system.. Over the period of 12 months, the flow of gas fed to the combustion system varied from around 800 m^3/hr to nearly 2500 m^3/hr.

At point A, it is clear that there is insufficient gas extraction, as demonstrated by high methane concentrations. In the period between point A and B, efforts are made to increase the volume of gas collected, leading to a fluctuating profile of extraction as a result of poor gas collection system characteristics and difficult gas balancing conditions (due to leachate level variations). It should also be noted that methane concentrations fluctuate in response to the varying extraction profiles.

At point B, a peak of extraction occurs, and methane concentrations are seen to drop below 50% by volume and then subsequently rebound when the collected volumes decline. This can be indicative of a gas collection system with sufficient gross collection capacity for the volume of LFG being produced; the flow is inconsistent because of the collection issues. Items to look at would therefore be condensate blockage and management, leachate extraction management, pipe falls, slotted areas above high and low leachate levels and improvements in balancing sensitivity (valve additions or changes).

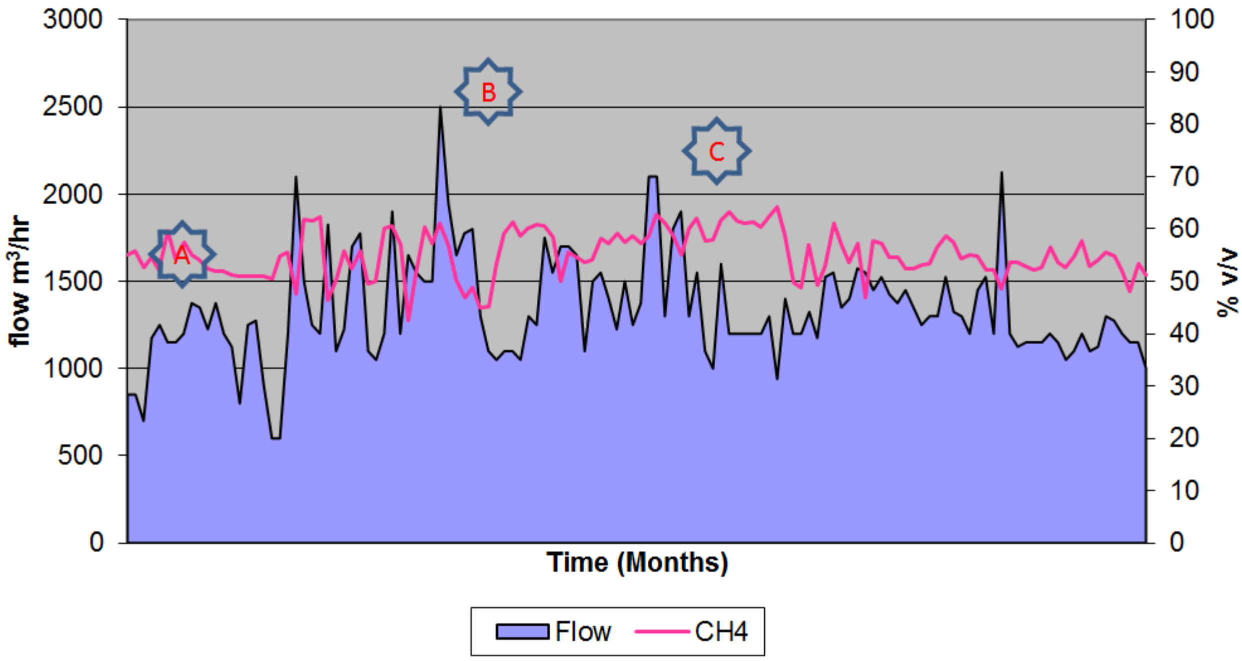


Figure 10.6: Example Site 2 - Impaired

At point C, the LFG extraction system is more stable, some improvements had been made and the volume of gas extracted is more consistently around 1400 m^3/hr. Methane concentrations remain above 50%, indicating that the volume of gas being extracted may be insufficient when compared against the volume being produced. It should also be noted that there is a general decline in the volume of gas collected and no perceivable trend of increase in the methane concentration. There is insufficient evidence in the example shown to understand whether the decline in gas collection is due to a decline in the gas resource or a gradual decline in gas collection efficiency. Further monitoring would provide more evidence to determine this. The data presented here (dropping collection, no significant increase in methane) suggest that this might be a decline in the production of gas and this was subsequently proven to be the case on the site.

Figure 10.7 shows how the data in *Figure 10.6* can be used to infer potential maximum achievable gas collection curves.

The yellow line could represent the maximum gas production curve, assuming a percentage of LFG can never be collected (in this assumption we have used 10%, the actual figure used on any site will reflect individual circumstances, such as open areas, capping and restoration types and well coverage). This could be used to compare to the gross production curves from the site's gas prediction model. The yellow line is set to follow the near peak in observed extraction (as methane concentrations remain high through the period shown and do not indicate over extraction). The yellow line rests below the maximum collection achieved at point B because the modeller considers this an unsustainable level of extraction based on site knowledge and the evidence before them here.

If methane concentrations were nearer 35%, the yellow line would be set to a significantly lower flow on the graph to reflect over extraction. Monitoring of gas concentrations, including CO_2 and O_2 would greatly assist in understanding the degree of over extraction, should this be the case.

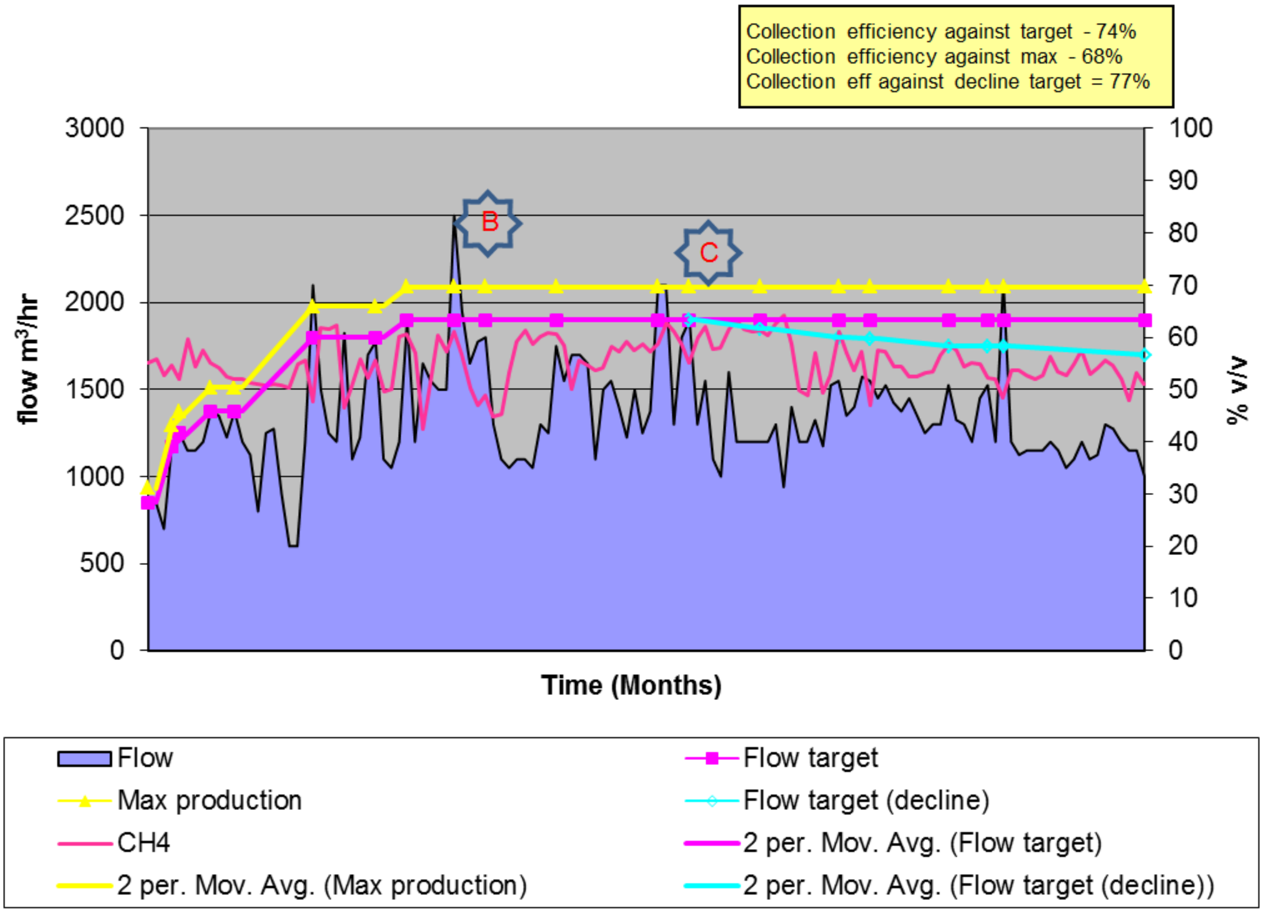


Figure 10.7: **Example Site 2 – Volume Predictions**

The pink target line represents the potential best expected collection target which is 10% below the yellow line as it is assumed in this case that 10% of the LFG cannot be collected.

At point C, the blue line diverges and seeks to represent the potential that the actual production of LFG is declining. Further monitoring and evidence would be required above that presented to determine the cause.

Using the actual collection figures, and these predictive curves, it is possible to work out some indicative site collection figures by measuring (calculating from the original data) the area between the actual collection line and the respective target and maximum lines. For the example above, and the assumptions used, it is possible to calculate a collection efficiency against the target (pink line) of 74% over the period and against the estimated potential gross gas production, a potential collection efficiency of 68%. If gas production was proven to be in decline, then over the period the gas collection efficiency against target would have been 77%.

Where predictions such as those undertaken above are produced, it must be remembered that they are indicative estimates used to inform and set targets for gas management practitioners, they are not absolute performance measurements. The pink or blue lines represent good gas management expectations.

10.3.3 Example Site 3 (real data of a site entering a 'death spiral' of collection)

A 'death spiral' or negative feedback cycle can result from:

- wells with leaks being turned off, increasing the pressure on the remaining wells
- increasing the vacuum on the remaining wells exaggerating existing defects or creating new air ingress pathways
- this then results in more wells being identified as 'oxygen rich' and being turned down or off
- moving more vacuum and expectation to the smaller number of remaining wells.

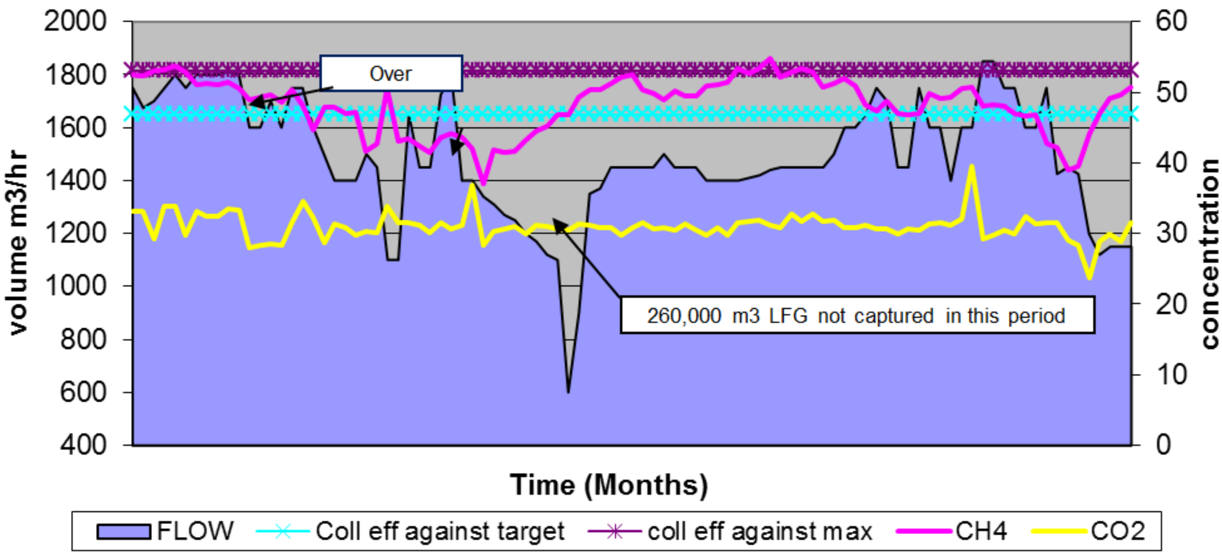


Figure 10.8: Example Site 3 – Death Spiral

In the example above, the 'death spiral' commences after the second labelled 'over' extraction peak leading to the rapid decline in extracted volumes. The very sharp drop at the end of this decline was the main LFG collection system being turned off in order to undertake repairs on air leaks, and to encourage the site to return to anaerobic conditions. It should also be noted that on the 2nd over extraction point, methane concentrations drop to below 38% by volume, highly indicative of over extraction.

On recovery, gas extraction continues at a rate of just over 1400 m^3/hr for a period, but methane levels climb to above 50%. This would suggest under extraction and reservoir enrichment. Towards the end of the period gas collection increases, but volumes collected become more unstable, leading to a series of peaks and troughs. This could suggest that the gas collection system had insufficient capacity and extent to enable continuous higher flows of LFG to be collected. However, as materially more LFG was collected, a corresponding drop in methane is seen, suggesting that the gas system capacity short fall is not huge, and that probably additive improvements to the system would be sufficient to establish good gas management.

The decline in gas collection right at the end of the period could suggest a problem with the gas system (flow constraints, rising leachate levels etc.). However, in this instance, it was due to a change in the combustion infrastructure, reducing for a short period the ability to extract maximum gas through the collection system.

The purple ‘maximum’ line represents an estimate of the likely target best efficiency for gas collection at the site. Using this and the data collected, it is possible to estimate that the process of the ‘death spiral’, recovery and system stabilisation shown in the graph, led to in excess of 260,000 m^3 of LFG not being collected. Again the influence of ‘events’ can be significant in the success or failure to establish good landfill gas management. Careful monitoring and interpretation of the data collected from the gas field could have identified the process early and prevented the event occurring.

10.4 Use of This Method

Currently, it is impossible to accurately and reliably measure all LFG produced, collected and lost from a landfill site. The WSGCE method is designed to allow the operator and regulator to understand with reasonable clarity and certainty the effectiveness of gas collection on the site, the events and activities that are influencing the success of the gas collection strategy and a feedback loop to remove or minimise each of the negative influences. Consistent and professional application of this method will enable an LFG collection system to be optimised, for related impacts (capping, new systems, leachate levels etc.) to be understood and the effects minimised and leads to the maximum practical level of LFG collection.

11 Gas Treatment

In the UK, the primary means of disposal of LFG is combustion. The combustion process converts, methane-rich emissions into gases that are relatively less harmful from a global warming perspective. The EU has committed to achieving a target of 20% of all energy consumption to be supplied from renewable sources by 2020. In order to meet these binding targets, the UK has committed to derive 30 - 40% of its electricity from renewable sources. Renewable energy is, therefore, a key component of the UK government energy strategy.

Utilising LFG to produce electricity reduces the quantities of greenhouse gases (GHGs) released to atmosphere. The technology for electricity generation from LFG is well established, it is a low risk technology and the environmental benefits are measurable.

The Landfill Directive requires that wherever LFG cannot be utilised, then it must be flared. More particularly, at Annex 1 it requires:

(1) appropriate measures must be taken in order to control the accumulation and migration of landfill gas;
(2) landfill gas must be collected from all landfills receiving biodegradable waste and the landfill gas must be treated and, to the extent possible, used;
(3) the collection, treatment and use of landfill gas under sub-paragraph (2) must be carried on in a manner, which minimises damage to or deterioration of the environment and risk to human health; and
(4) landfill gas which cannot be used to produce energy must be flared.

11.1 Flare Led Extraction Philosophy

Good practice is to operate gas utilisation plants on a ‘flare led’ basis. This provides consistency of extraction and allows the gas field to be balanced effectively. The gas plant / flare should automatically control the field vacuum or delivery pressure to the generators by controlling the LFG spilling to the flare. This has the effect of providing a constant vacuum to the waste mass. The generators will be used as the primary point of combustion. Any volume of gas in excess of this requirement will be spilt to the flare, in order to maintain a minimum set point vacuum or minimum flow throughput. If field vacuums rise too high, or the delivery pressure drops below a set point, it will indicate that the generators are taking too much gas for the field and gas consumption of the generators will be adjusted accordingly by reducing load.

The ability to operate most generators on part load provides extra flexibility to this operational philosophy.

11.2 Flaring

The flaring of LFG is the most basic means of controlled combustion. The design and specification of the flare dictates the combustion efficiency and this must match the emission standards in force. The two main types: elevated and enclosed, are discussed in more detail below.

Flaring should be employed on sites, or at times during a site's life, where energy generation is not achievable (either for commercial or practical reasons). The size of the flare should be sufficient to meet the rate of LFG production. It is, therefore, advisable to size the flare for anticipated peak production rates or design the plant with sufficient flexibility for up-sizing. Flare sizing in combination with utilisation is considered later in this chapter.

The turn down ratio (TDR) of a flare dictates the minimum LFG throughput while achieving certain emission standards. This is another key consideration when specifying a flare, as a higher TDR will provide a finer degree of control if the flare is purely being used to manage spill at a utilisation site. It can be useful to pair flares, for example, a large capacity with a low TDR for bulk treatment and a smaller capacity flare with a high TDR, for spill gas.

11.2.1 Types of Flares

As mentioned above, the UK uses two types of LFG flare; elevated or enclosed.

11.2.1.1 Elevated Flares

This type of flare is the most basic that is employed in the UK. Combustion takes place at the top of a gas delivery stack, so the flame is high up, primarily for health and safety reasons. However, this means that it takes place in the open and therefore the combustion process is not controlled. Typically, combustion temperatures are lower than with enclosed flares; the combustion efficiency is lower and the emissions do not meet the same standards.

Elevated flare

Portable elevated flare

Figure 11.1: Elevated Flares

11.2.1.2 Enclosed Flares

This modern type of flare was introduced into the UK market in order to achieve improved local emissions and a general reduction in the emission of greenhouse gasses to atmosphere. This improved performance is achieved through a controlled combustion of the LFG within a combustion chamber. This allows the burn time (retention time) and burn temperature to be controlled, permitting a homogenous temperature distribution across the combustion chamber.

The flares should be lined with refractory material on the interior and the combustion air supply controlled so as to achieve a minimum temperature of 1,000 ^{o}C (or less where a lower temperature is required to meet the relevant emission standards) and 0.3 second retention time.

Inclusion of an ultraviolet (UV) flame sensor detects when the flare is lit to prevent venting of unburned gases. A pilot line and slam shut valve control the ignition sequence to ensure that the flare lights in a safe and controlled manner. Flame arrestors should be fitted to each flare and pilot line.

'Lo Cal' flare

Enclosed flare

Figure 11.2: Enclosed Flares

11.2.1.3 'Lo Cal' Flare

Low calorific (Lo Cal) value flares allow the safe and efficient degassing of old landfill sites or sites with low quality gas. Lo Cal high temperature flares can provide greater gas control during the latter phases of a site, while the high temperature prevents pollution issues.

Lo Cal high temperature combustion is necessary on more and more sites due to higher standards of aftercare being required, falling gas volumes and lower gas concentration.

11.2.2 Permanent Application

Permanent flares should be of the enclosed design. Exceptions may be made where a site has very low volumes to dispose of (for example, a closed site a long way down the gas decline curve) or where they are used in combination with other disposal options as a secondary backup (for example, where an enclosed flare is used as the lead flare for spill gas and most engine outage scenarios and the elevated stack is required only in times of a complete generator outage).

11.2.3 Temporary Application

In certain circumstances, temporary flares may be required. For this specific application, temporary should be defined as periods of no greater than six months. Temporary flares may be of either the elevated or enclosed design, but are more commonly the former due to the fact that they are often more compact for storage and transportation and easier to establish and commission once on site. Due to the temporary nature of the installation, the impact of the lower emission standards is often of little concern. The completion of basic risk assessment screening can easily establish if this is the case.

Examples of such scenarios include:

- emergency environmental application (for example, to assist in the management of a specific environmental issue such as migration)
- during circumstances of failure of permanent plant
- as a pumping trial to assist in the sizing of permanent equipment
- extraction from operational areas or areas where flexibility of the extraction system will be required, such as during capping

11.2.4 Flare Commissioning Tests

Any new or relocated gas plant / flare (permanent or temporary) should undergo a minimum series of tests before being put into operation. These tests may include, but should not be limited to the following;

- 17th edition testing electrical, Part 2
- operational testing – start-up, shutdown, pilot light, temperature control
- test emergency features – emergency stop

11.2.5 Flare Maintenance

Routine maintenance of a flare should only take three to four days each year. Manufacturers generally offer service contracts to carry out this work. The checks most frequently cited by manufacturers and operators include:

- checking the liquid level in the knockout pots
- checking belts and bearings on the gas booster
- checking the pressure drop across filters and flame arrestors, as this indicates fouling
- cleaning the lens on a UV flame detector

If the flare is a standby to an energy recovery scheme, then it is important to check the regulators that control the switch-over of gas supply to the flare. An example maintenance schedule for a high temperature flare with electrical ignition and a UV flame detector is shown below. Not all of the components referenced will be present on all flares.

Specific guidance must be sought from the manufacturer of individual flaring systems. Flares can operate uninterrupted and unattended, provided that suitable telemetry links are established and maintained.

11.2.5.1 Flare Checks

The following checks should be undertaken as a minimum.

Task	Weekly	Monthly	Quarterly	Annually
Check flow rate, pressure, temperature and monitor inlet gases	x			
Check electrical control panel		x		
Check temperature control loop components			x	
Check control of ignition electrode		x		
Replace ignition electrode				x
Clean UV lamp		x		
Replace UV lamp				x
Check/clean filter in inlet knockout pot			x	
Check/clean/replace filters in gas sampling lines			x	
Check operation of all alarm functions			x	
Check operation of telemetry system			x	
Clean flame arrestors			x	
Check/clean motorised valves				x
Check condition of air throttle or damper		x		
Check thermocouples			x	
Check condition of terminal boxes		x		
Check condition of thermal insulation			x	
Check maintenance log	x			

Table 11.1: Flare Checks

11.2.5.2 Flare Trouble Shooting

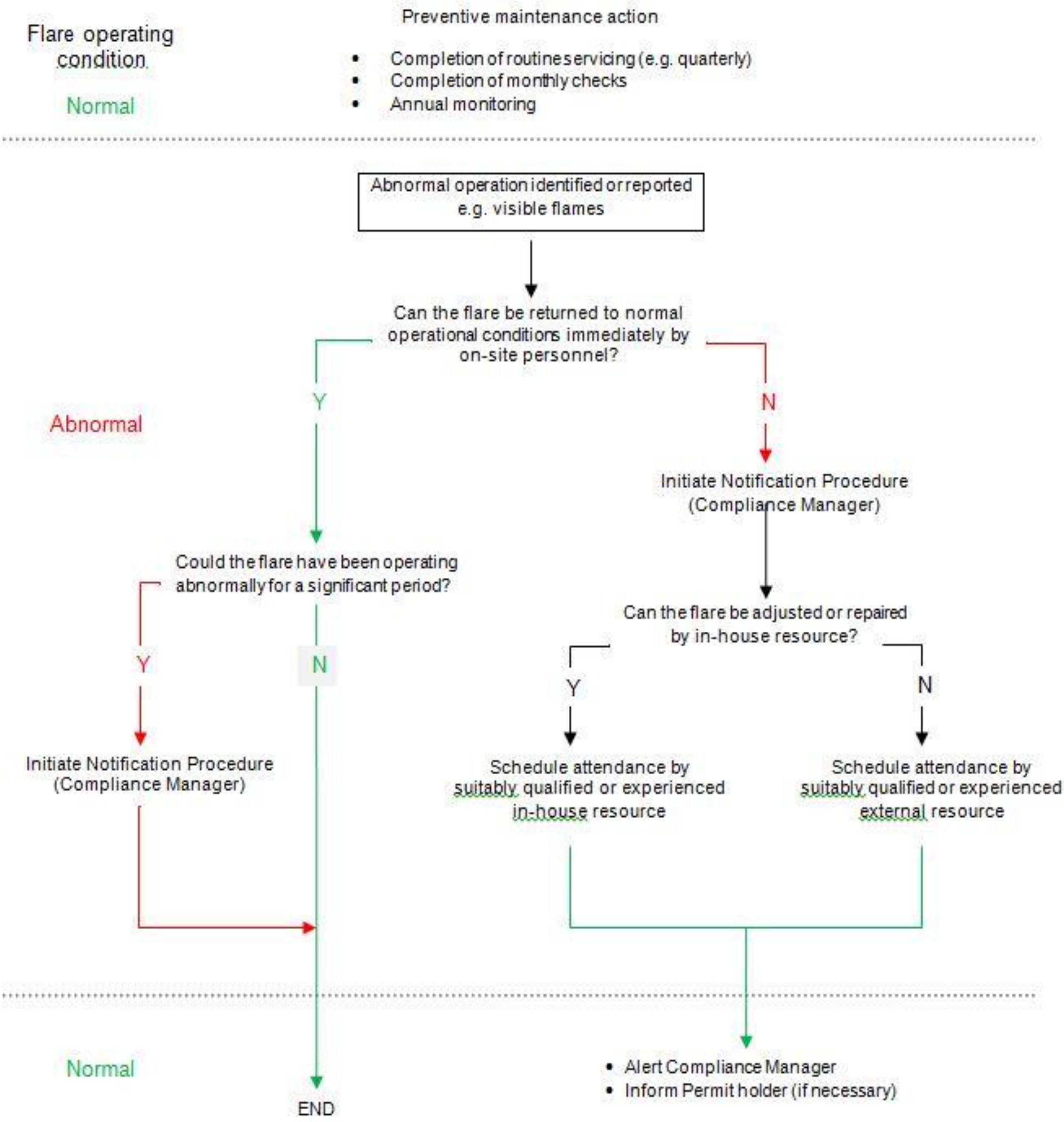


Figure 11.3: Flare Troubleshooting Flow Chart

11.3 Utilisation

The Landfill Directive states; LFG must be collected from all landfills receiving biological waste and the LFG must be treated and, to the extent possible, used. In the UK, due to economic interests being aligned with policy, the preferred method of disposal is through utilisation for power generation.

The most common form of utilisation from LFG is with the use of spark ignition internal combustion engines. A number of manufacturers offer these reciprocating engines specifically designed to run on LFG. The engine drives an alternator, generating electricity which is transformed to the correct voltage and exported into the National Grid.

Most generators can be operated on part load in order to match the gas production from the site to generator consumption. The minimum load achievable will vary according to the generator type; where this minimum is reached, a generator may need to be shut off. Most manufacturers also supply a range of engine capacities (measured in electrical power output) of engines. Common sizes range between 330 kWe to 2.4 MWe. Combinations of the numerous engines covered by this range can be applied to a site, in order to achieve a best fit between gas availability and installed capacity.

As a minimum, before coming into operation, all generators should undergo the following basic commissioning tests. These may include, but not be limited to the following:

- pressure test of gas, water and oil pipework
- 17th edition electrical testing, Part 2
- earthing / resistance testing
- G59/2 testing (Connection of Large Embedded Generation to the HV network)
- operational testing –start-up, shutdown, ramp up and download, performance test, noise test
- emissions test (at turbo or exhaust)
- test emergency features –emergency stop, fire detector, gas detector, fire suppression equipment (if fitted)

For basic key parameters to monitor and record for a typical LFG generator (see *Table 9-4: Typical Monitoring Frequencies and Parameters for Generators*).

11.3.1 Capacity Changes

Due to the constantly changing rates of gas production at a site in line with waste inputs, it is necessary and common to upsize and downsize the installed capacity in order to best retain this best fit between gas availability and installed capacity.

Where a drop in gas production is likely to be prolonged, a smaller generator may be installed to best match the gas production and vice versa. To this end, flexibility in installed capacity is required to allow best fits for the site to be made in order to match both short and long term changes in gas availability. The regulator should be informed of such changes as necessary. Where such a change will increase capacity above that permitted, then additional modelling and formal approval (in the form of a permit variation) may be required to ensure no adverse impact to the local environment as a consequence.

The less new or ‘green field’ opportunities that exist for development, the more capacity changes on existing schemes will become prevalent.

11.4 Process Plant

The process plant is considered to be the heart of any active extraction system. This is the part of the system that provides the energy that ‘pulls’ or ‘sucks’ the LFG from the landfill, through the network of transmission pipes and ‘pushes’ it to a point of disposal (engines or flare).

A typical process plant comprises of the following basic elements:

- **Gas boosters / pumps** – of the various designs of LFG pumps available, all serve the same purpose, that of supplying a ‘pressure lift’. These pumps can be specified to supply different maximum volumetric gas throughputs and different lifts, depending on the requirement of the site (size, disposal method, design of plant)
- **Condensate knockout facilities** – there are numerous designs of condensate removal equipment and there are often several locations for removal within compound which take the last opportunity to remove liquid from the gas stream before it enters the flare or the engine(s)

- **LFG isolation valve(s)** – these can be manual or automatic and are in most applications both. Manual isolation valves tend to be installed for use during planned work, whereas the automatic valves (electronic or pneumatic) form a part of the integral safety features
- **Particulate filtration** – although a lot of the entrained particulate should be removed from the gas dissolved in the condensate. That which does make it through to the process plant is filtered out using various sizes of basic filter. It is common to find a greater amount of particulate matter finding its way into and through the system following activity on the system, for example installation of new wells or bentonite resealing
- **Flame arrestor(s)** – these are installed at strategic points within the gas plant pipework. They prevent the 'flashing' of flames down the inside of the pipework
- **Monitoring equipment** – depending on the requirement of the operator, certain parameters will need to be monitored to varying degrees of accuracy and regularity. This can relate to gas quality, flow, pressure and temperature on either a continuous or manual basis
- **Pressure regulation** – this is required to manage the incoming gas to a pressure conducive with the disposal equipment. Not including this can lead to ineffective combustion

11.5 Clean-up

Over and above basic filtration of particulates, other LFG clean-up technologies may be employed on a site. Depending on the driver, clean-up technologies can be applied either pre or post combustion.

11.5.1 Pre-treatment

Pre-treatment is applied if it is necessary to clean the input gas prior to combustion. This is often the case when there are one or two components of the gas (such as siloxanes) that are affecting combustion and hence impair the performance of the generator. Cleaning the gas front end may also provide the additional benefit of cleaner emissions.

Examples of current clean-up technologies commercially available to the UK market are;

- **Refrigeration** – effective, but very energy intensive
- **Liquid scrubbing** – can be effective in removing soluble siloxanes and other organic compounds. Scrubbing with filtration can significantly increase media life
- **Activated carbon** – very effective but may be quickly overloaded as it absorbs many organic compounds as well as moisture
- **Regenerative (often proprietary) media** – USP (United States Pharmacopeia) approved media have moisture absorbent properties as well as absorbency of siloxanes. Substances that absorb moisture and are then "regenerated" by external drying

Any of these technologies can be used in combination to provide improved overall clean-up and the best fit solution for any site. Currently, these technologies are not widely applied within the UK due to the often restrictive costs associated with both their installation and operation. Installation tends to be restricted to sites with significant contaminant issues where the benefits associated with the installation and operation of the clean-up equipment (reduced engine maintenance) far outweigh the costs.

11.5.2 Post Treatment

Application of this technology is even less common within the UK. It is usually applied for environmental benefit only to clean up post combustion exhaust emissions.

11.6 Gas Compound Design

The compound location and design should be considered when the initial application for the landfill site is made. However, it may be necessary to relocate or expand the compound, in which case the opportunity should be taken to ensure the new compound meets best design and construction practice.

The compound should be designed to allow efficient utilisation of gas extracted from the landfill site. It should allow for safe, efficient operation and future expansion, whilst fully complying with the permits and planning permissions for the site.

11.6.1 Compound Location

The key constraints on compound location are:

- available space
- gas connection
- electrical export connection
- access for large vehicles
- location of nearby receptors for both noise and exhaust emissions.

The presence of local SSSI and archaeology or ecology constraints will also affect location. A power generation compound will need to contain a number of large items of plant and allow safe operation of the plant and access out of hours. The location for the compound should be sufficient to contain all proposed future plant for the life of the site, and allow maintenance and removal of plant. As such, it may occupy a large area of land.

Due to the weight of the plant and the risk of tilting (in particular of the flares) it is not advised to construct the compound on made ground or on the waste mass itself, and, although in certain cases this can be achieved, it will entail extensive civil works and increased costs.

The costs and complexity of connecting the incoming gas main and the outgoing electrical export connection should not be underestimated. Shortening and simplification of either of these can save significantly on costs and outweigh any additional civil works.

11.6.1.1 Entry and Exit

The compound should be designed to be easily accessed during construction and operation with negligible effect on the present and future operation of the landfill site.

Original installation and occasional removal / addition of large plant which involves large cranes and multiple vehicles should be considered. If possible, sufficient room should be maintained within the compound for locating a crane. Alternatively a designated crane location outside of the compound could be made.

To maintain the generators and ensure high availability, it is necessary for regular deliveries of oil and components which will also require safe access. Oil tankers or septic tanker vehicles in particular will be on site for up to an hour for off-loading and loading and a safe location must be provided.

To gain access to the compound, traffic must usually first gain access to the landfill site. Out of hours operation and access must be considered, or a separate entry direct from the highway provided.

11.6.1.2 Security and Signage

The compound should be fenced. Where room permits, a suitable distance between the external perimeter fence and internal structures within the compound should be maintained, to ensure maximum security and to prevent access over the fence using adjacent buildings. Security gates should be located in several locations (site dependent) to allow convenient access and emergency exit. All compounds should be secure due to the hazardous nature of equipment on site and to provide adequate security of assets.

Where possible, the office should be located adjacent to the main entrance and clearly signed as the first point of contact for all visitors or deliveries. Warning signs, such as DSEAR/ATEX, must be in clear view on exterior of the fencing.

11.6.2 Compound Contents

Normally, a power generation compound will contain the following:

- generator set(s)
- gas plant and flare(s)
- gas connection to the generator(s)
- fenced electrical transformer compound
- bunded clean oil, waste oil and coolant tanks
- standby generator, if required or standby generator electrical 'stab-in' for fast installation (this should be determined on a risk based approach)
- housed air compressor
- LV switch room
- distribution board
- service trench(es)
- suitable fire alarm system
- coolant tank or drip tray for containers
- office with voice and data communications (site dependent)
- welfare facilities, for example, toilet, washing and canteen facilities (especially on permanently staffed site)
- workshop (site dependent)
- storage facilities
- suitable parking (site dependant)
- designating area for use of cranes as required

11.6.2.1 Gas Connection to the Gas Plant

The incoming gas main from the field should enter the compound adjacent to the gas plant (boosters etc.) and enter the plant with no unnecessary bends, so as to limit loss in suction on the field. The gas main terminating at the compound should ideally be at the highest point of the pipe run so as to prevent condensate liquid from entering into the gas fans and engines.

The gas main should terminate at the gas plant with a butterfly valve, to allow isolation of the field and control of suction. Where more than one gas main is utilised, these should each have individual valves to allow balancing and control of suction.

It is generally required to measure the incoming gas volume, therefore a flow meter on each line is required.

11.6.2.2 Gas Plant and Flare

The flare and gas plant should be designed to cope with the maximum flow of gas produced on site (for instances when no generator sets are running). An exception may be made where, for example, a site has multiple grid connections and therefore the total loss of utilisation capacity is highly unlikely. This should be risk assessed on a site basis.

The plant should also be able to run down to very small volumes of gas to allow for decline and closure of site whilst still maintaining compliance with the site's permit. Typically, the plant will have a duty / standby arrangement of fans to allow for maintenance and repairs. Alternatively, for less sensitive sites, there should be a robust procedure in place to allow for rapid replacement or repair in the event of a booster failure. It is desirable to fit the plant with automatic or remote restart facilities in event of power failure, to ensure environmental control is regained as soon as possible after power returns. Suitable safety mechanisms must be installed to prevent start-up under certain conditions, for example, with personnel present.

The gas plant should feature a slam shut valve to isolate the gas field in event of plant failure or emergency; typically this will be air actuated.

Prior to the gas passing through any gas fans, it should be cooled and filtered in a coalescent filter (or similar) to remove condensate that might otherwise damage the fans. Gas fans should be fitted with individual flame arrestors to prevent any explosion passing back onto the field.

The gas lines to the flare should be fitted with individual flame arrestors to prevent any explosion passing back into the plant.

11.6.2.3 Gas Connection to the Generator Sets

The gas main should run from the gas plant to the generator set(s) and should be sized so as to allow for the maximum expected gas flow to achieve a velocity of less than 10 m/s (to minimise condensate carry over into the generators). It should be designed and installed so as to minimise pipe run and pressure drops. All pipework should be labelled with medium and flow and fit for use with LFG and DSEAR classification where appropriate, for example, flanges and monitoring points.

Depending on the specification of the generator, additional filtration of the gas may be required, for example using a Kelburn or Simplex type filter. It may also be necessary to lag the gas main to avoid cooling and condensate build up.

Slam shut isolation valves should be installed before each generator to stop gas supply in event of fire or gas alarm in the container. It is preferable to also install flame arrestors on each generator set.

11.6.3 Generator Sets

The overall compound should be sized in accordance to the maximum predicted gas curve. Provision in size should be made, to accommodate a sufficient number of generator sets to allow maximum utilisation of LFG produced in the landfill.

Exhaust stacks must be at a height and orientation determined by site specific gas modelling, typically 7 - 10 metres from compound level. Sampling points should be provided to meet LFTGN08. Where crankcase breather output is routed to the exhaust stack, this should be above the sampling points.

11.6.3.1 Noise

Typically, containerised generator sets are rated to 65 dB (A) at 10 metres. Where noise modelling has shown quieter sets are required, this will increase the cost and limit the choice of supplier. Alternatively, greater noise attenuation, such as acoustic fences and other barriers, can be installed.

11.6.3.2 Space

Containerised generators are usually designed to allow removal of the engine block itself from the front of the container for rebuild / repair. Where this is necessary, a clear distance of around 6 metres is required, but this should be checked with the supplier. Removable fence panels may be required to allow sufficient clearance.

11.6.4 Electrical Transformers

Typical generators provide power at 415 Volts which is required to be stepped up to the voltage of the local network for export. This is normally 11,000 Volts and is achieved by a dedicated transformer for each engine. Transformers should be located immediately behind the generator set so as to minimise cable runs and have appropriate warning signs with regards to the high voltages present.

There should be a minimum safe working distance of 1 metre around the transformer to allow working room for maintenance and safe means of exit so an area of at least of 4 metres x 4 metres is the minimum area required. Where it is necessary to further increase the voltage (to 33,000 Volts for example) an additional single transformer will be required.

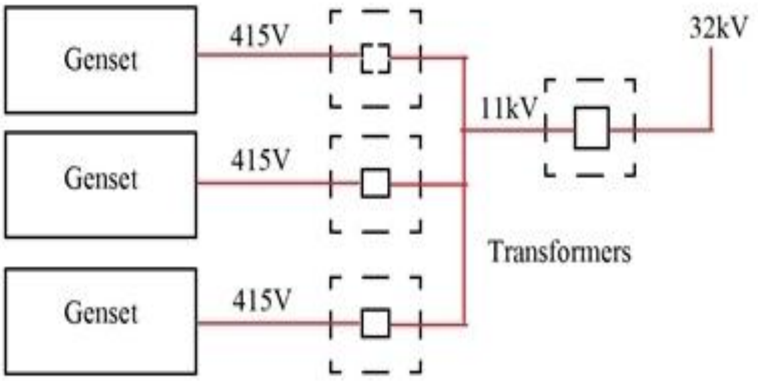


Figure 11.4: Power Schematic

11.6.5 Other Plant

11.6.5.1 Clean Oil, Waste Oil and Coolant Tanks

Oil and coolant tanks, with sizes corresponding to generator capacity, should be installed on site. These should be internally bunded to 110% and in compliance with *BS799: Part 5, Specification for Oil Storage Tanks*. These should be connected to the generators using a permanent connection with suitable isolation valves or using a retractable hose.

For retractable hose tanks, the recommended hose run should not exceed 30 metres. For permanent connections, the pipework should be protected against freezing and may need trace heating. At low temperatures, oil becomes very viscous and will not easily flow.

11.6.5.2 Standby Generator (Where Required)

A standby generator will allow operation of the gas plant and flare during periods of electrical outage, maintaining environmental control. Standby generators are usually installed where a risk assessment has highlighted the importance on the GCS in providing continued environmental control. If a generator is required, either as a condition of the permit or due to frequent electrical outages, it must be suitably sized to allow for site power to the flare and gas plant / compressor in case of shutdown. The requirement to install a standby generator on a permanent basis should be based on a site specific risk assessment that considers frequency of outages and sensitivity of the site such as odour or migration.

Depending on standby generator type, the connections may be permanently or manually connected on shutdown. Due to OFGEM requirements, the standby generator (especially diesel) must be mechanically interlocked so as to prevent operation during export from site.

The location of the generator should be convenient for the delivery of fuel and regular maintenance of the plant. Suitable arrangements for storage of fuel or provision for regular refuelling should be made for periods of extended outage. If it is considered unnecessary to install a standby generator on site on a permanent basis, then facilities and processes should be in place to allow for fast and efficient mobilisation and connection of a unit to site if required (for example, electrical 'stab-in', identified suppliers).

11.6.5.3 Housed Air Compressor

Typically, an air compressor is required within the compound to supply pumps on the gas field and local air actuated valves within the compound. Where possible, the compressor should be housed in a separate, vented container to reduce the noise. Connection of the air and power lines should be diverted into the service trench. Where operation of the compressor is critical to environmental control, it will be necessary to include monitoring and failure alarms.

11.6.5.4 LV Switch Room & Distribution Panel Board

The site should be designed to incorporate the low voltage (240 Volts) supply required for the power and lighting for the compound, including any low voltage supply required to extract LFG. This will require a distribution panel board to be installed at a suitable location, such as the office or workshop. Low voltage supplies within the compound could include:

- environmental flare control
- clean / waste oil and coolant tank pumps
- clean oil tank heater
- workshop
- offices
- compound power & lighting

At least 10% spare provision should be made for future expansion. Where electrical supply is provided for site operations unrelated to the gas control on site (for example leachate treatment works) this should be separately metered using OFGEM Schedule 4 metering, to allow claiming of Renewable Obligation Certificates (ROCs) for the usage.

11.6.5.5 Earthing

A suitable earth mat should be installed at the generator site and all equipment including, fencing and gates, should be connected to strategically located earth bars. Specialist earthing contractors for the site specific installations should be consulted.

11.6.5.6 Telemetry

A suitable telemetry system should be installed to provide off-site communication and status with regards to the critical plant. This should include trip alarms and status indication and, where necessary, a call out facility to alert technicians of plant shutdown.

Consideration should be given to future expansion of the telemetry to include future plant and increased data. Mobile phone reception should be assessed for suitability as a connection medium. Alternatives are to use the on-site network connections or the fixed telephone lines.

11.6.5.7 Services

All water and foul drainage services throughout the compound should be buried.

Where possible, services between the gas plant and flare, generator sets, transformers, compressor, distribution board and Low Voltage room should be diverted into the service trench. Services should not be surface laid except for temporary works.

11.6.5.8 Office / Welfare / Workshop

If present on site, the office and welfare structures can be brick built or more typically of a containerised steel unit or pre-fabricated design depending on planning requirements and expected duration on site. Ideally, the office should contain voice and data communications and be suitably heated and ventilated.

Different arrangements of office / welfare / workshop are common to suit site requirements and expected staff levels on site. It is common for low voltage distribution to be sited within the workshop, to eliminate need for separate dedicated Low Voltage room.

It is best practice to include recesses into bases to allow for buried service connection into the structures.

11.6.5.9 Civil Works

Suitably engineered concrete bases will be required for:

- generator sets
- gas plant and flare, transformers
- office / welfare facilities
- workshop
- LV room
- oil tanks
- standby generator
- air compressor

Ducts should be included in the bases as necessary.

11.6.5.10 Service Trench(es)

An accessible service trench of sufficient depth and width should be included in the design and should run in a direct manner between all generator and transformer bases as a minimum, to allow all services to be below ground level.

The trench should include covers which should be sufficiently reinforced to allow foot traffic and light wheeled use. Adequate drainage must be incorporated.

11.6.6 Compound Layout

The following drawing shows a typical design for a compound.

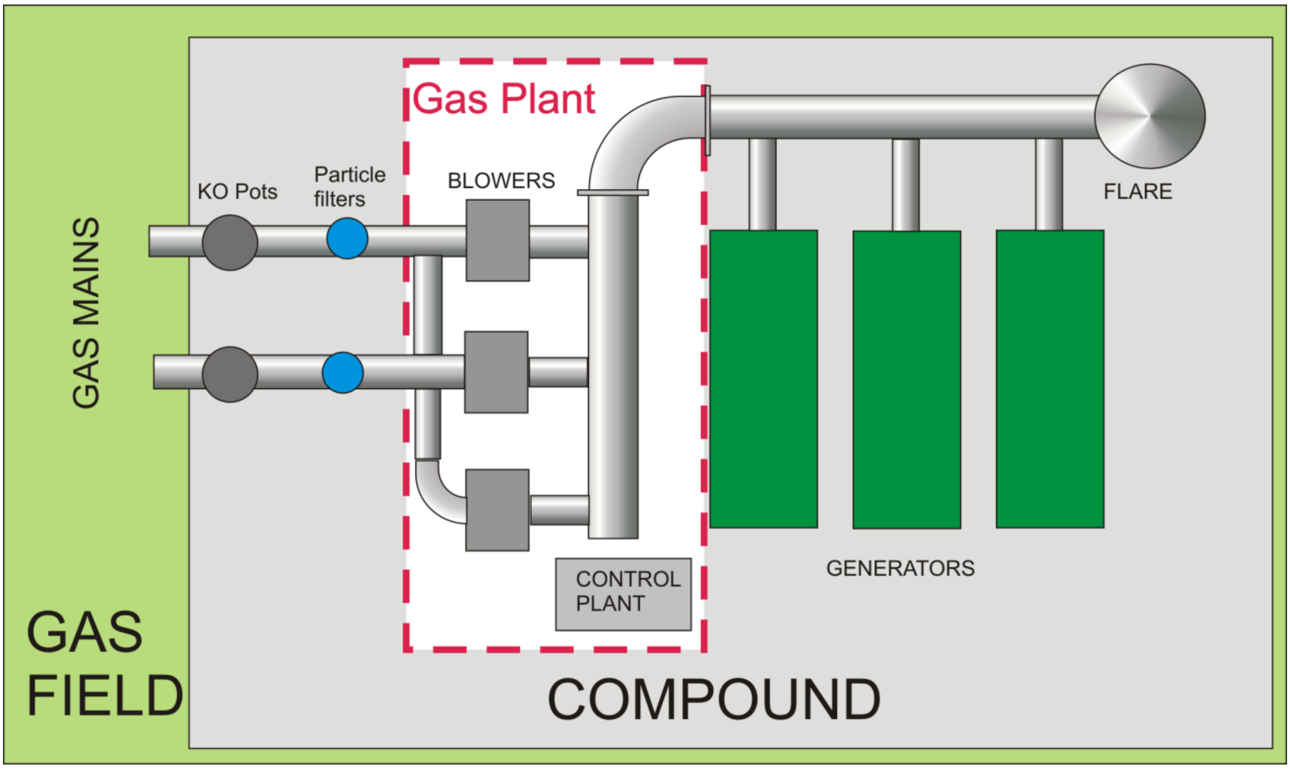


Figure 11.5: Gas Compound Example

11.6.6.1 Design Constraints

The compound should be designed to maximise efficiency and minimise expenditure as well as meeting Health and Safety and security requirements. In many cases the gas plant and flare will already be installed and this should be a driving parameter for the overall design.

11.6.6.2 Generator Sets

The generator sets should be located in close proximity to the flare or gas intake to the compound.

The distance between the generator and transformer should be kept to a minimum to avoid increasing cable costs. Access and egress to the generator sets should be clear, with a minimum door clearance of 1 metre once open. To minimise heat soak during hot periods, the generator sets should be installed a minimum distance of 3 metres apart, separated by an area of hard standing which may be used as an access route for operatives and parts delivery. Fixed gantries should be installed where necessary, to allow safe access to monitoring points on generator exhaust and routine maintenance of roof items.

11.6.6.3 Gas Connection

The gas line(s) should be as short and linear as possible, to avoid excess cost and minimise pressure drops.

Pipework should be designed with double lugged valves to allow isolation of each spur and removal of generators where necessary. Pipework should include blanked flanges at the termination point to allow further future expansion without excessive disruption.

Valves installed in the gas main should carry the manufacturer's ATEX label, complete with zone, distance and CE mark. Where expansion joints are used, alignment should be within normal workshop limits of ±0.5 mm, supported and installed with an isolation valve up stream.

Pipe joint gaskets should be equivalent to Klingersil C-4324.

11.6.6.4 Services

Cable runs between all equipment should be as short and linear as possible to minimise cable distances. Cables and services should be located in the accessible service trench where possible.

11.6.7 Site Access, Exit and Parking

The site should be designed to include safe access and egress routes. Areas for parking should be hard standing where possible.

Appendices

Appendix A The Changing Nature of Waste

A.1The Changing Nature of Waste on Landfill Production

In the following examples, the landfill site is operational and taking waste from 1991 to 2008 and there is assumed to be a constant total waste input and mix for the classic curve. For each of the 'peaky' and 'flat' alternatives it is assumed that the inputs reduce by the recycled or recovered components and the mix and therefore LFG production potential varies accordingly. It would not be correct to draw conclusions on the absolute impact of removing paper and cardboard by comparing the 'classic' and 'peaky' as this is not what has been modelled, as it was deemed impractical to remove 100% of any waste mix component. It is worth noting that the models do show significant difference in maximum gas potential, as well as shape.

A.1.1 Historic Gas Curve

The gas production curve presented below is typical of that seen from historic waste, where there was a general and consistent mix of food, green, paper, cardboard, wood, textiles and other garden wastes.

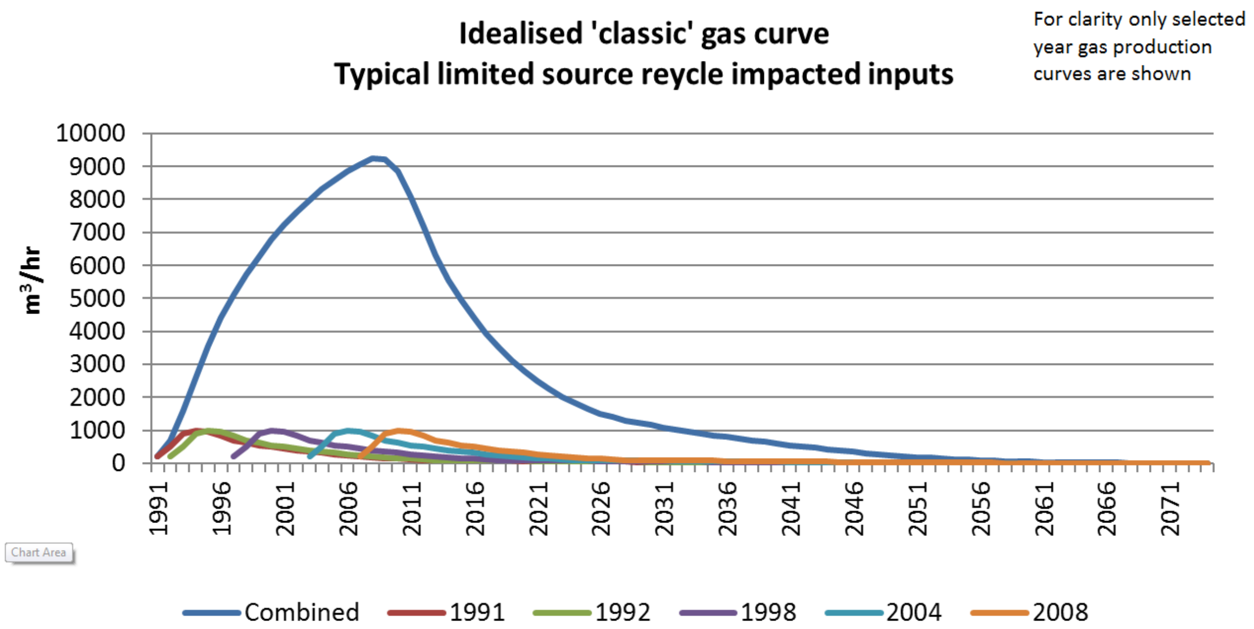


Figure A.1: Idealised Historic/Classic Gas Curve

A.2 Modern Gas Curves

Where recycling or recovery operations remove or reduce certain groups of waste this will impact on the shape and size of the gas production curve. In general, removal of food and green waste will impact on the scale of the peak of the curve, paper and cardboard on the initial regression curve shape and wood, textiles and other garden waste on the size and length of the tail of the gas curve. This is represented in the curves below.

A.2.1 Idealised Flat Gas Curve

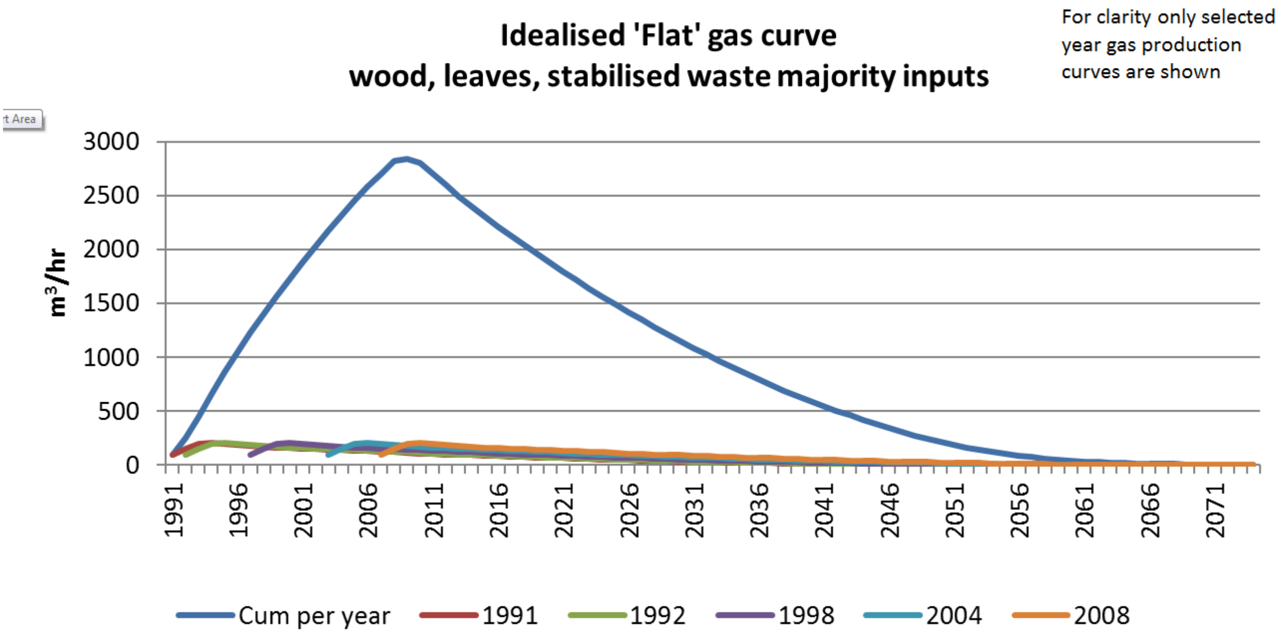


Figure A.2: Idealised Flat Gas Curve

A.2.2 Idealised Peaky Gas Curve

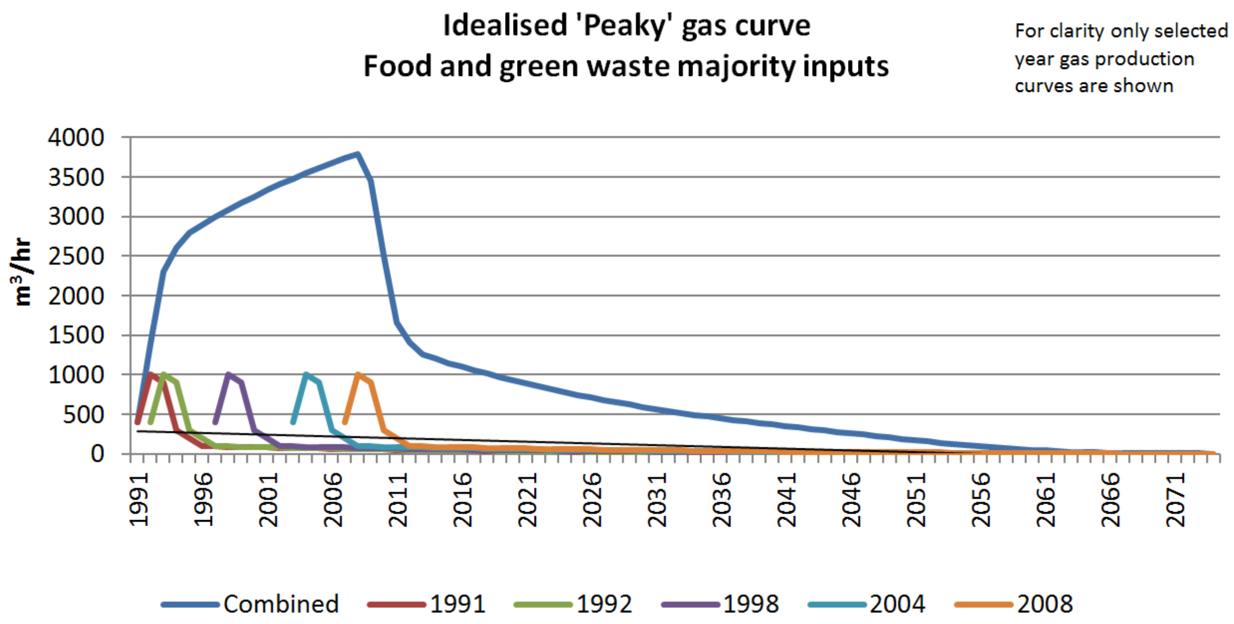


Figure A.3: Idealised Peaky Gas Curve

A.2.3 Idealised Waste Mix Gas Curve

It is clear that very few landfill sites have a consistent tonnage and waste composition mix will change each year for their operational lives. As such, accepting that over the life range of a normal landfill, and depending on the waste stream activity upstream of the landfill site there will be a morphing between different shapes and maximum potentials. Figure A.4 shows an idealised waste mix gas curve. The classic waste mix is shown in red. A realistic curve with the maximum food and green waste removal is shown in blue and a realistic curve with maximum extraction of paper and cardboard is shown in green.

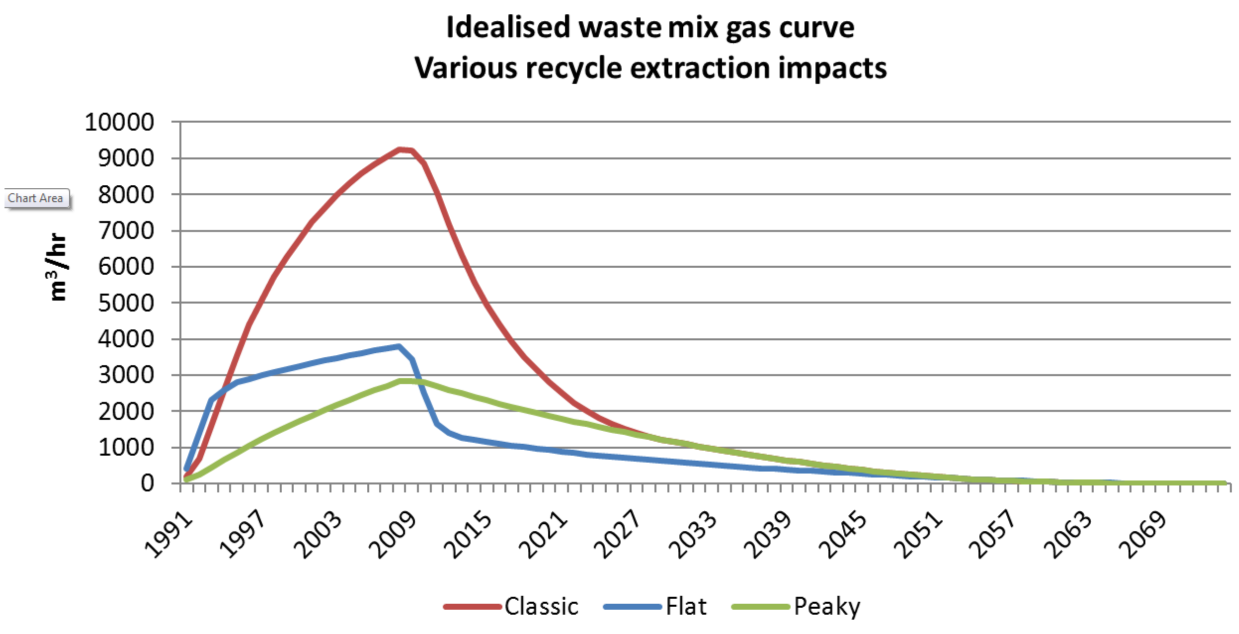


Figure A.4: Idealised Waste Mix Gas Curve

Appendix B Pressure Loss Tables

This appendix includes:

- pressure loss charts and pipework sizing
- maximum Flow m^3/hr
- minimum Pipe OD
- pressure loss
- pressure loss principles

B.1 Maximum Gas Velocity (m/s)

Flow (m^3/hr)	Pipe Size (mm)							
	63	90	110	125	160	180	250	355
10	1.1	0.6	0.4	0.3	0.2	0.1	0.1	0.0
20	2.3	1.1	0.7	0.6	0.4	0.3	0.1	0.1
30	3.4	1.7	1.1	0.9	0.5	0.4	0.2	0.1
40	4.5	2.2	1.5	1.2	0.7	0.6	0.3	0.1
50	5.7	2.8	1.9	1.4	0.9	0.7	0.4	0.2
60	6.8	3.3	2.2	1.7	1.1	0.8	0.4	0.2
80	9.1	4.4	3.0	2.3	1.4	1.1	0.6	0.3
100	11.3	5.6	3.7	2.9	1.8	1.4	0.7	0.4
200	22.7	11.1	7.4	5.8	3.5	2.8	1.4	0.7
400	45.4	22.2	14.9	11.5	7.0	5.6	2.9	1.4
600	68.0	33.3	22.3	17.3	10.5	8.3	4.3	2.1
800	90.7	44.5	29.8	23.0	14.1	11.1	5.8	2.9
1000	113.4	55.6	37.2	28.8	17.6	13.9	7.2	3.6
1200	136.1	66.7	44.6	34.6	21.1	16.7	8.6	4.3
1400	158.8	77.8	52.1	40.3	24.6	19.4	10.1	5.0
1600	181.5	88.9	59.5	46.1	28.1	22.2	11.5	5.7
1800	204.1	100.0	67.0	51.9	31.6	25.0	13.0	6.4
2000	226.8	111.1	74.4	57.6	35.2	27.8	14.4	7.1
2500	283.5	138.9	93.0	72.0	44.0	34.7	18.0	8.9
3000	340.2	166.7	111.6	86.4	52.7	41.7	21.6	10.7

Table B-1 Maximum Gas Velocity (m/s)

B.2 Maximum Flow (m^3/hr)

		Pipe Size (mm)						
		63	90	110	125	160	180	250
Velocity (m/s)	1	9	18	27	35	57	72	139
	2	18	36	54	69	114	144	278
	3	26	54	81	104	171	216	417
	4	35	72	108	139	227	288	555
	5	44	90	134	174	284	360	694
	6	53	108	161	208	341	432	833
	7	62	126	188	243	398	504	972
	8	71	144	215	278	455	576	1111
	9	79	162	242	312	512	648	1250
	10	88	180	269	347	569	720	1389

Table B-2 Maximum Flow (m^3/hr)

B.3 Minimum Pipe OD (mm)

Flow (m^3/hr)	Velocity (m/s) 1	2	3	4	5	6	7
10	67	47	39	34	30	27	24
20	95	67	55	47	42	39	34
30	116	82	67	58	52	47	41
40	134	95	77	67	60	55	47
50	150	106	87	75	67	61	53
60	164	116	95	82	73	67	58
70	178	126	102	89	79	72	63
80	190	134	110	95	85	77	67
100	212	150	122	106	95	87	75
200	300	212	173	150	134	122	106
400	424	300	245	212	190	173	150
600	520	367	300	260	232	212	184
800	600	424	346	300	268	245	212
1000	671	474	387	335	300	274	237
1200	735	520	424	367	329	300	260
1400	794	561	458	397	355	324	281
1600	849	600	490	424	380	346	300
1800	900	636	520	450	403	367	318
2000	949	671	548	474	424	387	335
2500	1061	750	612	530	474	433	375
3000	1162	822	671	581	520	474	411

Table B-3 Minimum Pipe OD (mm)

B.4 Pressure Loss (mbar)

Pressure loss per 100 metre pipe in mbar (no internal debeading) for SDR 17.6 MDPE pipe.

		Pipe Size (mm)								
		63	90	110	125	160	180	250	355	63
Flow (m^3/hr)	10	0.19	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00
	20	0.77	0.13	0.05	0.03	0.01	0.00	0.00	0.00	0.00
	30	1.74	0.29	0.11	0.06	0.02	0.01	0.00	0.00	0.00
	40	3.09	0.52	0.19	0.10	0.03	0.02	0.00	0.00	0.00
	50	4.83	0.81	0.30	0.16	0.05	0.03	0.00	0.00	0.00
	60	6.96	1.17	0.43	0.23	0.07	0.04	0.01	0.00	0.00
	70	12.39	2.07	0.76	0.40	0.12	0.06	0.01	0.00	0.00
	80	19.42	3.24	1.19	0.63	0.18	0.10	0.02	0.01	0.00
	100	79.70	13.02	4.76	2.51	0.73	0.40	0.08	0.02	0.01
	200	363.2	52.97	19.15	10.07	2.92	1.62	0.31	0.10	0.05
	400		122.9	43.53	22.77	6.58	3.65	0.70	0.22	0.12
	600		229.1	78.55	40.79	11.73	6.49	1.25	0.39	0.22
	800		385.8	125.3	64.37	18.37	10.16	1.96	0.62	0.34
	1000			185.2	93.89	26.55	14.66	2.82	0.89	0.49
	1200			261.1	129.8	36.29	20.00	3.84	1.21	0.66
	1400			357.0	172.8	47.62	26.19	5.02	1.58	0.87
	1600			481.0	223.9	60.61	33.24	6.36	2.00	1.10
	1800			651.9	284.3	75.29	41.18	7.86	2.47	1.36
	2000				492.7	120.0	65.00	12.30	3.86	2.12
	2500					177.2	94.81	17.75	5.56	3.06
	3000					339.9	174.6	31.74	9.90	5.44

Table B-4 Pressure Loss (mbar)

B.5 Pressure Loss Principles

The following section describes the principles for calculating flow losses. However, it is rarely necessary to go back to first principles and calculate these values. Spreadsheets, online calculators and modelling software are available to do the mathematics. These will normally store tables of values for frictional coefficients and pipe roughness.

B.5.1 Dependencies

Pressure loss depends on:

- gas properties
- pipe properties
- flow rate
- line Losses

At low flow rates the flow is said to "laminar" and the calculation is simplified. At higher flow rates the flow can be "turbulent" and the calculation is more complex.

B.5.1.1 Gas Properties

Molecular weight - kg/kmol

Gas compressibility - (z) at low pressures this can be assumed as 1.

Viscosity - measured in Centipoise this is dependent on temperature.

B.5.1.2 Pipe Properties

Pipe diameter (external)

Pipe wall thickness

Pipe roughness

B.5.1.3 Flow Rate

Flow rate in kg/hr or m^3/s (derived from density of gas).

B.5.1.4 Line Losses

The number of bends and in line fittings will increase the losses.

Appendix C Balancing Examples

C.1 Extraction Matches Production

Ideally, gas consumed will equal gas produced.

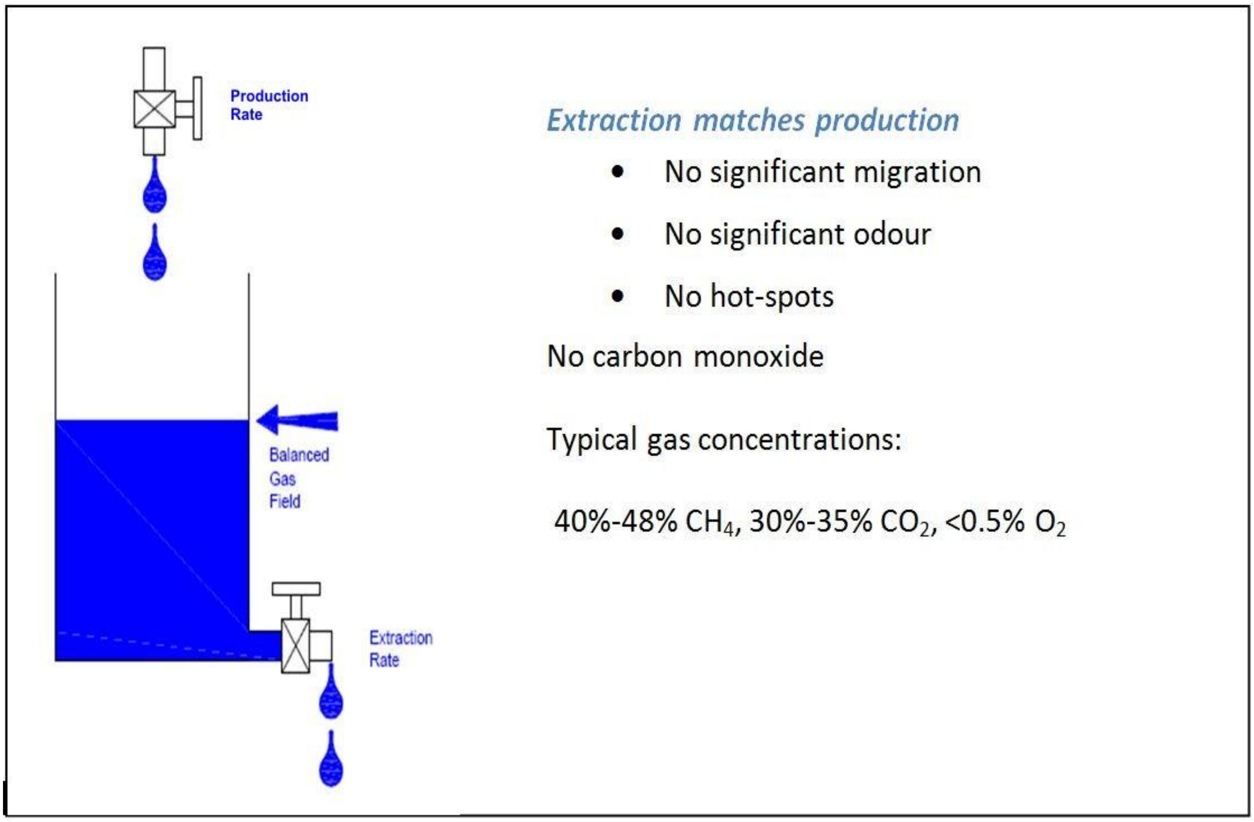


Figure C.1: Extraction Matches Production

C.2 Extraction Exceeds Production

Risk of air being drawn into site causing hot spots.

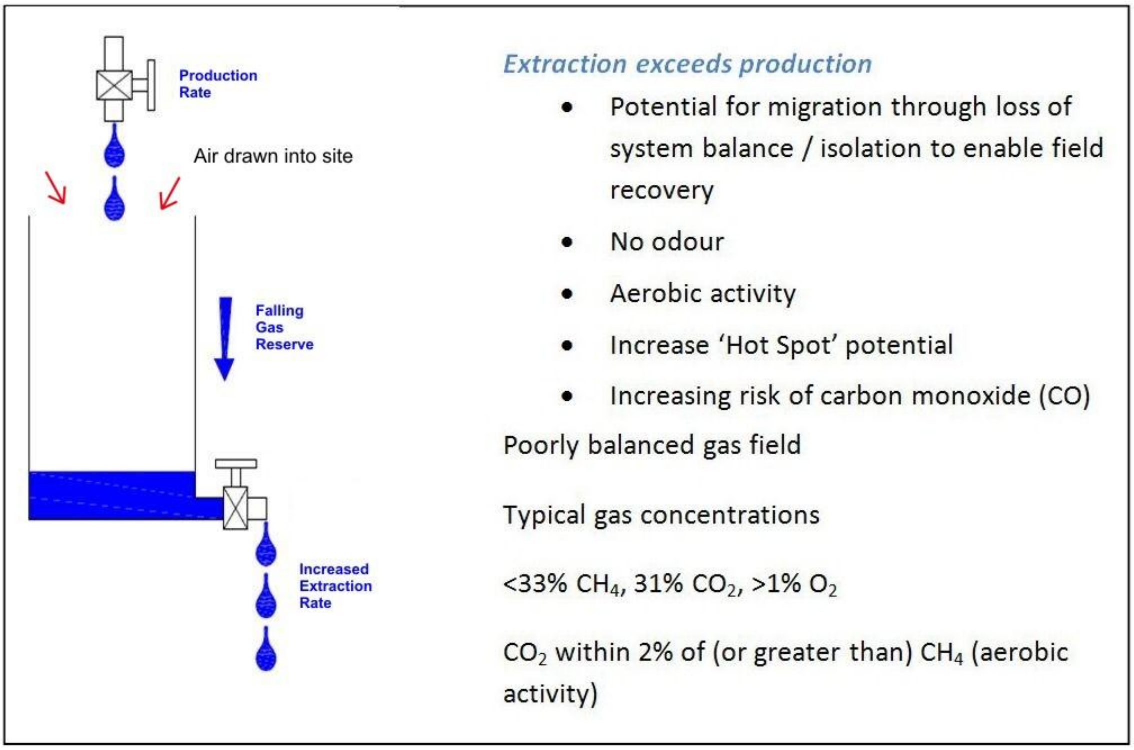


Figure C.2: Extraction Exceeds Production

C.3 Production Exceeds Extraction

Excess gas can leak to atmosphere.

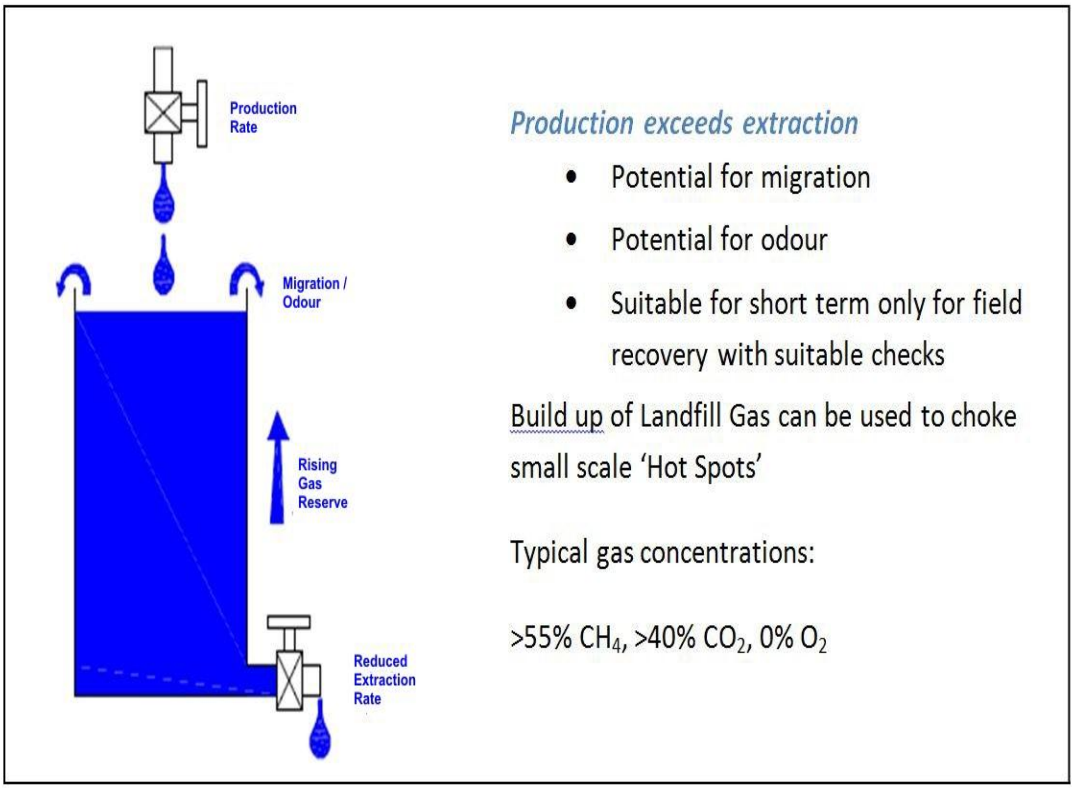


Figure C.3: Production Exceeds Extraction

Appendix D Vacuum Distribution Diagrams

The vacuum profile around a well will be dependent on the make up of the waste into which it is drilled. This appendix includes diagrams for the following scenarios:

- homogeneous waste
- elevated / perched leachate levels
- targeted vacuums
- blinding
- cross influence / interference vacuum
- vacuums and gas wells in 3D liners

The vertical effectiveness of a gas well below the casing is thought to be limited by decreasing permeability of the waste with depth. Conservatively, due to the potential for stratification resulting from the placement of cohesive soils as daily cover and increasing moisture content, effective vertical influence is likely to be limited to the thickness of a single lift of waste after considering settlement.

However, in a sealed system, it is likely that gas will slowly (unless prevented from doing so) move up in the direction of the pressure gradient into the gas well over time.

D.1 Vacuum in Homogeneous Waste

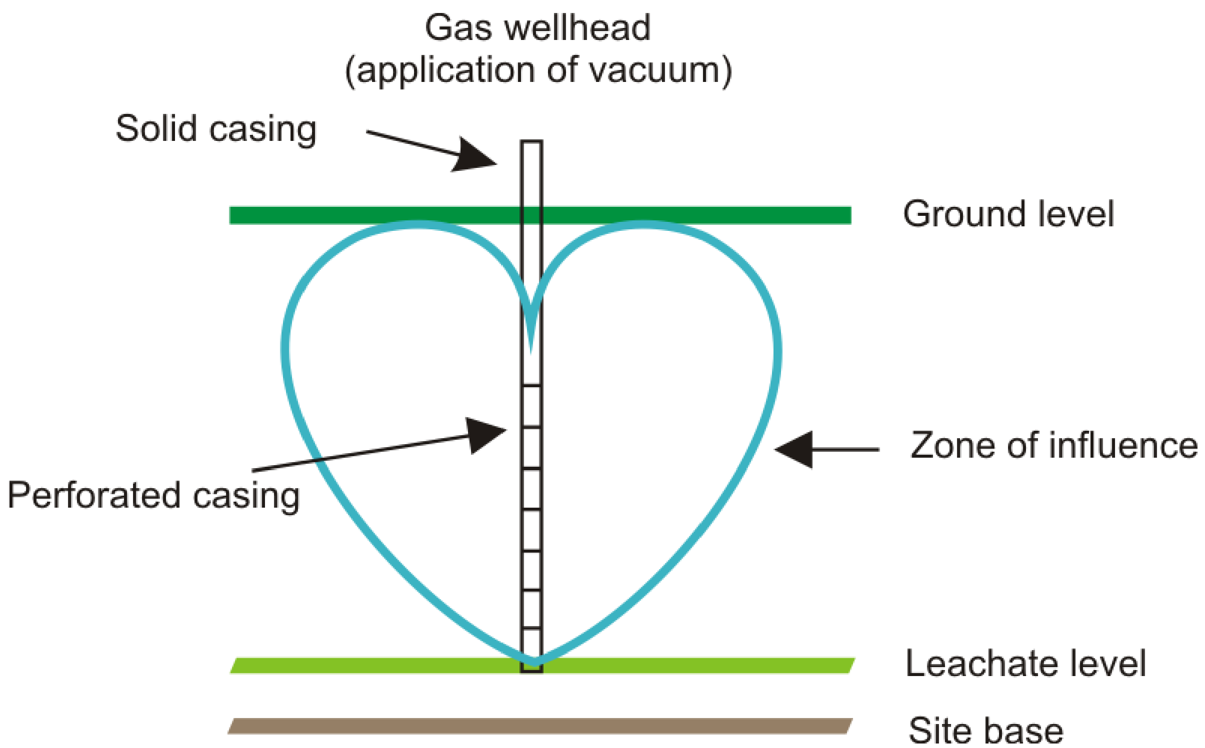


Figure D.1: Vacuum in Homogeneous Waste

D.2 Elevated / Perched Leachate Levels

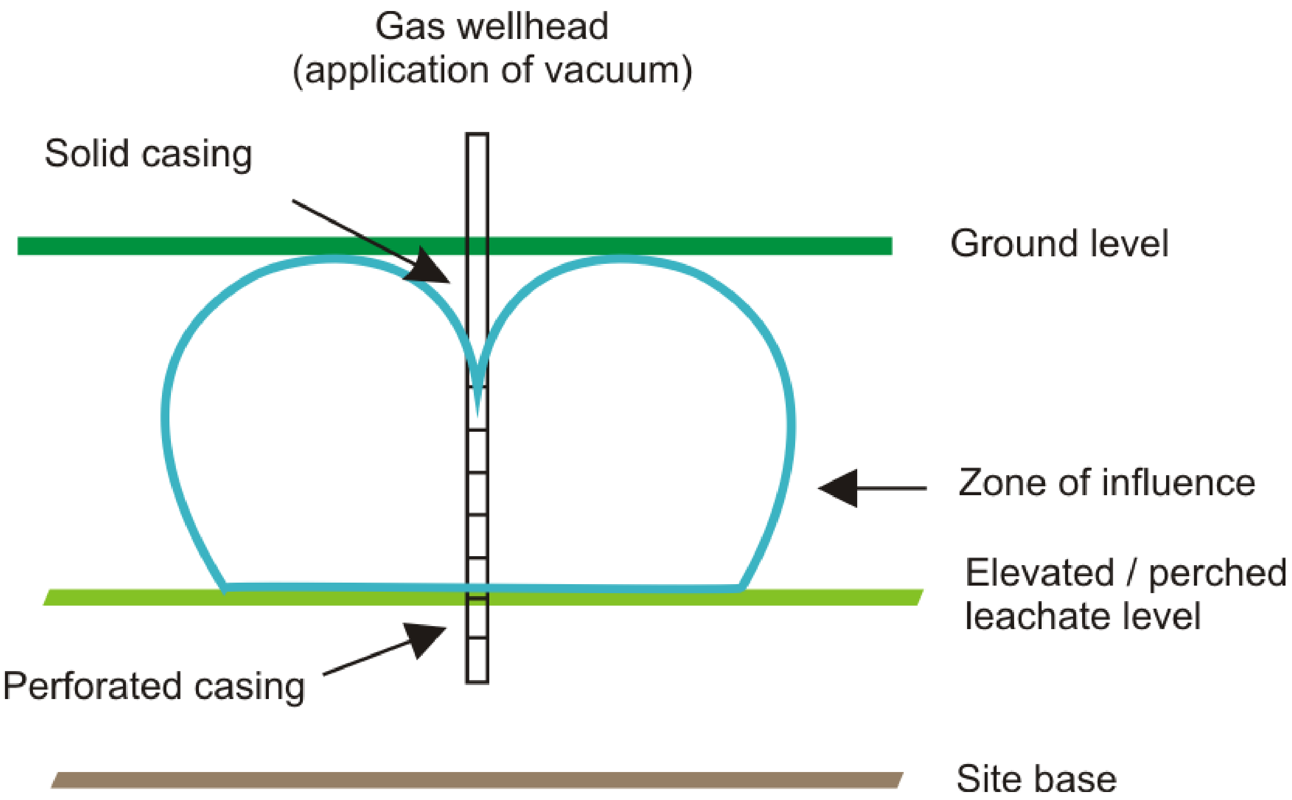


Figure D.2: Elevated / Perched Leachate Levels

D.3 Targeted Vacuums

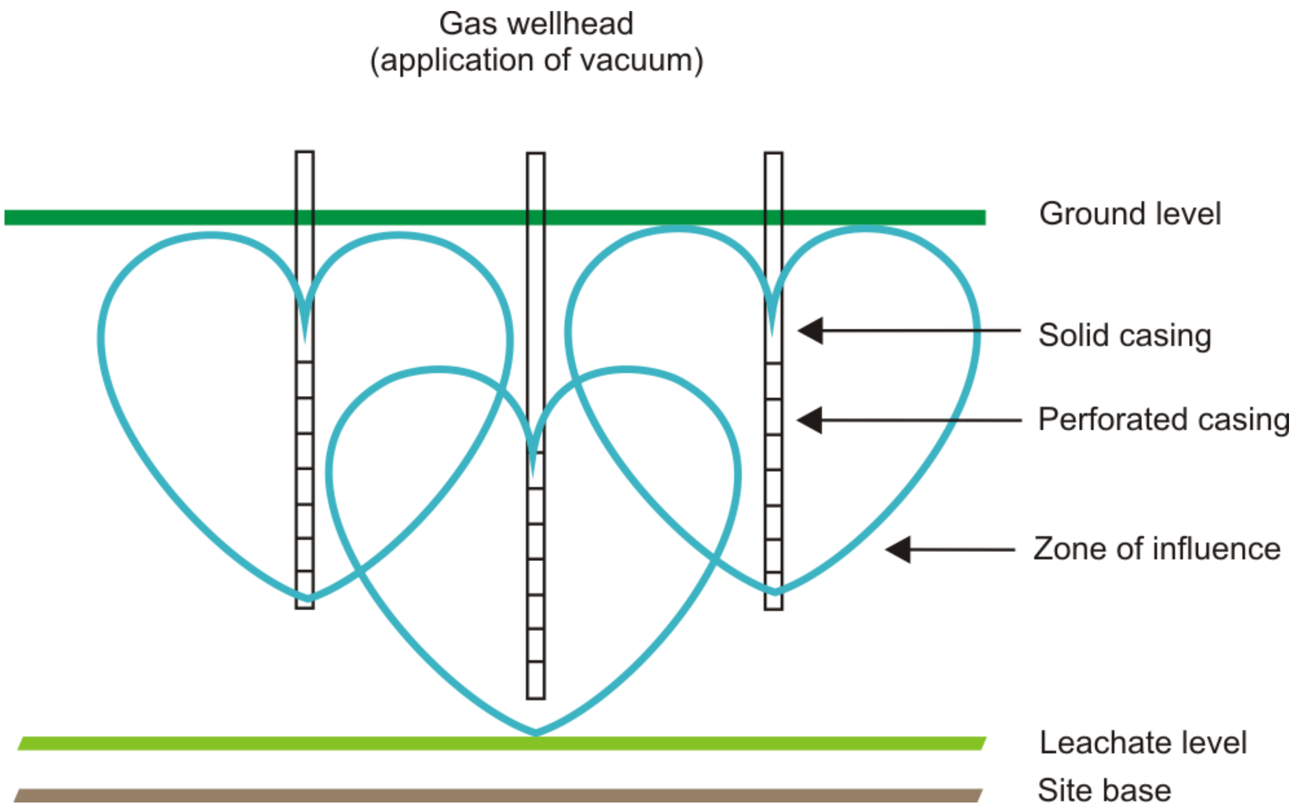


Figure D.3: Targeted Vacuums

D.4 Blinding

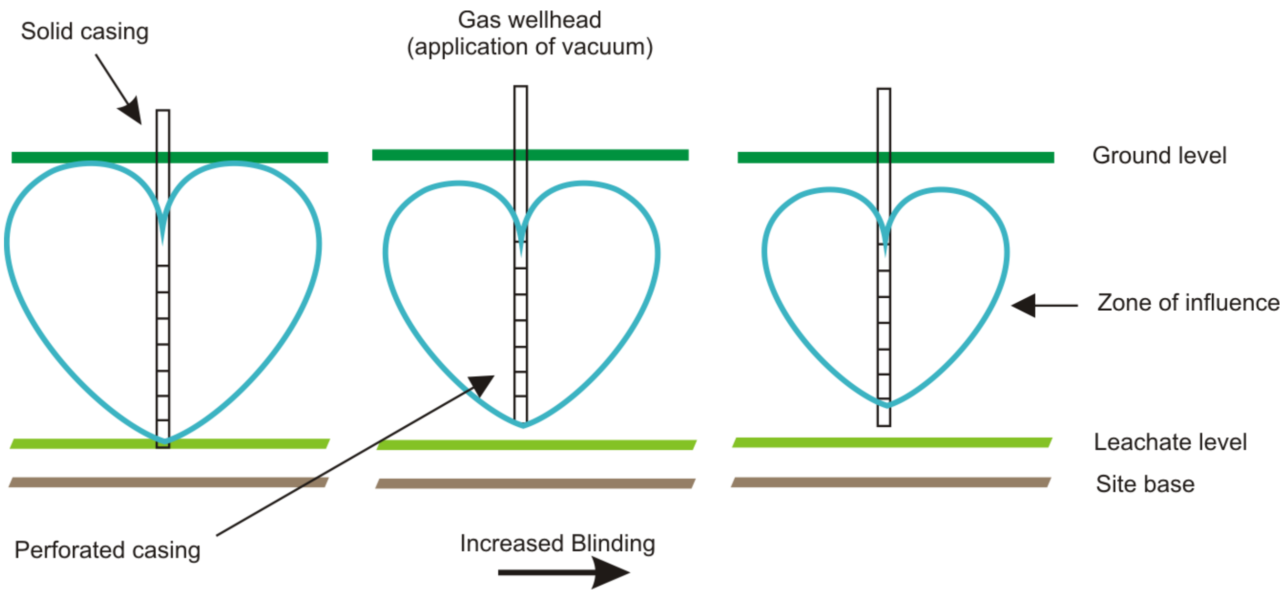


Figure D.4: Blinding

D.5 Cross Influence / Interference Vacuum

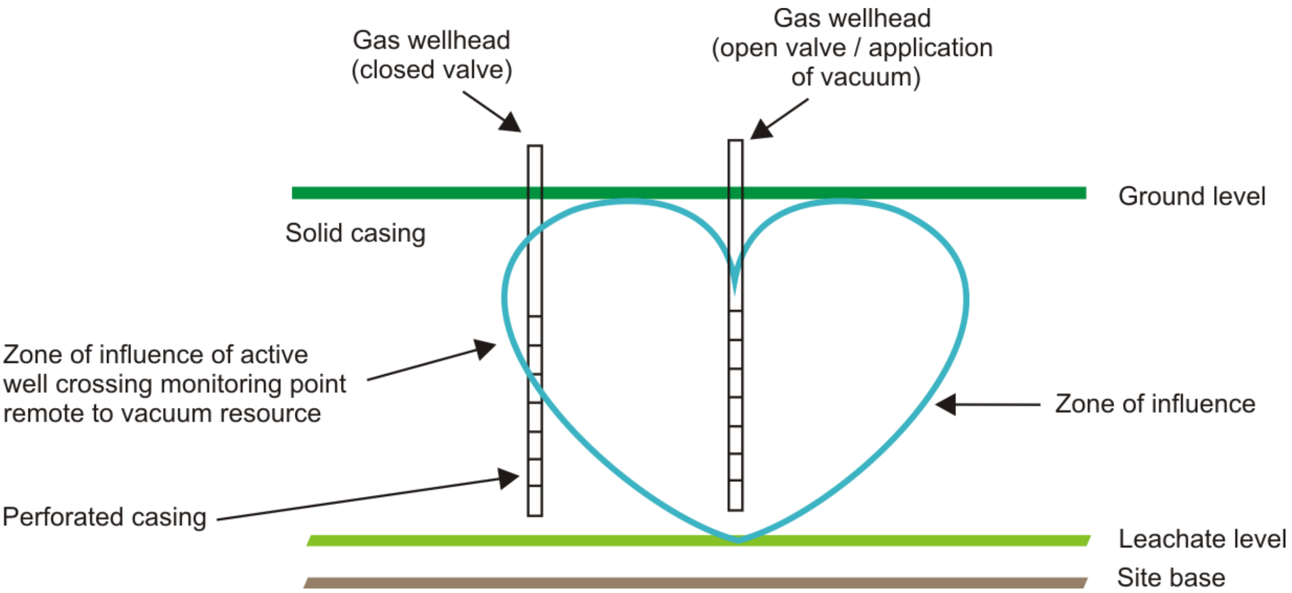


Figure D.5: Cross Influence/ Interference Vacuum

D.6 Vacuum Distribution 3D Liners

D 6.1 Installations of gas wells and distribution of vacuums in 3D liners.

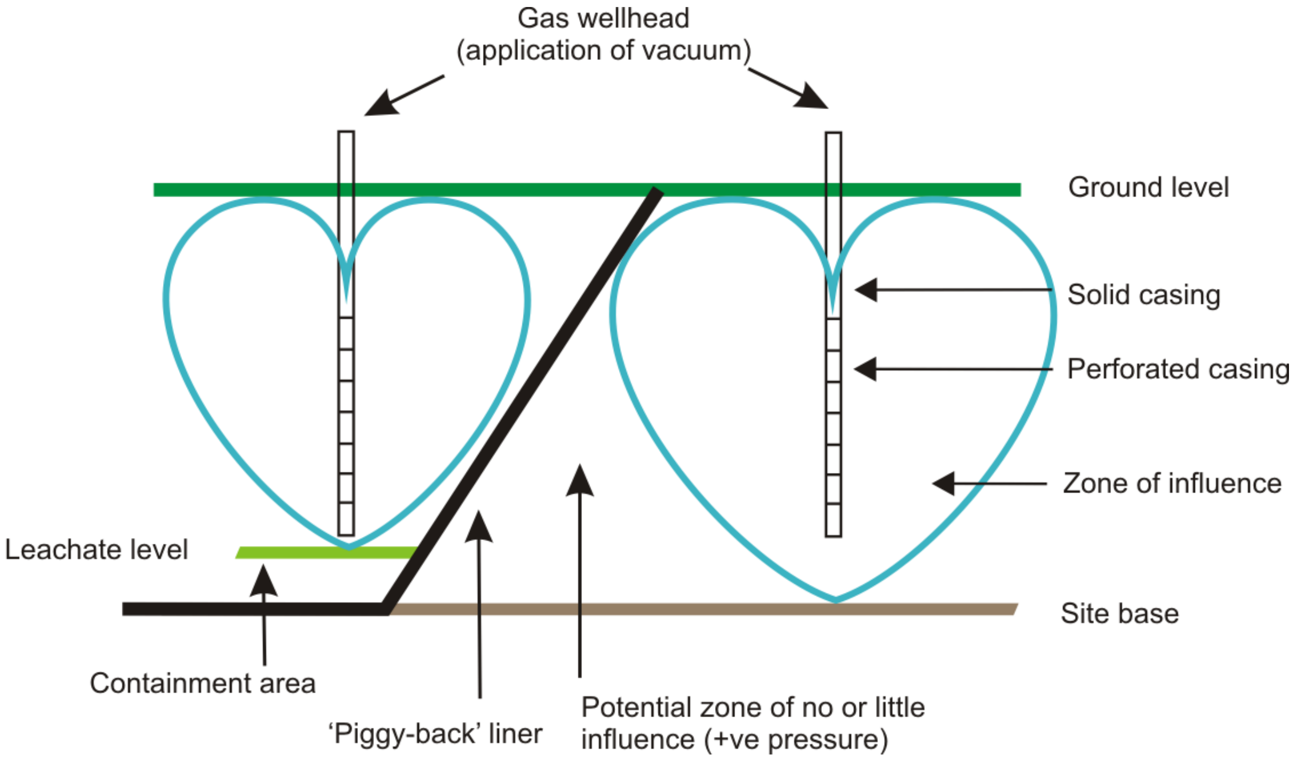


Figure D.6: Vacuum in 3D Liner

However close the well is placed to the liner, there is a potential 'zone of little influence'.

D.6.2 Vertical Gas Well in 3D Liner

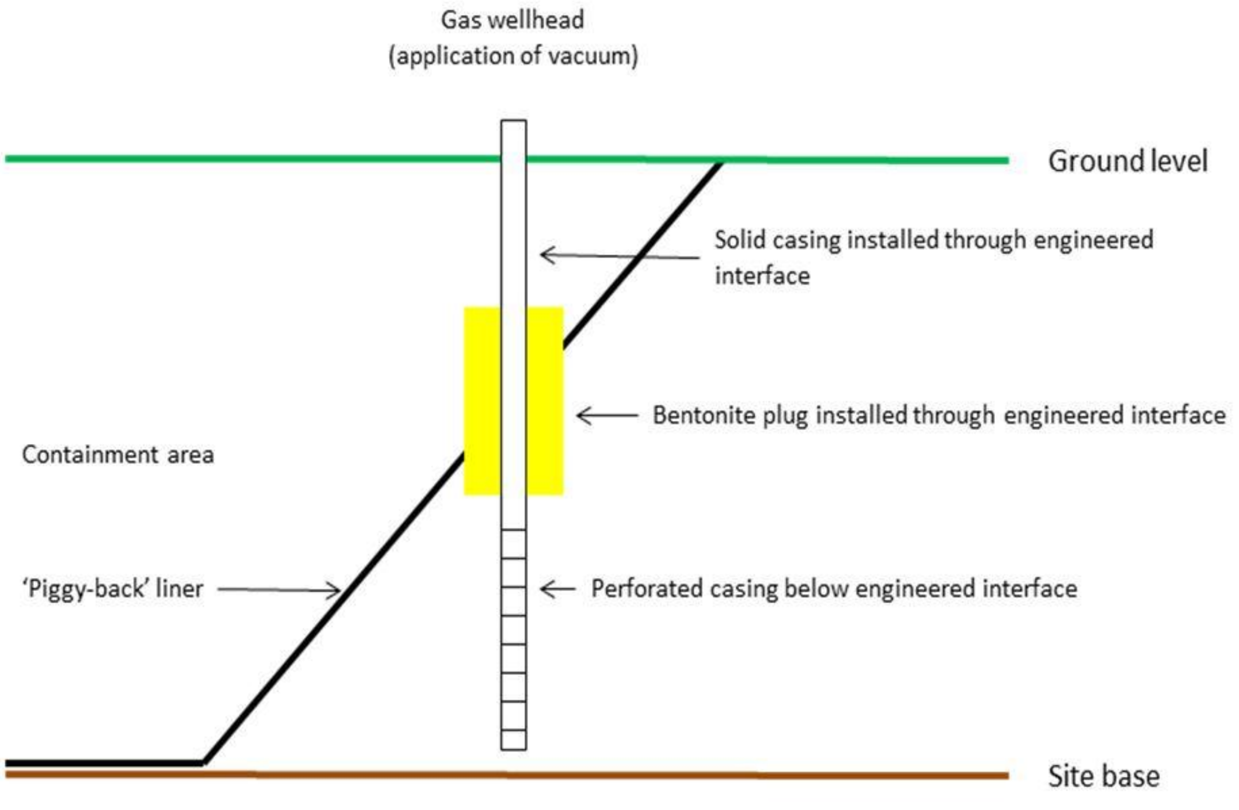


Figure D.7: Vertical Gas Well in 3D Liner

D 7 Under Liner Extraction Well

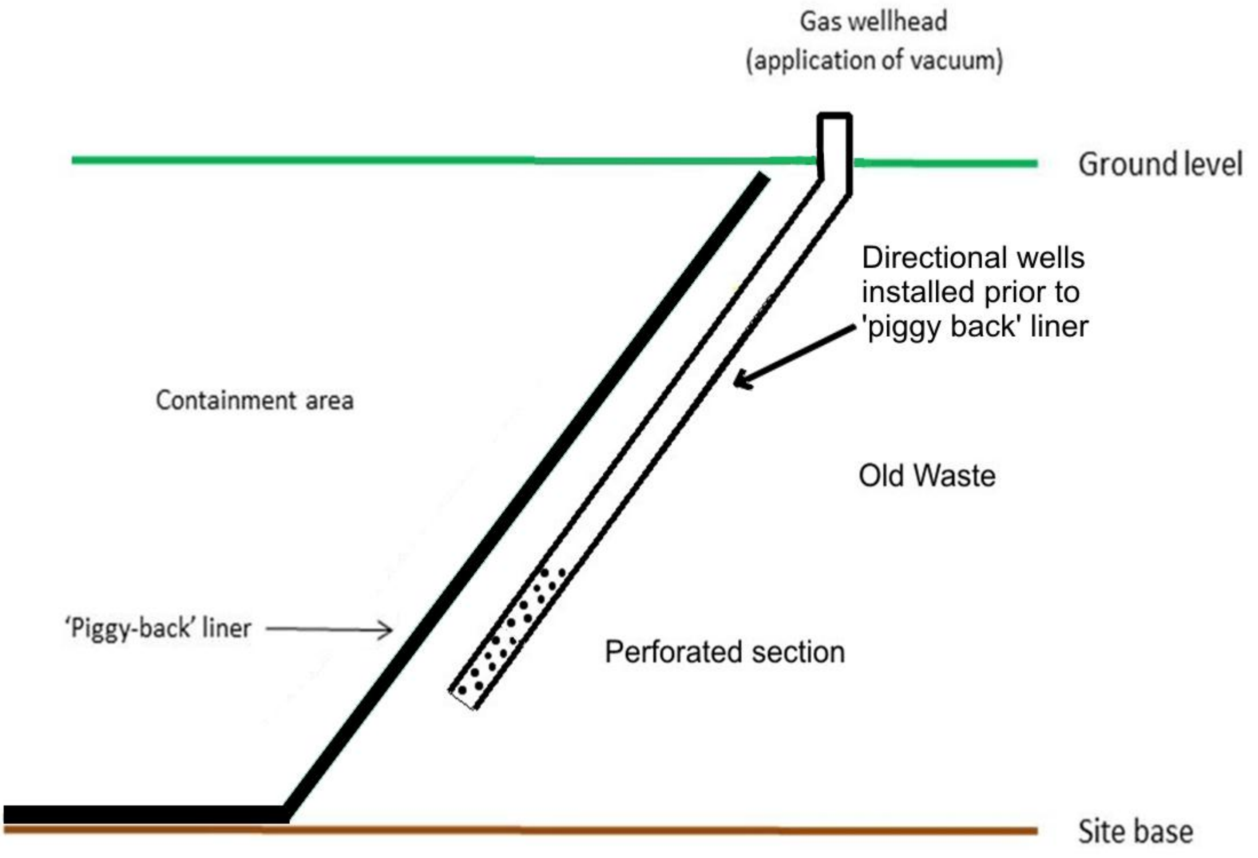


Figure D.8: Under Liner Extraction Well

D.8 Radius of Influence

Each well will have a radius of influence outside of which it will not draw gas. It is essential to drill wells so as to minimise areas which are not under influence, as these areas could allow migration to the air. The radii of influence should therefore overlap.

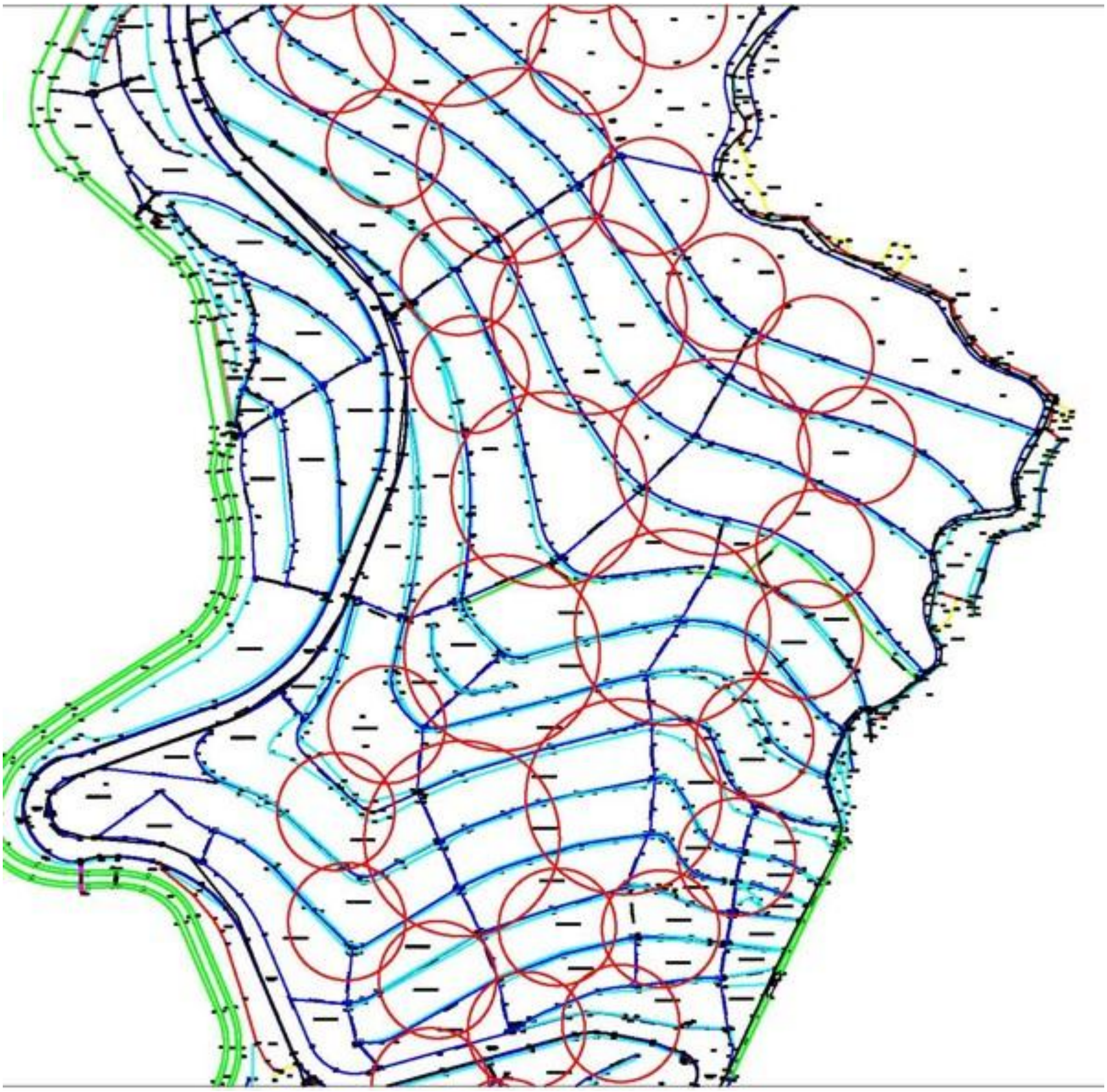


Figure D.9: Radius of Influence

Appendix E Knockout Pot Examples

Knockout pots are used to extract moisture (condensate) from the gas flow. The moisture is usually fed back to the waste, either directly (barometric or self draining) pot or by means of a pump (air or electric). Knockout pots can be made of MDPE or steel.

Within the gas field, self dewatering pots can be used and should be placed at low points in the pipework. Off the gas field, pumped pots must be used, for example, as the gas main enters the compound.

There are four main types of knockout pot used:

E.1 Electro Pumped

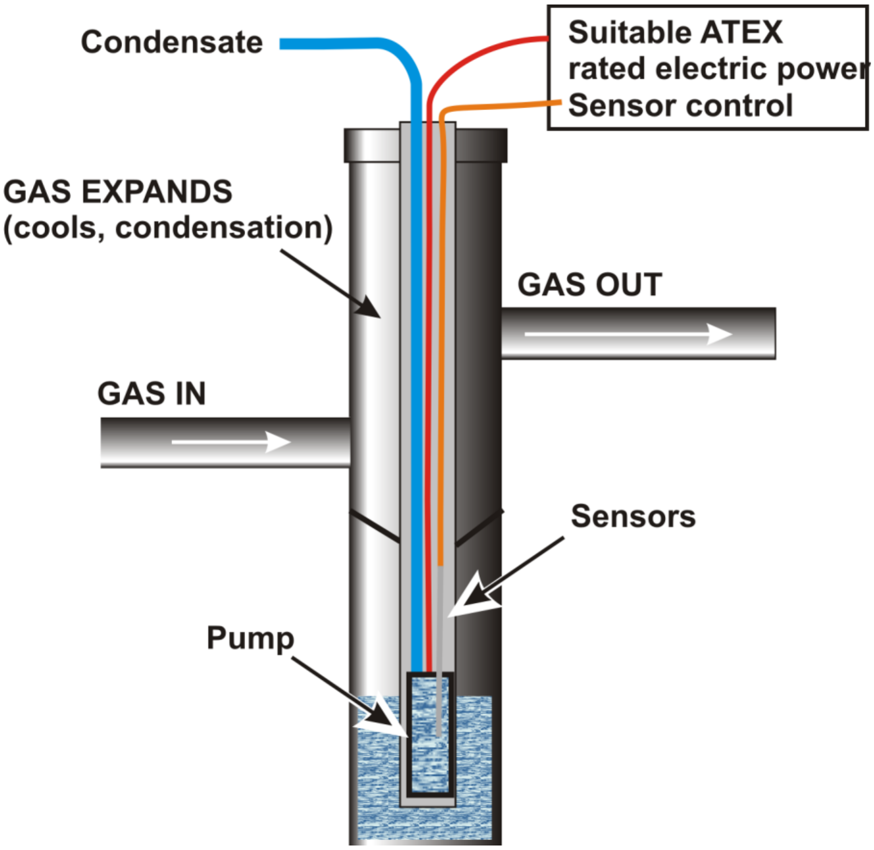
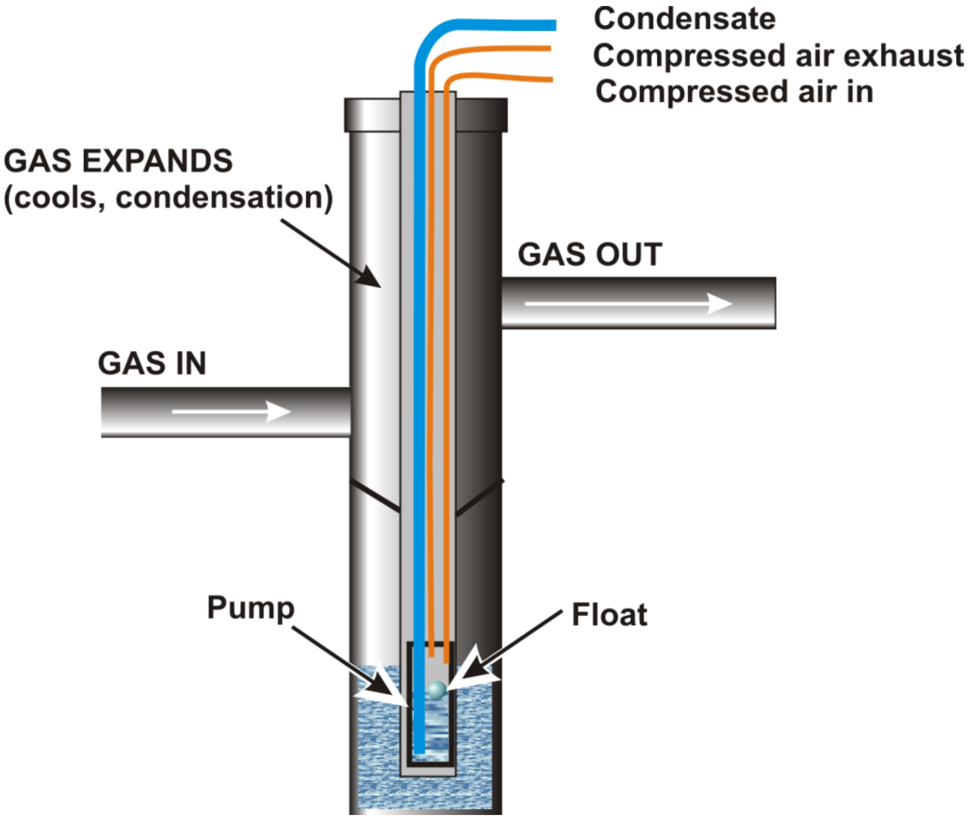


Figure E.1 Electric Pumped KO Pot

E.2 Air Pumped KO Pot



E.2 Air Pumped KO Pot

E.3 Gravity Draining KO Pot

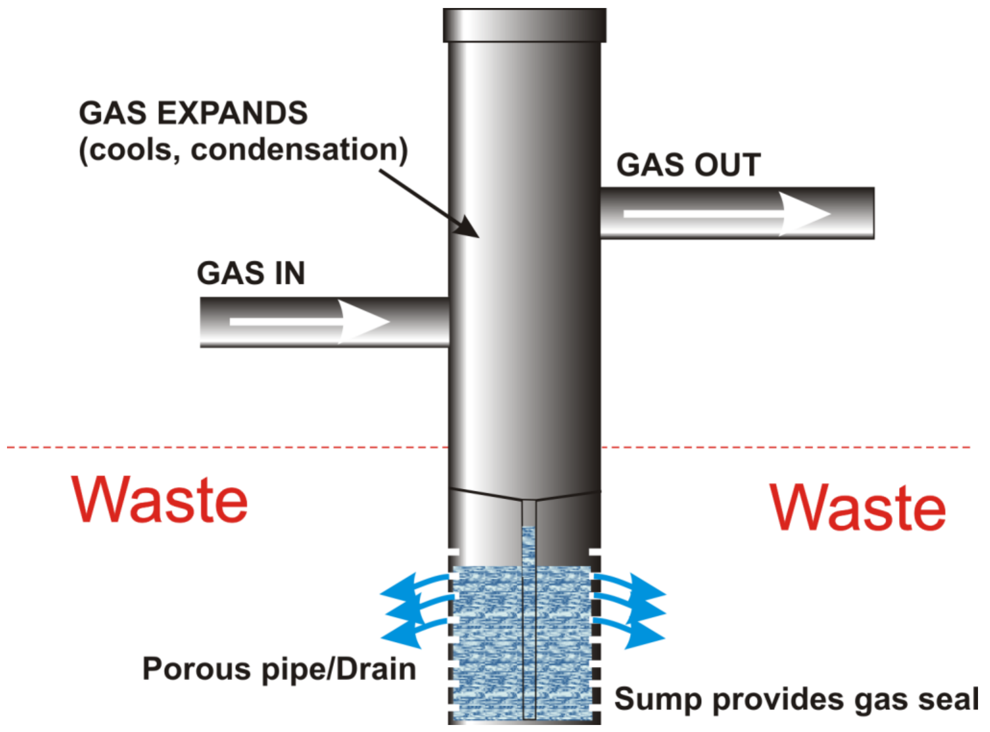


Figure E.3: Gravity Drained KO Pot

E.4 Barometric (Self Draining) Drain Leg

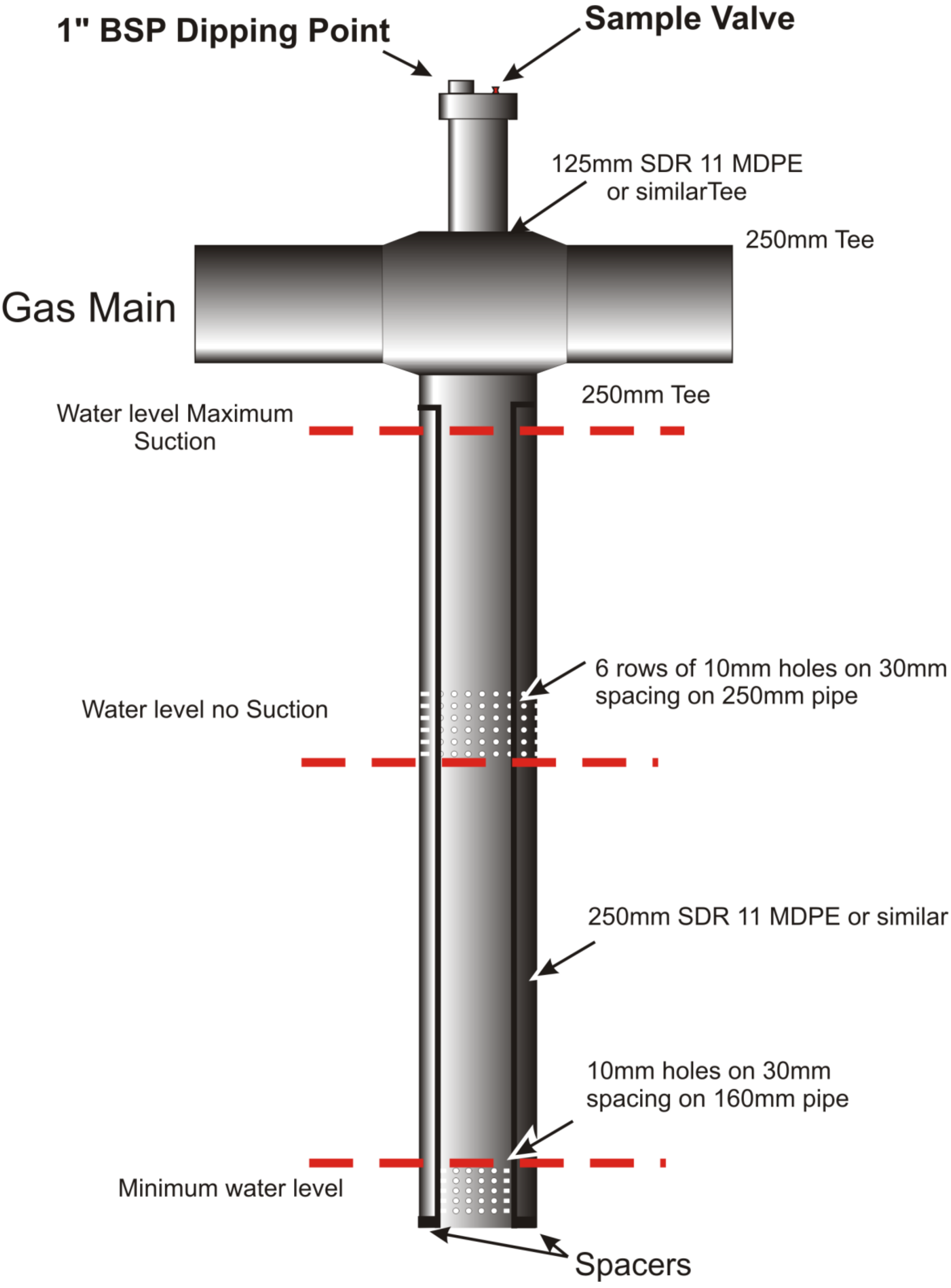


Figure E.4: Barometric (Self draining) Drain Leg

Appendix F Gas Well

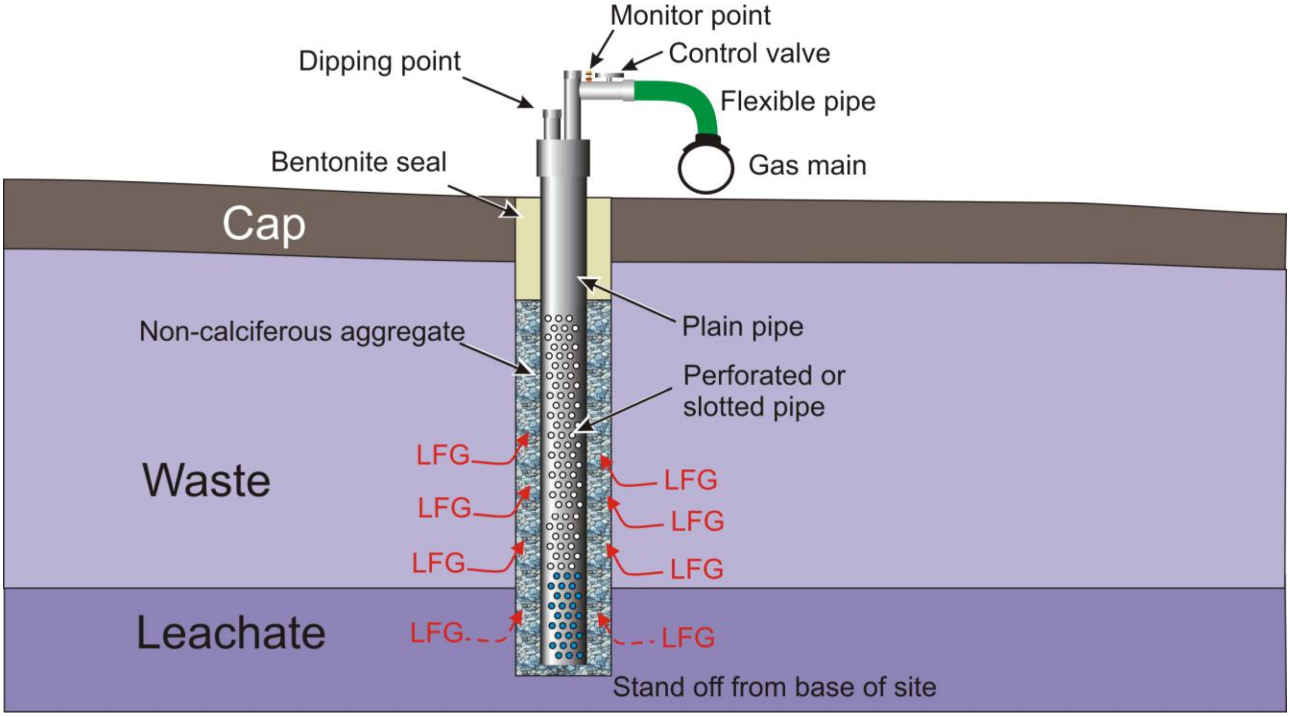


Figure F.1: Gas Well

Appendix G Gas Headwork Arrangements

G.1 Well Head with Sampling Point - Remote Valve

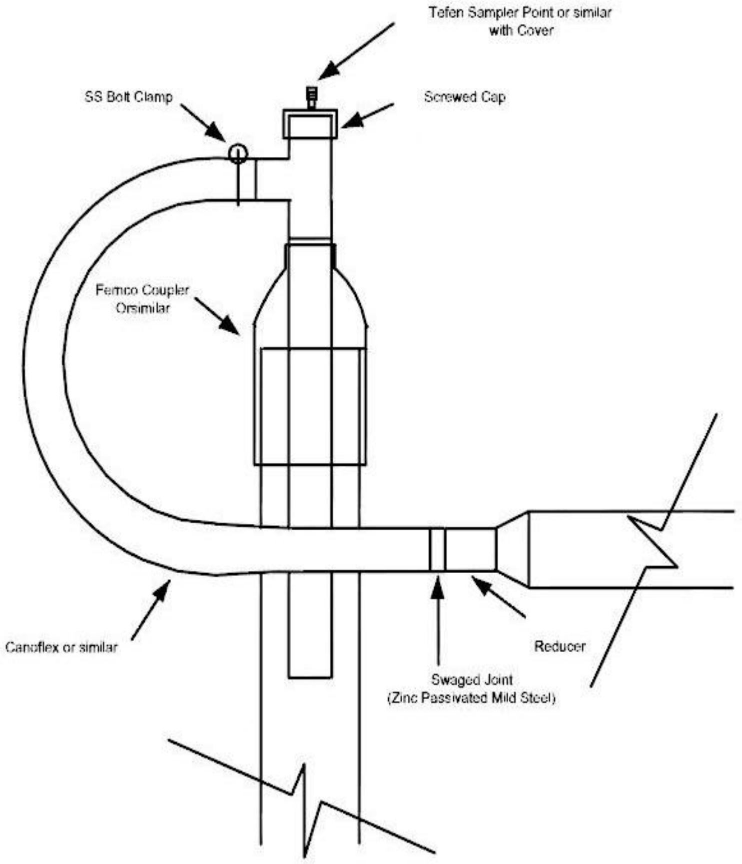


Figure G.1: Well Head - No Valve

G.2 Well Head with Sampling Point and Valve

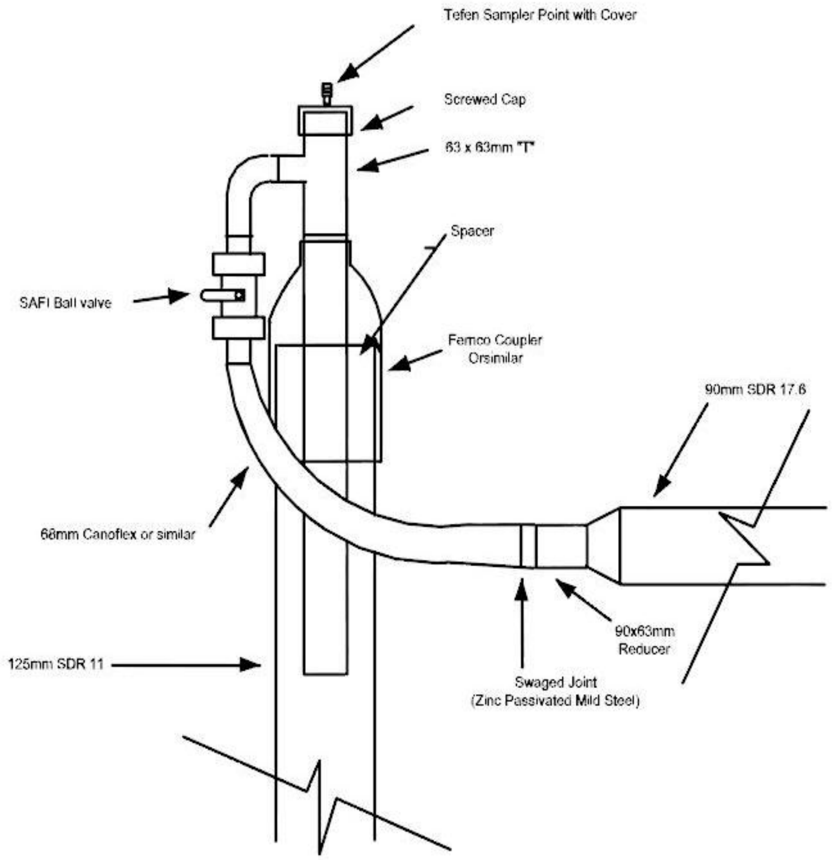


Figure G.2: Well Head With Valve

G.3 Impact Well (Assumed Remote Valve)

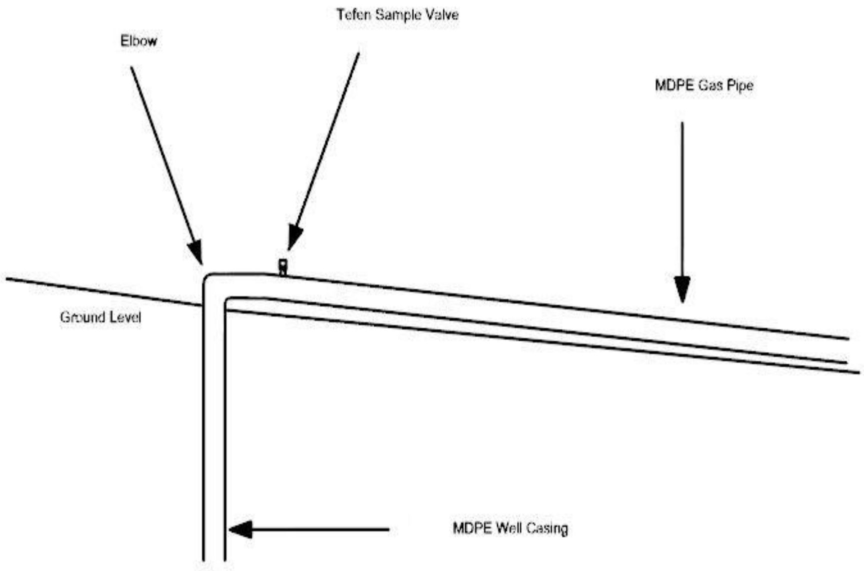


Figure G.3: Impact Well

G.4 Impact Well with Valve

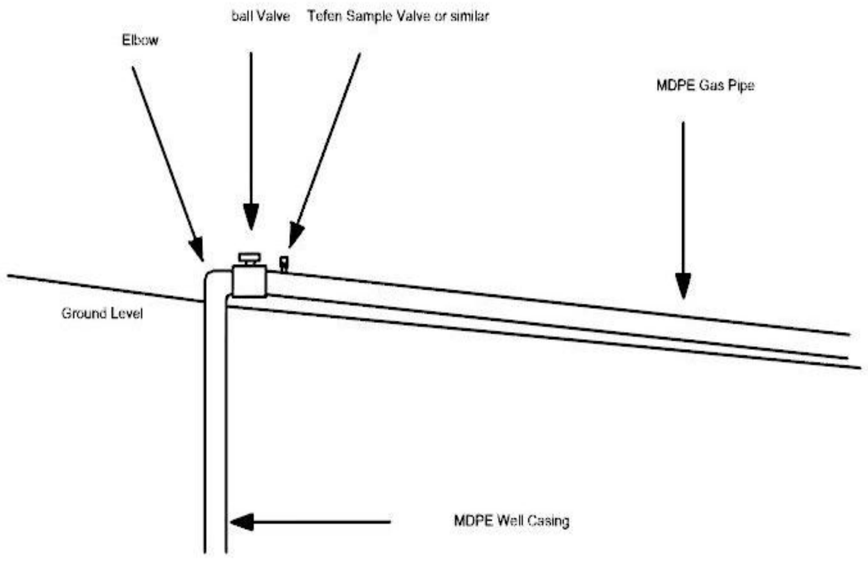


Figure G.4: Impact Well with Valve

G.5 Self or Back Watering Wellhead

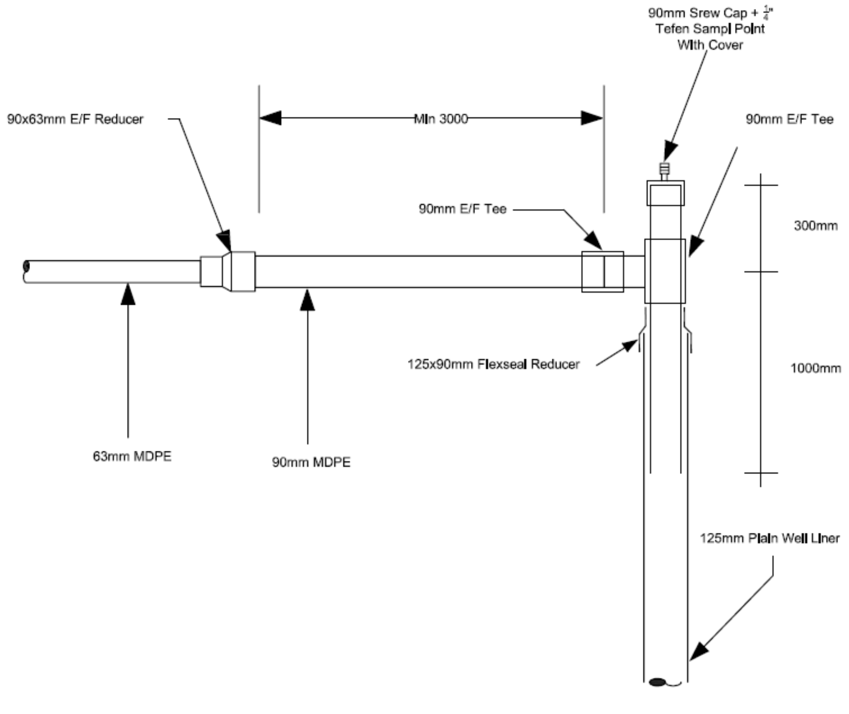


Figure G.5: Self or Back Watering Wellhead

G.6 Gas Well Cover

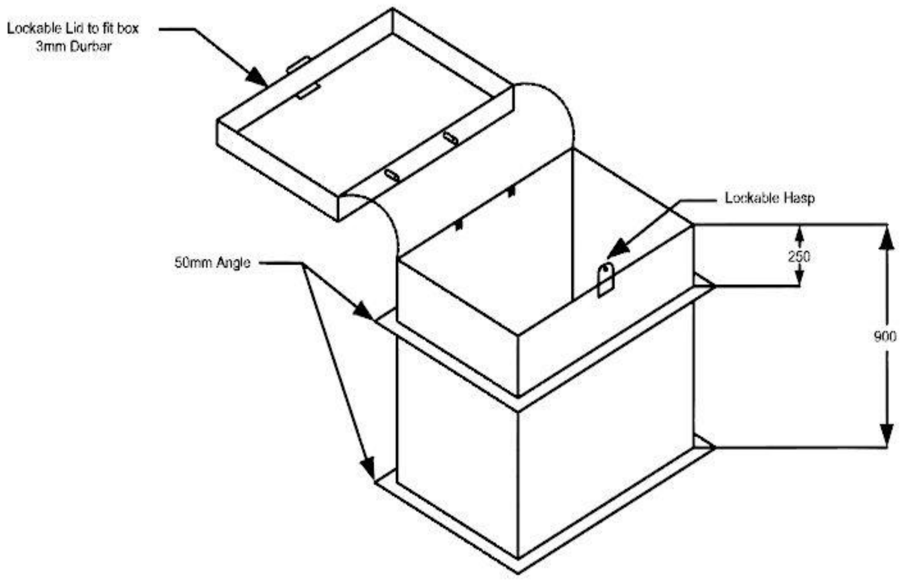


Figure G.6: Gas Well Cover

Glossary

Term	Definition
Aerobic	In the presence of air (oxygen)
Anaerobic	In the absence of air (oxygen)
Analyte	A substance or chemical constituent that is determined in an analytical procedure
Annulus	Ring shaped opening (for example, a borehole)
AOP	Analysis Operating Parameters
Asset management	The process of recording the equipment owned by the company and planning its serviceable life
Assets	Items owned by the company. Assets above a certain value are recorded in their own right For example, a gas field is an asset, as is a flare stack and a gas engine / generator. Smaller items, such as pipes and regulators, are parts that collectively make up the asset.
ATEX	ATEX Directives (ATEX 95 *equipment* directive 94/9/EC and ATEX 137 *workplace* directive 99/92/EC.
Bag sampling	Compound trace gas The process of filling a Tedlar© bag with gas to enable a detailed analysis
Balancing	Adjusting the gas extracted to meet the gas produced. Adjusting the flow from individual wells
Bentonite seals	A seal made of Fuller's earth that prevents the escape of gas from the cap of a well. Bentonite expands when wet to create a gas tight seal
Blinding	Where the waste mass blocks the perforations in the well reducing the effective vacuum
Biogas	Gas formed by digestion of organic materials
Borehole	A hole drilled outside the waste site for the purpose of monitoring or sampling.
Butt-fusion welding	A method of joining pipes by heating the ends and fusing them together under heat and pressure
Calibration	The process of ensuring a measuring device is accurate by comparing it against a known standard
Camera surveys	Using a camera with its own light source to inspect the inside of a well
Capping	The process of placing a layer of material over a site to prevent the release of gas and the ingress of air. Caps can be temporary or permanent, mineral or synthetic
Capping material	A landfill covering, usually having a low permeability to water. Permanent capping is part of the final restoration following completion of landfill/tipping. Temporary capping is an intermediate cap, which may be removed on the resumption of tipping
Carrier main	The main gas pipe fed by pipes attached to individual wells
Carrier sizing	Determining the required size of a carrier pipe in order to maintain a speed of 6 m/s uphill and 10 m/s downhill

Cell	The compartment within a landfill in which waste is deposited: The cell has physical boundaries, which may be a low permeability base, a bund wall and a low permeability cover
Closed sites	Landfill sites ceased to accept waste on a temporary or permanent basis
COD	Chemical Oxygen Demand. The concentration of oxygen required by bacteria to consume waste. (g/l)
Compliance balancing	The process of drawing of gas to prevent dispersal to the air, where there is insufficient gas to drive a generator
Condensate	Liquid held as a vapour within the gas
Contained (engineered)	A site artificially designed to prevent migration of waste liquids and gas to the surrounding area
COSHH	Control of Substances Hazardous to Health Regulations 2002
Cover	Daily cover material which may be used at the end of each working day to minimise odours, wind-blown litter, insect or rodent infestation, and water ingress. Final cover is the layer or layers of materials placed on the surface of the landfill before its restoration
CQA	Construction Quality Assurance
Dew point	The temperature at which vapour condenses out of a gas
Derivatisation	A technique used in chemistry which transforms a chemical compound into a product (the reactions derivate) of similar chemical structure, called a derivative
Dilute and Disperse	A landfill designed to allow leachate to disperse naturally into the ground and therefore be diluted by groundwater
Dip tapes	A calibrated tape holding a sensor (liquid or temperature) to calculate the depth within a well
Dipping	Using a sensor to dip into a well to measure liquid level, gas pressure or temperature
Drain legs	A simple device that collects moisture from a gas flow
DNPH	dinitrophenylhydrazine
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations 2002 (the UK implementation of the European Union ATEX directives)
Electrofusion welding	A method of joining pipes by using a heated collar to melt the ends
Emission	The direct or indirect release of substances, vibrations, heat or noise from individual or diffuse sources in an installation into the air, water or land.
Exceptions report	A report which includes only parameters which are out of specification
FID	Flame Ionisation Detection
Flare	A device for burning off excess waste gas
Flow meters	A device to measure the flow rate (l/s) of a gas
Flow velocity	The flow rate (m^3/s) divided by the cross sectional area (m^2) of the pipe
Flux box monitoring	A box, about 3 m x 3 m that collects and funnels gas from the cap to allow the measurement of leakage
Fuel consumption curves	A graphical representation of the amount of gas used over a set period. For example, l/hr
Fuller's earth	Calcium Bentonite
Fusion box	The power supply that connects to a fusion cap to heat it and allow fusion welding

Gas composition	The component gases within a gas flow. For example, air is composed of nitrogen, oxygen, carbon dioxide and other trace gases. LFG is composed of methane and carbon dioxide, with traces of ammonia, hydrogen sulphide and other gases
Gas decline	The reduction in gas production over a set period
Gas drainage layer	A layer of high gas permeability placed just below the cap to facilitate gas collection
Gas flow	Rate in m^3/s of the gas flow
Gas plant	The equipment use to extract gas and deliver to flare or generator
Gas pumping trials	Test wells used to estimate the gas production within a new site
GCS	Gas collection system
Generator	Device used to produce electricity; driven by a rotating engine
Groundwater	All water that is below the surface of the ground and in direct contact with the ground or subsoil
GUP	Gas Utilisation Plant
GWCS	Gas Well Condition Survey
H&S	Health and safety
H_2S	Hydrogen sulphide
Herring Bone system	A method of connecting wells to a central pipe
High Compliance Sites	Sites in especially environmentally sensitive areas
Horizontal systems	Gas wells installed horizontally as a site is filled
ICoP	Industry Code of Practice
Image mapping	A map showing the position of wells and another parameter such as temperature, methane content or oxygen
Interstitial	Occurring in the interstices (spaces) between other material
Intrinsically safe	Apparatus that is designed to be safe under dangerous conditions - usually refers to equipment that can be used in an explosive atmosphere because it will not produce a spark
Inventory	Parts held in a store room
Knockout pot	A device for removing condensate from gas by allowing the gas to expand and cool
Knockout pump	The pump contained within a knockout pot
KO	Knockout
KPI	Key Performance Indicator
Landfill Design	The process of designing a site to ensure maximum gas production and minimal pollution
Leachate	Liquid formed in a landfill site as a result of water infiltration (rainfall) or liquid disposal (now banned). Leachate is generally collected at the base of the site and treated before disposal. Older sites allow leachate to disperse into the groundwater below the site.
Leachate recirculation	The practice of returning leachate to the landfill from which it has been abstracted
LEL (Lower Explosive Limit)	The lowest percentage concentration by volume of a flammable substance in air which will allow an explosion to occur in a confined space at 25^oC and normal atmospheric pressure, and where an ignition source is present
LFGRA	Landfill Gas Risk Assessment

Liner	A natural or synthetic membrane material, used to line the base and sides of a landfill site to reduce the rate of leachate and gas emissions
Liquid dips	The process of measuring the level of liquid in a well
Mains gas	A commercial methane-rich gas distributed through underground pipes to domestic, commercial and industrial customers
Manifold system	A way of joining pipes from a set of wells into a single gas main
Marsh gas	Gas produced from marshes and bogs
Methane	Volatile gas compound (CH_4) comprising one carbon atom and four hydrogen atoms
Methanogenesis	The process leading to the production of methane
Methodology	A way of working through a process
Monitoring	A continuous or regular periodic check to determine the on going nature of the potential hazard, conditions along environmental pathways and the environmental impacts of landfill operations to ensure the landfill is performing according to design. The general definition of monitoring includes measurements undertaken for compliance purposes and those undertaken to assess landfill performance
MSW	Municipal Solid Waste
Odorant	Strictly, chemical compounds added to mains gas to impart odour or, more widely, particularly odorous volatile organic compounds in landfill gas
Odour threshold value	The concentration of an odorous gas, detected by 50 per cent of an odour panel
Operational balancing	Matching the collection of gas to the production of gas
Operational sites	Waste sites that are still receiving waste
Permeability	A measure of the rate at which a gas will pass through a medium. The coefficient of permeability of a given fluid is an expression of the rate of flow through unit area and thickness under unit differential pressure at a given temperature (litre/time).
Personal gas alarms	A device which measures your exposure to hazardous gases such as carbon monoxide, methane, hydrogen sulphide or the lack of oxygen.
pH	An expression of hydrogen ion concentration, specifically, the negative logarithm of the hydrogen ion concentration. The range is from 0 to 14, with 7 as neutral, 0-7 as acidic, and 7-14 as alkaline
Phase	An area of a landfill site that is prepared, operational, temporarily restored or restored
Pivot tables	Data tables that allow analysis of complex data. Also called Cross-Tabs
Planned maintenance	A service activity performed against a regular schedule
Pollution	The addition of materials or energy to an existing environment system to the extent that undesirable changes are produced directly or indirectly in that system: a pollutant is a material or type of energy whose introduction into an environmental system leads to pollution
Portable gas analysers	Analyser that can be moved around a site allow you to measure the content of the gas
ppb	Parts per billion, method of expressing concentration. 1 ppb is a thousandth of a ppm (see below)
ppm	Parts per million, method of expressing concentration. 10,000 ppm v/v equates to 1 per cent gas at standard temperature and pressure (STP) by volume
Pressure meters	A device to measure gas pressure

QIR	Quality Improvement Report
Receptors	An area, building or person where gas collects. May be several km from the site
Recirculation	Collecting leachate and re-introducing it to the landfill
Regulator	Environment Agency, Scottish Environment Protection Agency or Northern Ireland Environment Agency.
Restoration	The process of turning a landfill site back to usable land, for example, by topsoil and planting
Ring main	A gas pipe that forms a circular path allowing gas to flow in either direction, increasing the effective capacity
SCADA	Supervisory Control and Data Acquisition
SDR	Standard Dimension Ratio
Seasonal differences	The change in gas production due to seasonal variations in temperature and atmospheric pressure
Settlement	The amount by which a landfill surface sinks below its original level due to a combination of mechanical compaction, compaction by its own weight, and degradation of the waste, for example, a tipped waste thickness of 40 m settling by 8 m would have undergone 20 per cent settlement
Siloxanes	Formed from the anaerobic decomposition of materials commonly found in soaps and detergents
Soil overtips	Excess material used to restore a closed site allowing for settlement
STP	Standard temperature and pressure
Stock control	A system to record stock location quantity and transfers
Synthetic seal	A seal made of synthetic material that prevents the escape of gas from the cap of a well
Temperature / gas profiling	Measuring the temperature of gas at varying depths of a well
Temperature dip	Measuring the temperature at varying depths within a well
Term	Definition
Temperature probe	Device for measuring the temperature inside a well
TVA	Total Volatile Acids. The concentration of volatile acids present in a waste mass (g/l)
Trigger/action levels	Trigger levels are compliance levels and, in order to meet trigger levels, action levels should be set at a level at which the operator can take action to remain compliant. These may form part of the site's permit
UEL (Upper Explosive Limit)	The highest concentration of mixture of methane and air which will support an explosion at 25^{o}C and normal atmospheric pressure, and in the presence of a flame
v/v	By volume (as in % v/v or ppm v/v); usually applied to gases
w/w	By weight (as in % w/w)
Waste over tips	The addition of new waste to a site after it has been capped
Well head	The top portion of a well, usually containing a valve and various monitoring parts
Well sizing	Calculating the size and depth of well required to efficiently collect gas
Zone	Part of the site surface deemed to be of generally uniform character such that the area concerned is assumed to be suitably homogenous in the context of surface emissions

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