CHAPTER 1: INTRODUCTION TO GASSIM 2.5

1.   INTRODUCTION TO GASSIM2.5

This chapter aims to describe the background behind GasSim2.5, outlines the program, details how the manual is organised and informs you what you will need to run GasSim2.5 and where to obtain technical support. This version of the manual has been issued to accompany GasSim2.5, which was launched in 2011.

About GasSim

The principal drivers behind the development of GasSim2.5 are concern over the potential health effects of living near and working on landfills, and the need to reduce the emissions of greenhouse gases to the environment. UK Government sponsored research (Elliott et al, 2001) has indicated a statistical (but not necessarily causal) relationship between an adverse effect on human health, e.g. birth defects, and landfill proximity. Additionally, under the Kyoto agreement, the UK is obliged to reduce emissions of greenhouse gases. Methane is potentially the second most important anthropogenic greenhouse gas, after carbon dioxide, and is emitted from landfills in significant quantities.

These concerns are reflected in the following European Union (EU) directives, which apply to the generation and management of landfill gas (LFG):

- Waste Framework Directive (the revised Directive 2008/98/EC, 19 November 2008)
- Landfill Directive (1999/31/EC, 1999); and
- Integrated Pollution Prevention Control (IPPC) Directive (codified version) (Directive 2008/1/EC, 15 January 2008).

The European Union Waste Framework Directive requires that waste is recovered or disposed without using methods that could endanger human health or harm the environment. The Landfill Directive requires waste operators to prevent or reduce negative effects on the environment and classifies landfills. The Landfill Directive defines LFG as 'all gases generated from landfilled waste' and requires:

- Appropriate measures to control accumulation and migration of LFG;
- Collection of LFG from landfills receiving biodegradable waste and the treatment and use of LFG. Where the gas cannot be used to produce energy, it must be flared; and
- Minimisation of damage to or deterioration of the environment and risk to human health by the collection, treatment and use of LFG.

The Integrated Pollution Prevention and Control Directive and the Landfill Directive require that preventative measures be taken against pollution through flaring and utilisation of LFG. The Landfill Directive is implemented in England and Wales by The Environmental Permitting (England and Wales) Regulations (2010). Closed landfills fall into three categories:

- Landfill sites that close after 16 July 2011 (Landfill Directive closed landfills). These are subject to the requirements of the Landfill Directive;
- Site that are permitted and closed before 16 July 2011 (closed landfills). Closed landfill are regulated by a range of conditions that were originally imposed through waste management or waste disposal licences. All

existing close landfill licences have become environmental permits, but due to the variability in their requirements the conditions and standard remain inconsistent. This was the subject of the Closed landfill Review, and

- Site that are closed but no longer have a permit (historic closed landfills). The Environment Agency does not regulate closed historic sites.

The technical requirements of the Landfill Directive have been implemented in England and Wales via the Landfill (England and Wales) regulations 2002 (Amendment Regulation 2005). The following gas control measures are set out in the Regulations:

- Appropriate measures must be taken in order to control the accumulation and migration of landfill gas;
- landfill gas must be collected from all landfills receiving biodegradable waste and the landfill gas must be treated and, to the extent possible, used;
- landfill gas which cannot be used to produce energy must be flared; and
- the collection, treatment and use of landfill gas must be carried on in a manner which minimizes damage to or deterioration of the environment and risk to human health.

The Environment Agency exercises its regulatory powers for LFG under The Environmental Permitting (England and Wales) Regulations (2010) (EPR). Landfills requiring active control will be regulated under the EPR as 'installations' and the LFG management system may either be part of this installation or separately permitted to a third party operator. All power generation plant where the plant is sized at > 3MWth input (approximately 1MWe output) must have their combustion plant regulated under EPR. The Regulations cover the design, construction, operation and maintenance of the LFG management systems and require:

- Gas management systems to control the migration and release of LFG;
- Minimising the LFG contribution to global warming;
- Management of odour from LFG; and
- Reporting of releases of named pollutants (Pollution Inventory), this will require monitoring of gas generation, surface emissions, and combustion plant emissions, including tracking and reporting the changes to these emissions through time.

Therefore it has become Environment Agency (Agency) policy that gaseous emissions from permitted landfill sites will be regulated according to site-specific risk management practice to minimise the impact on:

- Health from trace components and combustion products;
- The local environment by odour and vegetation stress; and
- Global atmosphere by ozone depletion and global warming through greenhouse gases.

Prior to the Agency issuing an Environmental Permit, a planning consent is required for the landfill. The Local Planning Authority will control issues relating to the development of new landfills. LFG and its management will be taken into account during the planning process for developments involving greater than 50 000 tonnes of waste input per year and/or occupying an area of 10 ha or greater, and some other sites requiring an Environmental Impact Assessment (EIA). This EIA will be the starting point for the risk assessment required under the EPR.

The Environment Agency has published a series of guidance documents on the management of LFG and the monitoring of emissions (Environment Agency 2004a; 2010a, b, c, d, & e). The overarching *LFTGN03, Guidance on the Management of LFG* outlines the link between a systematic risk assessment and an on-going Gas Management Plan for the site. This includes a gas monitoring plan to help the landfill operator and regulator quantify the parameters which the operator will need to know, through measurement or calculation. These measurements are necessary for monitoring local pollution prevention gas management measures, and for the yearly reporting requirements of the European Pollutant Emissions Register (EPER) known in the UK as the PI (Pollution Inventory).

It is under this framework of mainly new regulations and technical guidance that GasSim2.5 was originally developed from the HELGA framework (Gregory et al., 1999) for the Agency under a contract entitled Development of the Health and Environmental Risks from LFG. A fundamentally important aspect of this approach is to quantitatively evaluate the risks of the main processes and the magnitude of the impacts, GasSim2.5 considers the uncertainty in input parameters using a Monte Carlo Simulation.

GasSim2.5 provides a standard risk assessment methodology for the Agency, operators and consultants. It is designed to aid LFG risk assessment, by enabling LFG generation, emissions, migration/dispersion and impact to be assessed in a reproducible manner by those familiar with the subject, but without the need to build multiple models.

IPPC is a Pan-European regulatory requirement, and outside of IPPC, the use of GasSim2.5 as a resource estimation tool and as an impact assessment tool is widespread, with half the registered users operating outside the UK.

The Conceptual Model

The conceptual model (Figure 1.1) has a modular structure. Each module incorporates the effects of additional processes. Progression to successive modules is only necessary if this information is required, e.g. LFG generation and emissions can be determined without proceeding through subsequent modules to optimise time and data collection constraints.

GasSim2.5 considers the landfill as individual cells, each with its own engineering and waste composition. This approach has been implemented to enable the simulation of changes in landfill engineering designs and legislative requirements through time, and the changes in waste composition and characteristics that have resulted from both legislative and social changes. The model is probabilistic with the exception of the atmospheric dispersion module.
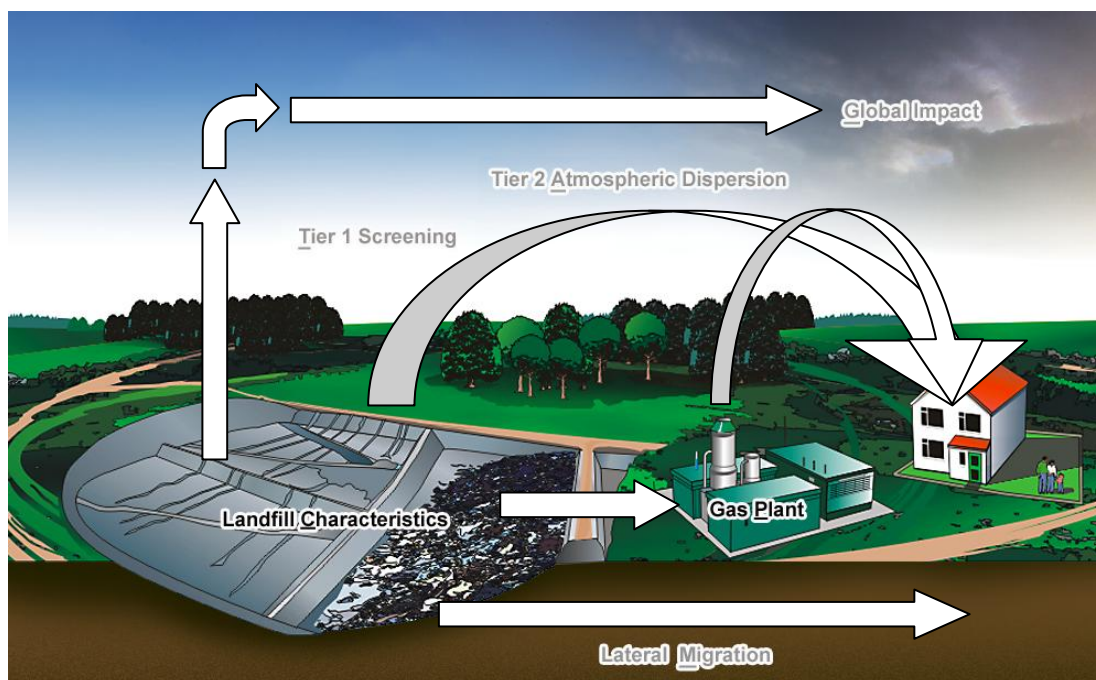
Figure 1.1: The GasSim2.5 Conceptual Model

The model is divided into four key parts, i.e. the:

- Source term module;

- Emissions module;

- Atmospheric dispersion module; and

- Lateral migration module.

The source term determines the generation of LFG for an individual cell, phase, or site based on the mass of waste deposited and the waste composition of the waste streams. The waste is degraded following a first-order decay model that calculates the LFG generation for up to 200 years. The emission module takes this output and uses it to calculate LFG emission of bulk and trace gases to the environment after allowing for LFG collection, flaring, utilisation (energy recovery), and biological methane oxidation. This is undertaken by using information on the site gas collection system, flare, engine and engineered barriers (cap and liner), if present. It is assumed that LFG generated and not collected is in equilibrium and will be emitted from the landfill cap or liner at a steady state, i.e. the model does not consider transient storage of LFG. Additionally the model calculates the concentrations of other major and trace gases emitted from flares and engines following combustion.

The environmental transport modules simulate the dispersion of emitted LFG via both atmospheric dispersion and lateral migration, and it is recommended that these modules are used as a screening tool with more complicated modelling being undertaken if required.

The atmospheric dispersion routines are split into a Tier 1 screening module, and a Tier 2 implementation of the USEPA's AERMOD model. This uses identical mathematics to the USEPA's version of the software, but the Tier 2

implementation is a simplification to allow for reasonable runtimes. Terrain and building downwash are excluded from the model, the receptor types have been aligned to regulatory requirements, and a single year of sample meteorological data is included within GasSim2.5 for each Environment Agency Area in England and Wales, with the exception of those dominated by complex terrain. It is possible to extract the source and receptor data should a full Tier 3 simulation be required following Tier 1 and Tier 2 assessment. It is expected that this will only be required if building downwash or complex terrain is a factor, or if air quality objectives may be approached or exceeded.

Lateral migration simulates the transverse migration of LFG through the unsaturated subsurface by advection and diffusion. The geosphere has been simplified into one zone, which is simulated using a conservative 1-dimensional linear pathway to provide the maximum concentration at a given point. A loss term is available, through atmospheric mixing in an unconfined migration pathway, if this can be justified. The gas concentrations along the pathway can be used to determine the potential for vegetation stress, including the migration of LFG and its component gases into buildings.

Determining the global warming potential and ozone depletion potential of the emissions assesses the landfill's impact on the global atmosphere.

GasSim2.5 General Assumptions

GasSim2.5 has been developed to provide a standard risk assessment methodology that will aid a nationally consistent approach to the Agency's statutory duty in respect of gaseous emissions from landfill sites. The central conceptual model is a landfill containing biodegradable wastes, which generate bulk gases comprising mainly methane and carbon dioxide. It may not be suitable for landfills where waste or gas composition do not fit this pattern, e.g. hazardous waste sites without biodegradable wastes. The default values within GasSim2.5 will not be suitable for assessing sites taking unusual waste streams.

GasSim2.5 has the following general assumptions:
- GasSim2.5 can only be used to assess the risk of exposure from LFG and cannot be used to assess exposure from soils or groundwaters;
- The model operates at steady state with a minimum time period of 1 month for generation and emission forecasts;
- Migration of gas is not modelled in the saturated zone;
- The model does not determine the pressure generated by the landfill and to simplify the model pressure has been excluded from all modules;
- LFG can be collected from cells while filling with sacrificial or permanent gas collection systems, in the presence or absence of temporary or permanent caps to the cell in question. Uncollected LFG is emitted directly to the atmosphere;

- GasSim2.5 does not simulate acute time frame, low probability events, e.g. the rapid lateral migration of gases into buildings that could result in the development of an explosive atmosphere, as these events do not lie within the context of a long-term risk assessment model;

- Atmospheric dispersion uses a Tier 1 screening method compliant with Agency PPC guidance, and a Tier 2 atmospheric dispersion model, AERMOD, which allows reporting of annual average concentrations and short-term concentrations using criteria embedded in the relevant European Directives, and Air Quality Regulations for individual countries;

- Lateral migration is determined using a conservative one dimension advection and diffusion equation. The diffusivity is determined for the diffusivity of the gas in air, which is corrected for the porosity and moisture content of the medium. Atmospheric mixing is considered as an optional loss term, but methane oxidation is not included in this module;

- The biological methane oxidation module assumes that all fissures/discrete features emit the same quantity of gas and that these emissions are not reduced by methane oxidation;

- The impact of odour is assessed using AERMOD and comparing either the odour concentration expressed in odour units per cubic metre or a pure substance mass concentration with a corresponding odour annoyance threshold;

- Vegetation stress is only assumed to impact the environment where the concentrations of methane and carbon dioxide are above defined threshold; and

- The global atmosphere risk model determines the tonnes equivalent carbon dioxide for global warming potential and tonnes equivalent fluorotrichloromethane for ozone depleting potential based on the UN FCCC approaches.

Additional Functions going from GasSim2 to GasSim2.5

GasSim2.5 is a natural successor to GasSim2 and has a number of new features.

GasSim2 supported no more than 100 items on the results graph menus which limited the number of usable trace gases to less than 97. GasSim2.5 supports more than 150 trace gases on the results graph menus.

Additional functionality to enable an additional set of degradation rates for each cell have been introduced along with a facility to set the year and month when the degradation changes from one type to the other to enable various scenarios during a sites development to be considered.

The calculations have been changed to use a monthly time step; some input parameters have been changed to allow the user to specify a month as well as a year; and some results screens have been changed to allow the user to select either a single month or a yearly average. Note that the gas generation calculation assumes that waste is inert for the three months following the month in which the waste is deposited (whereas the old version assumed that there was no degradation during the year the waste was deposited).

Cells can now be flagged as surcharging areas and these are then allowed to overlap other cells. These surcharging areas do not allow lateral migration (like landraise) and some of the gas from the underlying cell that would have become a surface emission is made available for gas collection in the surcharged cell.

Uses of GasSim

GasSim2.5 is designed to provide those concerned with the management of LFG (waste regulators, operators, planners and others) with a means of assessing the risks to the environment and human health associated with LFG emissions.

GasSim2.5 allows the user to:

- Assess LFG management options, to aid in landfill design and operation by identifying gas that is lost uncontrollably that could otherwise have been utilised, hence minimising the environmental impact;
- Simulate atmospheric dispersion to assess the potential exposure of neighbouring residents;
- Model the dispersion of odorous releases to air, to assess the impact of odour on neighbouring properties;
- Calculate the global impact, to determine the potential of the landfill to cause global warming and determine the emissions of gases with a global warming potential in accordance with the Guidelines for Company Reporting on Waste to Monitor Environmental Performance and / or emissions trading;
- Report the emissions of gases covered by the European Pollutant Emissions Register (EPER), also known as the Pollution Inventory (PI) – in a suitable format; and
- Determine the limit of vegetation stress, to assess the impact of laterally migrating methane and carbon dioxide on vegetation adjacent to the landfill.

Program Outline

GasSim2.5 has been designed to be similar in design and layout to its sister applications LandSim Release 2.5 (Landfill Performance Simulation by Monte Carlo Method, 2003) and ConSim Release 2.5 (2009). The model has been encoded using Microsoft's Visual Basic and C++ programming languages, therefore users with experience of Microsoft Windows will find the program easy to navigate. The program follows all Windows conventions in terms of using the mouse, the appearance of input dialogue boxes and results screens.

In short, GasSim2.5 enables LFG generation, emissions, migration/dispersion and impact/exposure to be assessed by those with no in-depth knowledge of programming.

The main screen shows a cartoon, which guides you along the process of defining the source term (Landfill Characteristics), the gas management options, and details of the contaminant transport pathways (from the source to the various receptors). At each stage along the pathway pop-up dialogue boxes are accessed by clicking on active areas of the cartoon or from drop-down menus. These are used to enter data that enables GasSim2.5 to determine the LFG generation, the emissions from the landfill and combustion products, the lateral migration and atmospheric dispersion of these emissions, and the impact on human health, the local environment and the global

atmosphere. The dialogue boxes are customised to the chosen landfill design and probability distributions for the default parameters are provided to prevent unnecessary data entry.

GasSim2.5 is a probabilistic model, which uses the Monte Carlo simulation technique to select randomly from a pre-defined range of possible input values to create parameters for use in the model calculations. Repeating the process many times gives a range of output values, the distribution of which reflects the uncertainty inherent in the input values and enables you to ascertain the likelihood of the estimated output levels being achieved. Whether you choose to display the GasSim2.5 output graphically or in statistical format, report quality printouts can be produced.

How this Manual is Organised

This section presents a brief introduction to GasSim2.5, its aims, structure and how it can be used.

Chapter 2 gives a guide to installing GasSim2.5 and getting started. The chapter also provides some background to the dialogue boxes, probabilistic risk assessment, and touches on quality assurance issues.

Chapter 3 shows how to enter parameters in order to set up and run a GasSim2.5 assessment, looks at issues for landfill risk assessment (for odour, global impact, vegetation and receptors) and describes the options for running a simulation. The chapter also details simplifying assumptions behind the model that must be borne in mind when assigning input parameters values and ranges.

Chapter 4 describes what GasSim2.5 predicts, how to interpret the statistical results and how the output graphs can be customised. The chapter also describes the important elements of a performance assessment and how to deal with modelling errors.

Chapter 5 contains suggested ranges of input parameters such as trace gases, engine and flare destruction efficiencies, etc.

Chapter 6 is a reference chapter, which outlines the theory behind GasSim2.5 and presents equations used and assumptions made. Although you will probably not need to consult this chapter regularly it is recommended that you familiarise yourself with the assumptions made.

Chapter 7 presents a brief description of the verification and validation of the GasSim2.5 model.

Your Experience

Don't let GasSim2.5's apparent ease of use deceive you. **This program is intended solely for use by experienced professionals with a sound background in landfill engineering, LFG contaminant transport and risk assessment.**

Your approach will be the key to obtaining useful results. Crucial to their validity will be your thoroughness when developing models, assessing the input parameters and working out uncertainties in the system. GasSim2.5 requires that you justify all expressed uncertainties and the output and printed record are locked together with a filename/timestamp system. Therefore you must be able to justify each input parameter. Your justifications are held in these records for subsequent audit.

What You Will Need

To run GasSim2.5 you will need an IBM compatible PC or laptop with a processor with a speed of at least 1GHz with 1GB RAM. GasSim2.5 was developed to operate under Windows XP Professional, with Service Pack 3. Other earlier versions of Windows may be compatible but this has not been tested. GasSim2.5 is not compatible with Windows NT. We have not experienced difficulties using GasSim2.5 with Vista or Windows 7, although the software was not specifically developed for these operating systems. Hard disk space for temporary files generated while running gas generation and emissions modules may vary from 10MBytes to 100MBytes or more depending on the complexity of the simulation. The AERMOD module within GasSim2.5 can easily generate 6GB of results files, so users should allow a minimum 10GB free disk space on their C drives. Some simulations may require more disk space than this. It is possible to select other network drives for AERMOD output.

GasSim2.5 runs at a screen resolution of 1024 x 768.

Technical Support

Golder Associates (UK) Ltd offer technical support for GasSim2.5 according to the terms of the licence agreement.

Training packages for novice and experienced users can be purchased from Golder Associates (UK) Ltd. (see the GasSim2.5 web site www.gassim.co.uk for more details).

For problems running the program or for technical enquiries, help files are available within GasSim2.5 either from the Main Menu or through buttons in each input window.

If you have problems installing the program or getting the code running on your computer, please call the Help Desk (available from 9.30 to 5.00 Monday to Friday) or contact us by fax or e-mail.

GasSim Help Desk
Golder Associates (UK) Ltd
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E-mail: gassim@golder.com

CHAPTER 2: GETTING STARTED WITH GASSIM 2.5

2.   GETTING STARTED WITH GASSIM2.5

This chapter has two major sections:

a)   How to install and use the GasSim2.5 program, and

b)   A brief introduction to the philosophy of risk and risk assessment.

This second section should be read even by those familiar with the concepts of risk assessment.   The advice on choice of input parameters is likely to be extremely useful.

A.   THE MECHANICS OF GETTING STARTED

How to Install GasSim2.5

GasSim2.5 is usually obtained by downloading from the website www.gassim.co.uk as a zip file. If you cannot download the demonstration file, a CD may be provided. To install the software, close any open applications and place the CD in the CD-ROM drive, or extract the files from the zip file.

Click OK to start installing the program and follow the on-screen instructions. If the installation does not start automatically and the Setup program is not activated, run the Setup program from the download or on the CD to manually start the setup process.

You must use the Setup program to install GasSim2.5. The files downloaded or those files on the installation CD are compressed and cannot be copied directly to your hard drive. To uninstall GasSim2.5 you should use the Add/Remove Programs application in the Control Panel. **If you wish to install further updates to the GasSim2.5 software that may be issued from time to time, it is essential that you uninstall the current version of the model prior to installing the update.**

The downloaded software, or that found on the CD, is a demonstration version. You cannot **load, save, save as, print**, or otherwise record or retain any work performed on the demonstration version, although the full functionality is retained for users to explore GasSim2's features. To make the demonstration version fully functional, you should go to the **Help>Licence** function on the menu bar and follow the instructions provided there (and also on the website www.gassim.co.uk). Registration involves assigning the software to a particular PC or laptop. It is therefore recommended that you decide on the hardware on which you want to install GasSim2.5 before applying to Golder for a user license.

Keying Convention, Mouse Use and Windows Standards

GasSim2.5 follows the usual Windows conventions:

- Mouse action;
- Drop down menus triggered by the <Alt> key with navigation by arrow keys;
- Drop down menus triggered by <Alt> key with navigation by key letters (which are capitalized and underscored on the menu names); and
- Accelerator key sequences (e.g. Ctrl + S to save a file, indicated on the drop down menu item).

This manual has been written around mouse driven use, which is likely to be the most convenient way for most people. However, an experienced user may find the keyboard short cuts faster. In terms of mouse use, the standards used by Microsoft in developing Excel have been our guide, and if you are in doubt anywhere in GasSim, try an Excel mouse operation. For example, double clicking on the scale of a graph will open a scale change dialogue. We have also built in a number of pop-up features and in several instances you will find the appropriate menu items available with a single click of the right mouse button.

To exit the dialogue boxes without making or saving changes use the Cancel buttons available. It is not possible to damage the GasSim2.5 program by any combination of events with the program.

Starting the Program

To start the programme double click (two fast clicks) the GasSim2.5 icon, or select GasSim2.5 from the start menu.

During loading GasSim2.5 will display a graphic showing the software version.

To continue click the New Project or Open Project options.

Selection of the New Project option will open the project data file. You will need to populate the data fields and eventually save this with a unique file name. Open Project will request that you select an existing project file. These options are described in Chapter 3.

Closing GasSim2.5

To close down GasSim2.5 select the Exit option from the File menu. You will be prompted to check that you have saved your work. If you wish to close the program without saving select No, otherwise choose Yes, and GasSim2.5 will save and close down.

B. THE PRINCIPLES OF RISK ASSESSMENT

The key principles behind risk, risk assessment, performance assessment and the issues of uncertainty are described in this section.

Hazard and Risk

Before you use the program it is important that there is a common understanding of the purpose of an assessment, and the general philosophy behind risk and performance assessment.

The term risk is the chance of something occurring – a loss, injury or untoward outcome. We need to be clear on the definitions, which are based on those published by the DETR (2000):

- Hazard: a property or situation that in particular circumstances could lead to harm; and
- Risk: a combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence.

Risk Assessment

The purpose of risk assessment is to make rational, transparent, justified (defensible) decisions. If there are no decisions to be made, there is no point in carrying out a risk assessment. For example, the decision may be about the acceptable standard of care or safety or about an investment strategy, but at some stage you will need to ask the basic question: "What should we do?" At this point you need to be aware of the fundamental points. A risk assessment:

- Is carried out in the context of the decision;
- Evaluates all alternative outcomes including both uncertainties and chance; and
- Has some criterion against which the results/outcomes are to be compared in arriving at a decision.

The goal of the regulators is to protect human health and the environment from the detrimental effects of landfills. The overall principles of risk assessment applied to LFG are given in the *Guidance on the Management of Landfill Gas* (Environment Agency, 2004a). This describes the approach to hazard identification and prediction of risk as well as the Tiered approach that concentrates attention onto those factors that are significant. GasSim2.5 is consistent with the systematic methodology made in this guidance. It performs risk estimation by calculating the

probability of contaminant concentrations in LFG exceeding the vegetation stress and odour threshold values and the impact on the global atmosphere.

A complete LFG risk assessment involves 4 parts:

- Source term;
- Emissions module (the landfill characteristics and gas utilisation);
- Environmental transport by lateral migration and/or atmospheric dispersion; and
- Impact (odour, vegetation stress and global impact).

The source term, and to some extent the emissions module, defines the hazard component. The emissions and environmental transport modules determine the potential for uncontrolled release and the outcome is assessed using the impact modules.

The quantity of waste, the composition of the waste streams, the landfill engineering and the moisture content are defined in the 'Landfill Characteristics' dialogue box. The source term supplies the concentrations of bulk gases (CH_4, CO_2, H_2) by determining the LFG generated from the mass of degraded carbon, and the quantity of trace gases present within the landfill from the concentration of trace gas in one cubic metre of bulk gas. The option is also available to allow the trace gas concentrations to degrade with time.

The emissions module calculates the quantity of LFG that is utilised by engines and flares using the gas collection system specification defined in the 'Gas Plant' dialogue box. The flares and engines burn the LFG resulting in reductions in the majority of the bulk and trace gas concentrations but also creating combustion products (e.g. NOx, CO, etc.). The remaining LFG that is generated but not utilised is emitted uncontrollably through cap, liner or open/active areas of the landfill. The proportion of LFG that migrates in each direction is determined by the cap and liner properties.

The environmental transport mechanisms are divided into lateral migration and atmospheric dispersion. The 'Lateral Migration' module simulates the movement of LFG emitted through the liner in the geosphere. The Tier 1 screening module uses Environment Agency AQMAU defined criteria rather than the H1 screening tool to screen out insignificant impacts, as GasSim uses the distance between source and receptor, and the H1 screening tool does not. The Tier 2 'Atmospheric Dispersion' module uses the USEPA's AERMOD model to simulate the behaviour of pollutants and their odour. It considers the impact of flare, engine and cap emissions, and determines the atmospheric concentrations and dispersion of pollutants and their odour impact under various atmospheric conditions.

The 'Global Impact' module assesses the release of greenhouse and ozone depleting gases.

Performance Assessment

GasSim2.5 is designed to simulate landfills for risk assessments and EPER (PI) reporting. The smallest time step has been defined as one month for gas generation and emissions, and the model assumes steady state conditions during each month, although the exact conditions for each month will change in each iteration, as influenced by the variability defined in the input parameters. Screening using the atmospheric dispersion module can be performed at an hourly level.

To keep the analysis in GasSim2.5 manageable within a Monte Carlo environment, steady state models are used. Necessarily, steady state models are for single scenarios. In reality, situations change and a series of assessments, which represent different scenarios for the landfill, must be carried out. In essence, this means that typically, GasSim2.5 assessments will not consist of a single scenario, but of several. The terminology is that performance assessment is analysis of a single scenario.

Performance assessment is the systematic consideration of those aspects of a situation that lead to the computed risk. Performance assessment looks at the possible behaviours of a system, allowing for uncertainties in knowledge about the system being modelled. This includes uncertainties about the processes occurring and uncertainties about the parameters controlling those processes. The overall performance is expressed in terms of uncertainty in one area - the effect on the environmental impact.

GasSim2.5 adopts a 'top down' approach to performance assessment, starting from a desired performance statement and identifying the factors that contribute to performance, with each factor broken down into greater detail where required. This means that, for example, if you have detailed monitoring results and a well-defined conceptual model, the results can be used directly in GasSim2.5: Your parameter assessment would be based on the detailed model.

Time is an important factor to consider when developing scenarios for a landfill. The impact of processes occurring in a newly constructed facility is likely to be quite different from the performance of the same facility, say, 50 years after closure. Time can affect the infiltration (if the cap deteriorates for instance), the system parameters (such as the gas collection efficiency) and the LFG composition.

A reasonable estimation of how landfill risk may evolve can be obtained by analysing the system under three sets of circumstances:

- Prior to closure;
- Immediately after closure and restoration; and
- 50 years after closure.

In each set of circumstances, virtually identical analyses will be carried out, with the exception of a few changes to input parameters.

The user must understand that the model has been developed to look at the long-term impacts of LFG and not necessarily short-term effects and impacts. The model will not simulate the short-term transient risk of a low pressure system causing excessive LFG migration and subsequent explosive or asphyxiation risk. Such a model would require a minimum time step of around 1 hour. GasSim2.5 has a minimum time step of 1 month in the generation and emissions modules, and so is totally insensitive to transient effects of a duration of less than 1 month. However, on the basis of a known or modelled emission rate for a given year or month, the atmospheric dispersion module will give an assessment of air quality on a regional or local basis according to hourly meteorological data inputs.

Representing Uncertainty

The basic idea in all probabilistic assessments is that a probability can represent a judgement about uncertainty. This is often referred to as the Bayesian view, after the 19th Century mathematician, Bayes, who put forward the idea.

It is easy to see that people in everyday life use Bayesian approaches by noting that betting is an exercise in judgmental probability. Money is deliberately put at risk by the gambler on the expectation of gain based on the offered odds.

This betting example illustrates the important point that assessing uncertainty cannot create a desired outcome. No risk assessment can create certainty where there is uncertainty. Decisions based on risk assessment however maximise the opportunity for the desired outcome. The key to probabilistic risk assessment is how we quantify chance. The basic concept is that a number (or probability) between 0 and 1 is used to represent the chance of an event occurring. An assertion that the probability = 0 implies absolute confidence that the event will not happen, and likewise, a probability of 1 implies absolute confidence that it will. A judgement that there is an evens chance of the event occurring is simply represented as a probability of 0.5 (or 50%). By expressing judgement as a number we can be sure of unambiguous communication and the ability to calculate consequences.

In principle there are three types of uncertainty:

- Conceptual: we are unsure of the process occurring;
- Model: we are using a simplified version of reality to allow us to apply equations and create a model; and
- Parameter: we are unsure of the values to use in the model.

When using GasSim2.5, you are expected to deal with the first two types of uncertainty by ensuring that the conceptual model used and the assumptions made in the equations are representative of the environmental regime at your site, and by making decisions based upon an appropriate probability of outcome. Parameter uncertainty (and to some extent model uncertainty) is dealt with by allowing specification of a range of values for each input parameter rather than a single number, as explained in the next section.

Describing the uncertainties in input parameters in a risk assessment is different from design, in that it is essential to take an equal and unbiased account of both the 'upside' (positive) and the 'downside' or negative possibilities. This neutral approach would be regarded as unconservative in terms of design, but its importance cannot be overstated, since the purpose of risk assessment is to make rational, transparent, justified (defensible) decisions.

Input Distributions

In order to account for uncertainties in parameter values and for simplifications in the calculation method, GasSim2.5 allows you to use a range of values for each input parameter (although a single value is still an option if you wish). For clarity and ease of communication, each range is described based on the shape of its frequency or probability histogram.

Imagine a soil with a porosity of exactly 0.3. The probability of the porosity measured in any one test being 0.3 is 1 (100%), and in a series of porosity tests, the result will be 0.3 every time. The frequency of occurrence of any other value is zero. Without actually attaching numbers to the axes, the frequency of occurrence and the probability can be plotted on a histogram, and will show as a single column.
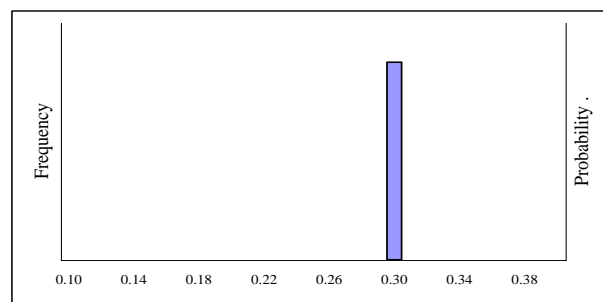

Now imagine that you do not know what the porosity is, but you can state that it will be somewhere between 0.2 and 0.3, and that there is an equal chance of it being any value in between. In a series of porosity tests you would therefore expect any given result (for example 0.22) the same number of times as you would expect any other result (0.21, 0.23, 0.24 etc.). The probability of each result is equal. This can be plotted on a histogram as a series of columns of equal height and is called a uniform distribution.
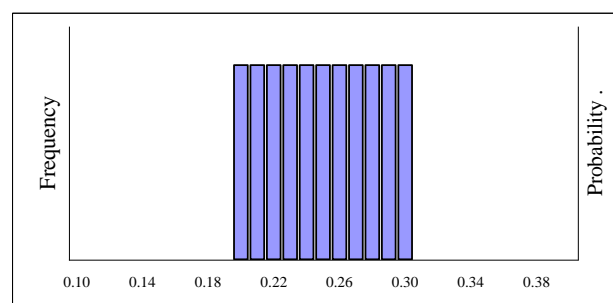
Moving on to a more realistic scenario, some porosity values are more likely to occur than others (higher probability of occurrence, or greater frequency in a series of tests), and perhaps one value (say 0.22) is the most likely to

occur. This is reflected in the plot (a series of columns of increasing then decreasing height), and the distribution is termed a triangular distribution, for obvious reasons.
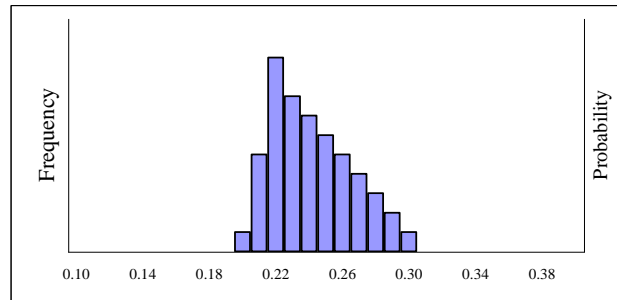
The process can continue for any number of distribution types, for example a normal distribution (which is bell-shaped), where the probability or frequency of occurrence of any particular porosity may be described using a mean and standard deviation.

You have a great deal of control over the input range (or distribution) in GasSim2.5 and the following points provide a description of the different distributions that can be selected.

- Uniform Distribution. Where it is possible to specify a minimum and maximum possible value for a parameter and where there is an equal chance of all the values in between (or where there is no further information), a uniform distribution is appropriate;

- Triangular Distribution: Where, in addition to minimum and maximum values, it is possible to identify a value that is most likely to, a triangular distribution may be used;

- Log Uniform or Log Triangular Distribution: When parameter values vary by orders of magnitude, the specification of a log uniform or log triangular distribution (uniform or triangular distribution of the logs of values) avoids skewing the distribution towards the upper or lower values;

- Normal or Log Normal Distribution: Many natural parameters follow a statistically normal/log normal distribution, that is described using a mean value and a standard deviation from the mean; and

- Other Distribution Types: GasSim2.5 permits the definition of input distributions other than those specified above. If there are sufficient available data fitting these distributions, then they are available to you, although it is anticipated that in the majority of cases the simpler distributions will be appropriate.

The choice of input distribution may have a profound effect on the predicted results and it is important that the distribution type you use is justified based on the available data. This not only involves the pattern of data values, but also is influenced to a great extent by the quantity of data available. The issue of how much data provide a statistically correct source is complex, but the following points may prove helpful in defining distributions when few data values are available:

- The data available defines both your knowledge of the system and your lack of knowledge. When specifying the distribution type best fitting your data, it is necessary to be honest about what you know, and to use professional judgement to adequately describe the uncertainty associated with your data. For

example, if only two measured concentrations are available, it would be difficult to defend the choice of an exponential input distribution, even if the two points fitted this distribution. A uniform distribution may best express your uncertainty;

- In many instances there may be a theoretical reason for the data to follow a particular distribution, or the end points of some ranges may be set (e.g. minimum rainfall possible is 0);

- Eliciting expert opinion (i.e. obtaining the view of a recognised authority in a specific subject) is a perfectly reasonable and justifiable method of quantifying uncertainty - find out what the experts consider to be the highest possible value, or the most likely etc. Remember though, expert opinion is no substitute for site-specific data;

- Measured parameters that vary solely due to measurement error tend to follow normal distributions;

- The data may not adequately describe actual conditions, but may be skewed (for example, cable tool drilling samples may not represent the full fines fraction). The specified distribution may be adjusted to redress this;

- 'Ranking' may be possible. Relative likelihoods (i.e. A is twice as likely as B) are usually easier to express than absolute probabilities, but are then simple to convert to a probability; and

- Data, even if sparse, may sometimes conform closely to a particular distribution.

There will be instances where there is a large base of data, and a distribution may be defined that closely represents the data. A number of commercially produced software packages (such as Palisade Corporation's "Bestfit" and Decisioneering's "Crystal Ball") are available to help you determine the most appropriate distribution of a data set.

Uncertainty Versus Variability

Many properties and processes are naturally variable. You would expect, for example, trace gas concentrations to vary from place to place within the waste mass. When looking at a range of monitoring data, it should be remembered that this data includes both true uncertainty (caused by test error, interpretation etc.) and true variability. Variability is also important because it does not automatically follow that the average case realistically represents reality – sometimes the weakest point in the chain may be the controlling factor.

In the case of landfills, there has been little investigation into the effect of variability on overall performance. Consequently, there is little guidance on how to use knowledge of variability even when variability can be distinguished from test uncertainty. At this stage, therefore, you may want to allow your input distributions to include both uncertainty and variability. This is the easiest course of action in any case. Its effect is to overstate the true parameter uncertainty but it is entirely reasonable to do this because, in effect, doing this naturally includes the corresponding parameter uncertainties.

Justifying Your Choice of Parameter Values

The main element of a probabilistic risk assessment is expressing uncertainties in terms of probabilities. Because probabilities are often subjective, it is essential to make a note of why particular judgements were made. The process of obtaining and justifying probabilities and values is usually called elicitation.

Human bias can distort the elicited probabilities and these possible distortions must be recognised and dealt with. Common biases are motivational (the individual has a personal stake in the action selected), availability (a greater amount of information unduly influences the judgement), timing (overall experience is undervalued in comparison to the most recent piece of information), and hidden assumptions. Two good papers among a wide variety of literature covering biases and how they can be avoided are Tversky & Kahneman (1974) and Spetzler & Von Holstein (1975).

Some people doubt that such a 'soft' process as elicitation can actually result in 'hard' numbers for mathematical use. However, encoded probabilities have been tracked in the commercial business and reported results show that they correspond to the actual outcome frequencies (Balthasar et al 1978; Kabus 1976; Sander 1969). GasSim2.5 uses this same approach that has proven successful in other disciplines.

The quality of a risk assessment depends on the quality and quantity of data put into the assessment, which can range from a single person's view to an evaluation by one or more groups of experts in a formal setting. However, costs and time required increase as the assessment becomes more defensible.

When deciding which level of probability assessment to employ, select the one that is most appropriate for the circumstances. If it is a simple check, then a risk assessment based on self-assessment is reasonable. If it is potentially contentious or the risks are high, then more defensibility should be used.

CHAPTER 3: SETTING UP AND RUNNING A SIMULATION

3. SETTING UP AND RUNNING A SIMULATION

This chapter will explain how to input data into the model and run a GasSim2.5 program. The theory and equations behind the model are described in Chapter 6.

Entering Data – General Points

Before starting to enter Project details a number of general points need to be made regarding the form of data entry. A large number of the individual inputs in the Landfill Characteristics, Gas Plant and Lateral Migration elements of the model can be entered as probability density functions (PDF's). There are a number of methods of entering these inputs. Where a PDF can be entered as the input into a field, a small grey box with an arrow at the far right of the field will appear (as indicated by the arrow in the screen below). You can, as in the example below, use a single number rather than a PDF if you so wish.

Degradation Rates for Waste Moisture Conditions (y-1)		Dry	Average	Wet	Saturated	User Defined 1	User Defined 2
	Slow	SINGLE(0.013)	SINGLE(0.046)	SINGLE(0.076)	SINGLE(0.013)	SINGLE(0.046)	TRIANGULAR(0.046, 0.076, 0.076)
	Moderate	SINGLE(0.046)	SINGLE(0.076)	SINGLE(0.116)	SINGLE(0.046)	SINGLE(0.116)	TRIANGULAR(0.076, 0.116, 0.116)
	Fast	SINGLE(0.076)	SINGLE(0.116)	SINGLE(0.694)	SINGLE(0.076)	SINGLE(0.694)	SINGLE(0.694)

The values of individual input parameter distributions may be edited in four ways:

1. You can input parameter distributions in a structured manner through an input distribution window (select the input parameter you require and click on the grey box at the right hand end of the parameter space to get the input distribution window to appear).
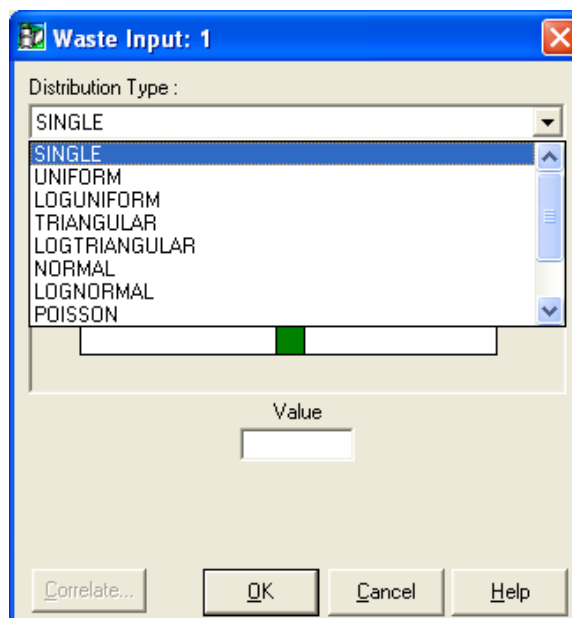
You can then select the appropriate distribution type from a drop down menu, and type in the values required.
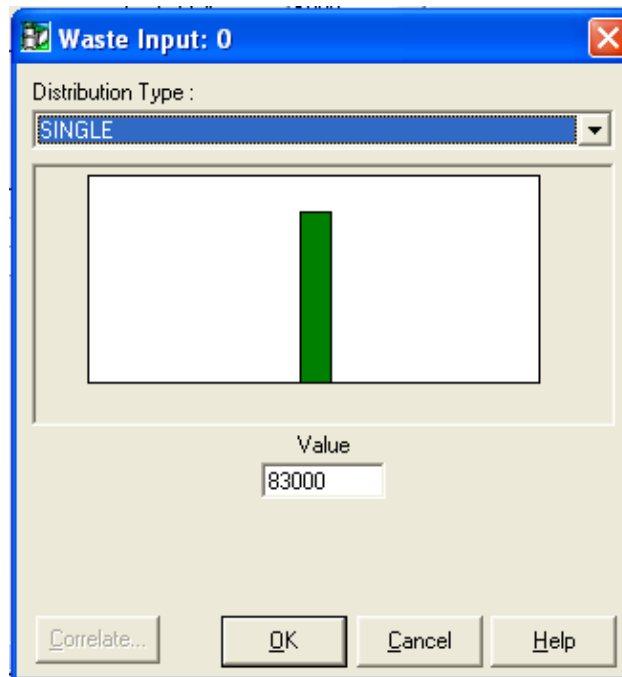
2. You can type the PDF, in words and figures, into most of the parameter spaces. (However, this function is not available when distributions are entered into GasSim2.5 input tables.) You will find that if you type 'un', GasSim2.5 will automatically complete the word 'uniform', and you will only need to add the required values, separated by a comma. Similarly, 'tr' brings up a triangular distribution, etc. As you become familiar with the use of the model, you can select the input method that best suits you. See below for a full list of the distribution types and abbreviations;

3. In addition to the above, it is also possible in most cases to use the cut, copy and paste facility (Ctrl + X, Ctrl + C and Ctrl + V) on existing parameter distributions;

4. Tables can be cut or copied and pasted from Excel using Ctrl + X, Ctrl + C and Ctrl + V. Templates are provided with the installation set for the fictitious example site Greendale, which can be modified for individual sites. This is probably the fastest way to build a dataset and get data into the model; and

5. When the full screen mode is running, and you cannot see the toolbar at the bottom of the window, you can toggle between applications using the Alt + Tab command. This is very useful when you are copying data from Excel to GasSim2.5 menus and the site plan is in view.

Where input distributions are impossible (e.g. minimum value greater than maximum) or outside a defined range then GasSim2.5 will highlight the values in red and will not accept the input.

The following distributions are available:

Table 3.1 Probability Density Functions

Distribution	Abbreviation (and syntax)
Single (value)	None - just enter value
Uniform	UN (min, max)
Triangular	TR (min, most likely, max)
Normal	NO (mean, standard deviation)
LogUniform	LOGU (min, max)
LogTriangular	LOGT (min, most likely, max)
LogNormal	LOGN (mean, standard deviation)
Binomial	BI (No. of trials, Prob)
Exponential	EX (mean)
Poisson	PO (average)

Within GasSim, you will be expected to input data in commonly accepted units (for example, infiltration as mm/year, trace gas concentrations as mg/m^3). Input fields indicate the units you should use.

Many parameters will have a set of default parameters and default distributions. These are intended to allow simulations to run when there is little site-specific information available. They are based on professional judgement of what has been found for "typical" MSW landfills. Where site-specific data is available it should be used in preference to default data. When default values are changed, the user is required to justify this in a record box.

Retrieving (Opening) an Existing GasSim2.5 Model

Previously saved models (files with extension .gss) can be retrieved using the 'Open' option under the 'File' menu on the main GasSim2.5 toolbar or by selecting Open Project from the GasSim2.5 start menu. In order to find your previously saved file you should ensure that you browse to find the correct drive and directory. Only files with the extension '.gss' in the current directory will be listed.

Click on the name of the model you wish to retrieve and choose the 'OK' button. The current simulation will then revert to that saved if no changes have been made to the model since it was last saved (i.e. you have selected 'Cancel' rather than 'OK' when exiting from any input fields), otherwise you will be prompted to save the previous model before the model you wish to retrieve is opened.

A productive way of using GasSim2.5 is to develop a model with the required configuration, which can then be saved with several file names. Retrieving each of these files allows minor changes to be made, e.g. changing the flare and engine capacities to represent the effect of increasing or reducing gas utilisation, with other aspects of the model remaining intact. Remember to change the notes about your simulation (if appropriate) through the 'Edit' and 'Project Details' menus.

Each simulation file stores its complete file path to ensure that the correct results are displayed. If a *.gss file is renamed outside of the GasSim2.5 program, or used on a mapped drive, when you run a simulation you will get the error message "Either the Model name or time of last save has been changed. Statistics cannot be reloaded." To resolve this problem, save and rerun the simulation. In addition to the *.gss file that is generated, when a model is run, a subdirectory with the same name as the file is generated and intermediate result files used solely by

GasSim2.5 are stored in this directory. If you wish to load the results of a previously run model (Load Results in the File menu) access to the subdirectory that contains these intermediate results files is needed.

Compatibility with GasSimLite and Earlier Versions of GasSim

You will not be able to successfully read and use existing GasSimLite or GasSim v1 files into GasSim2.5. GasSim2.5 is designed to be able to read and convert GasSim v1.5 and v2 files. Earlier versions of GasSim and GasSimLite files should be converted to functioning GasSim v1.5 or v2 files before attempting to read in as a GasSim2.5 file.

GasSim2.5 will create a single celled landfill of dimensions specified in GasSim v1.5. It is then recommended that you use the cut and paste facility to create a new GasSim2.5 version with improved spatial representation to fully benefit from the features of GasSim2.5. The file will normally report "data missing" errors on parameters that were new in GasSim2 and GasSim2.5 compared to previous versions such as; temporary cap infiltration rate, biosphere moisture, porosity and information relating to the change from a yearly to a monthly model time step. GasSim v1.5 did not have the spatial or multi-cell functions and so any converted files will show a very simple display in GasSim2.5. To use the full capability of GasSim2.5 you will need to add the additional information such as mapping and cellular structure.

GasSim2.5 will open a GasSim2 model specification. However the file will normally report "data missing" errors on parameters that are new in GasSim2.5 such as information relating to the change from a yearly to a monthly model time step.

It is strongly recommended that you check all the input parameters to ensure that errors have not occurred during the conversion.

Once a simulation has been run, GasSim2.5 will overwrite the .gss file and the model will not be reverse compatible. It may therefore be prudent to save the imported file under a different name so that the previous file retains its integrity.

Menu System

The data input boxes are opened by clicking the mouse button and by experimentation with the various menus and input screens you will find your optimum means of navigation around the model.
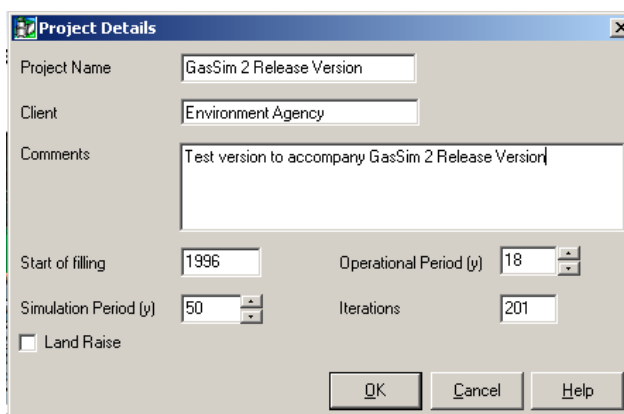
To exit the dialogue box and save the information you should click OK. To exit without saving the information can be carried out by clicking Cancel or clicking the top right hand corner of the box.

Certain menu options and entry graphics will remain greyed out (e.g. 'Tier 1 Screening', 'Tier 2 Atmospheric Dispersion', 'Lateral Migration', and 'Global Impact') until an initial model run for gas generation and emission has been performed.

Project Details

This window is accessed through Edit and Project Details on the main menu. The 'Project Name'. 'Client' and 'Comments' will be printed on all hardcopy outputs. The window also requires:

• The 'Start' year that waste deposition commenced in the landfill;

• The 'Operation Period' (the number of years that waste deposition occurred);

• The 'Simulation Period' (the number of years that the simulation will run after waste deposition has finished);

• The number of 'Iterations' (the number of times that the model will be run using the Monte Carlo simulation; An increased number of iterations will provide greater confidence in the results); and

• Whether the model should simulate a land raise or a landfill.

It should be noted that after the Project Details are set and you have started entering data in the source model, if you increase the number of operational years in the 'Project Details', this will have a knock-on effect and will automatically add years *to the end* of the Source table. Therefore you cannot add or insert years to the model prior to the initial filling data inputs. Conversely, reducing the number of operational years may lead to the loss of data for years at the end of the filling life.

Landfill Characteristics

Cell Layout

Landfill characteristics can be entered by clicking the cartoon icon on the screen. If a background map of the site to be modelled is available as a dxf file, this can be imported by clicking the 'pencil' icon in the top right of the screen and selecting the relevant file. A grid is also available to help the user. The required grid spacing can be altered within this domain box.

There are a number of boundaries, which can be represented on the plan. For simple sites, the boundary of waste filling is usually similar to the site boundary, and so one boundary will suffice for both the boundary of the waste and the boundary of the site. For complex sites, the Permit boundary and land ownership boundary may go beyond the waste boundary. In such instances, one boundary needs to be within the other. A third scenario also exists, where there are two adjacent landfills modelled. In this case, a boundary needs to be drawn around both landfill sites.

The site boundary can be defined by clicking the top left 'polygon' icon and then progressively clicking the mouse to draw the boundary shape. The boundary shape can be adjusted by left clicking over the boundary. This site boundary must be defined prior to adding any individual cells.

Cells or phases of the landfill are defined within the boundary by a similar method, having clicked the define cell icon at the top of the screen. Cells or phases may only be created within a landfill boundary. The proximity of the cell boundary to the landfill boundary is used in GasSim2.5 to determine whether the cell edge is an internal or external edge, and consequently whether lateral emissions, surface emissions (at an open internal cell edge), or no emissions (if the cell boundary is in full contact with waste) are permitted from that boundary.

GasSim2.5 has the capability to consider the opening of existing landfill areas and the surcharging of additional waste. This is possible by specifying additional waste cells after the specification of the initial underlying cell. These cells must be specified as a surcharging area by selecting the 'surcharging area' tick box.

The location of the gas plant can also be added to the domain by the 'gas plant' icon. The flare icon is a circle, and the gas engine icon is a horizontal rectangle; both are coloured red and are relatively small symbols. You can zoom in and out of the large site picture (seen below) by using the icons on the top left of the screen.
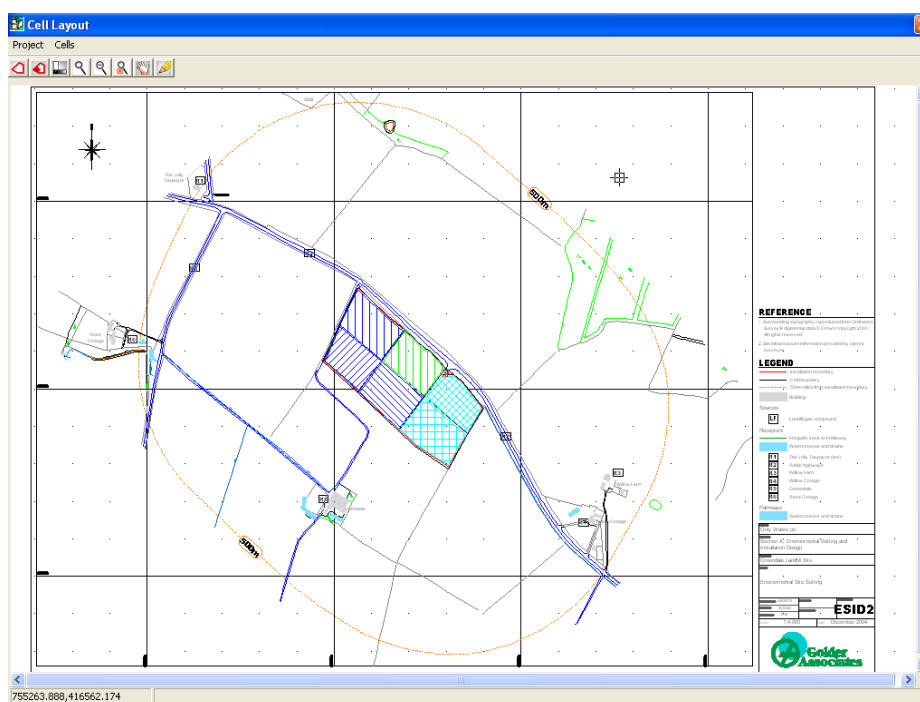
Cell Details

Details for each cell can be entered via the drop down menu at the top of the screen or by left clicking over the specific cell on the cell layout domain.

The dialogue box requires the selection of several modelling options:

- Simulation Calculations – this tick box determines whether the model should calculate gas generation from this cell. This function can be used to toggle on/off individual cells if analysis of the performance of an individual cell is required;

- Combustion Emissions - this tick box determines whether the gas generated in this particular cell is available for the modelled gas combustion plant. For example, this option (together with the option below deselected) enables the simulation of a neighbouring landfill which is not the purpose of the assessment but whose gas is pumped to the combustion plant; and

- Fugitive Emissions- this tick box determines whether the gas generated in this particular cell is available for fugitive release to the atmosphere. For example, this option allows the fugitive impact of an adjacent landfill to be assessed in combination or separately from the landfill being studied.
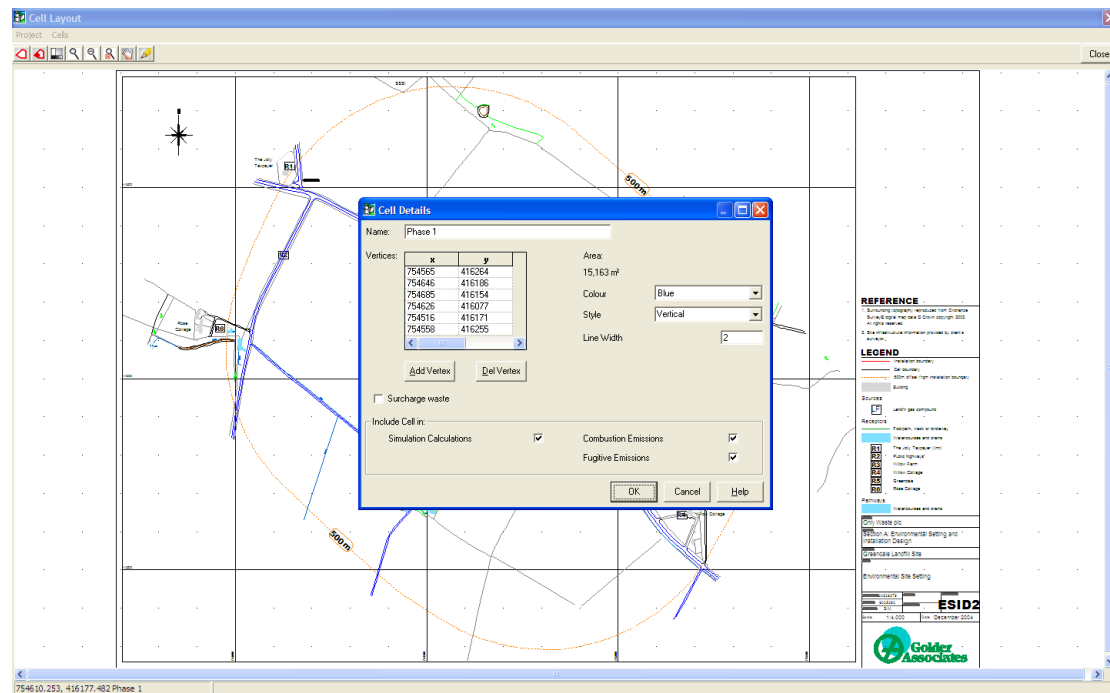
Cap and Liner Data

Cap and Liner data is accessed via the drop down menu within the 'cell layout' window. This allows you to define the engineered controls, installed during the construction of the landfill, to prevent the uncontrolled release of LFG. These are important inputs as GasSim2.5 assumes that any unutilised gas is lost uncontrollably via the cap and liner.

Cap and Liner Details	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Infiltration					
Uncapped Infiltration [mm/yr]	NORMAL(500.0,	NORMAL(500.0,	NORMAL(500.0,	NORMAL(500.0,	NORMAL(500.0,
Capped Infiltration [mm/yr]	NORMAL(50.0, 5	NORMAL(50.0, 5	NORMAL(50.0, 5	NORMAL(50.0, 5	NORMAL(50.0, 5
Temporary Cap					
Thickness [m]	UNIFORM(0.3, 0.	UNIFORM(0.3, 0.	UNIFORM(0.3, 0.	UNIFORM(0.3, 0.	UNIFORM(0.3, 0.
Hydraulic Conductivity [m/s]	LOGUNIFORM(5.	LOGUNIFORM(5.	LOGUNIFORM(5.	LOGUNIFORM(5.	LOGUNIFORM(5.
Cap Type	Single Clay	Single Clay	Single Clay	Composite	Composite
Thickness [m]	UNIFORM(0.9, 1.	UNIFORM(0.9, 1.	UNIFORM(0.9, 1.	UNIFORM(0.9, 1.	UNIFORM(0.9, 1.
Hydraulic Conductivity [m/s]	LOGUNIFORM(5.	LOGUNIFORM(5.	LOGUNIFORM(5.	LOGUNIFORM(5.	LOGUNIFORM(5.
Layer 2 Thickness [m]	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?	SINGLE(0.002)	SINGLE(0.002)
Layer 2 Hydraulic Conductivity [m/s]	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?	LOGUNIFORM(5.	LOGUNIFORM(5.
Liner Type	Single Clay	Single Clay	Single Clay	Composite	Composite
Thickness [m]	UNIFORM(0.9, 1.	UNIFORM(0.9, 1.	UNIFORM(0.9, 1.	UNIFORM(0.9, 1.	UNIFORM(0.9, 1.
Hydraulic Conductivity [m/s]	LOGUNIFORM(5.	LOGUNIFORM(5.	LOGUNIFORM(5.	LOGUNIFORM(5.	LOGUNIFORM(5.
Layer 2 Thickness [m]	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?	SINGLE(0.002)	SINGLE(0.002)
Layer 2 Hydraulic Conductivity [m/s]	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?	LOGUNIFORM(5.	LOGUNIFORM(5.
Layer 3 Thickness [m]	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?
Layer 3 Hydraulic Conductivity [m/s]	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?
Layer 4 Thickness [m]	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?
Layer 4 Hydraulic Conductivity [m/s]	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?
Land Raise Depth [m]	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?	#UNDEFINED?
Installation Dates					
Temporary Cap Year	1997	2000	2003	2006	2009
Temporary Cap Month	January	January	January	January	January
Permanent Cap Year	1999	2002	2005	2008	2011
Permanent Cap Month	January	January	January	January	January
Sacrificial Gas Collection Year	1997	2000	2003	2006	2009
Sacrificial Gas Collection Month	January	January	January	January	January
Permanent Gas Collection Year	2000	2003	2006	2009	2012
Permanent Gas Collection Month	January	January	January	January	January
Geosphere					
Ground Surface (mAOD)	50	49	49	48	48
Water Table (mAOD)	38	38	39	39	40
Unsaturated Zone Moisture Content (% v/v)	UNIFORM(2.0, 8.	UNIFORM(2.0, 8.	UNIFORM(2.0, 8.	UNIFORM(2.0, 8.	UNIFORM(2.0, 8.
Unsaturated Zone Total Porosity (% v/v)	UNIFORM(14.0,	UNIFORM(14.0,	UNIFORM(14.0,	UNIFORM(14.0,	UNIFORM(14.0,

Gas Collection Efficiency Estimates [%]

	No Cap	Temporary Cap	Permanent Cap
Sacrificial Gas Collection System	TRIANGULAR(10.0, 30.0, 50.0)	TRIANGULAR(40.0, 50.0, 60.0)	TRIANGULAR(55.0, 65.0, 75.0)
Permanent Gas Collection System	TRIANGULAR(50.0, 60.0, 70.0)	TRIANGULAR(75.0, 85.0, 95.0)	TRIANGULAR(90.0, 95.0, 97.5)

OK   Cancel   Help

Infiltration

The infiltration option allows you to define the average rate of water entering the landfill through the capped and uncapped areas annually (mm/yr), per unit area. The infiltration is effective rainfall entering the waste (i.e. rainfall less run off, evaporation and transpiration). This information can be entered as a PDF, as described in the section above.

When selecting an infiltration rate you should consider other fluid flowing into the landfill i.e. the inflow of groundwater or disposals of liquid waste. The volume of leachate recirculated and the leachate head can be ignored at this stage, as this information can be input directly into the waste moisture content dialogue box.

The calculated infiltration rate for the site in any year will depend on the proportion of the cell that is capped, and that which is uncapped or temporarily capped.

Cap and Liner Types

You are required to select the cap and liner design that best represents the cell that is being simulated from a drop down menu at the far right of the field.

Cap types that are represented include "single clay", "single liner", "composite" and "none". Lateral liner types include "single clay", "single liner", "composite", "double clay", "double liner", "double composite" and "none". The basal liner is assumed to be impermeable to gas due to the presence of leachate at the base of the landfill.

GasSim2.5 will then require the 'Thickness' and 'Hydraulic Conductivity' for each layer to be defined. Inputs that are not required will be greyed out. The permeability of the cap and the liner are entered as hydraulic conductivities as this information should be readily available. Note that the layers are numbered from top to bottom in all cases, e.g. for a Composite Cap, Layer 2 represents the membrane and for a Composite Liner, Layer 2 represents the clay. GasSim2.5 then determines the gas conductivity of each material using method detailed in Chapter 6. GasSim2.5 then uses the cap and liner gas conductivity to model the uncontrolled release of gas, which is assumed to be limited by the least permeable layers.

A temporary cap can be included in the model, again on a cell specific basis. Thickness and Hydraulic Conductivity for this are also required. GasSim2.5 then requires the timescales for when the temporary and permanent caps are installed along with associated sacrificial and permanent gas collection systems.

The sacrificial or permanent gas 'Collection Efficiency Estimates', defined as a PDF, should be defined based on your experience of the particular landfill. However the default values provided can be used if needed. These have been determined from site measurements from a confidential client and site, where the various cap and collection systems were all found on a single large site, and the emission rates from the various cap and collection permutations were assessed against the amount of gas collected for flaring. A value of 100% should not be used here, as it is unrealistic that any collection system will be 100% efficient.

If a land raise is being simulated the depth of its base below ground level is required. Data regarding the depth to water beneath the site and moisture content and porosity of the unsaturated zone are also input into the Cap and Liner dialogue box. These data were previously entered in the lateral migration module. They are now used to help GasSim2.5 determine the vertical thickness of the lateral emissions pathway.

Biological Methane Oxidation

Methane emissions can be reduced as they pass through the landfill cap by microbes. The proportion of the methane that is converted to carbon dioxide by 'Biological Methane Oxidation' should be defined on a cell-specific

basis, as the amount of methane oxidation is dependent on a number of factors including the cap thickness and permeability. GasSim2.5 simulates the reduction of methane using two approaches. The simplest is the reduction of methane by the proportion suggested in the Intergovernmental Panel on Climate Change (2006) ('IPCC') guidelines, which is 10%.

The second approach calculates the methane oxidation rates for the different cover materials. This can be simplified to a methane oxidation range of between 10 - 46%, with a mean of 25%, occurring if the soil thickness above the cap (entered) is greater than 300 mm. If the soil thickness is thinner, it is assumed that no methane oxidation will occur. Additionally you are required to enter the percentage of fissures on the site. GasSim2.5 assumes that LFG will pass through the fissures without methane oxidation occurring. The default value for fissures is set at 10%, based on the measurements obtained using the Environment Agency's methane emissions measurements procedures (2010d). To select this option click the 'Simulate Fissures and Soil Cap' under the cell it is required for. This will allow 'Soil Depth' and '% Of Area Occupied by Fissures' to be defined.

The photo-degradation of chlorinated trace gases by sunlight in the atmosphere is not included in the calculation of biological methane oxidation. Reactivity is not included in various other modules too, for example, oxidation of certain other VOCs in the cap or oxidation/conversion via lateral migration.

Waste Inputs

The 'Waste' input screen requires the quantity and composition of waste deposited for each operational year and month in each cell or phase defined in the model; the year and month that waste deposition commenced and ceased.

The 'Waste Input' rate (in tonnes) is required for each operational year. If this value is not known precisely, then a PDF can be used to represent the uncertainty. In most cases there will be a good record of the initial void space and current void available, so a reasonable estimate of the inputs can be made.

Waste Input - Phase 1

Start of Filling: 1996 / January   End of Filling: 1998 / December

Year	Waste Input (t)	Cumulative (t)	Domestic (%)	Civic Amenity (%)	Commercial (%)	Industrial (%)	
1996	UNIFORM(7.00E	85000	UNIFORM(85.0,	UNIFORM(3.0, 5.	UNIFORM(5.0, 1	SINGLE(0.0)	SING
1997	UNIFORM(7.00E	170000	UNIFORM(85.0,	UNIFORM(3.0, 5.	UNIFORM(5.0, 1	SINGLE(0.0)	SING
1998	UNIFORM(9.00E	277500	UNIFORM(85.0,	UNIFORM(3.0, 5.	UNIFORM(5.0, 1	SINGLE(0.0)	SING

Waste Moisture Content   Trace Gases   OK   Cancel   Help

The type of the waste (i.e. the percentage of the waste deposited that is domestic, commercial, industrial, inert etc.) is also entered for each year. It should be ensured that percentages equal 100%, or if PDF's are used, the most likely values approximate to 100%. When PDF's are used, to avoid losing or gaining mass unintentionally, GasSim2.5 ensures that the figures are normalised back to 100% on each iteration of the model. If single values are used, you should ensure that all waste types sum to 100%, including inert waste types, or an overestimate of gas production could occur when GasSim2.5 performs the normalisation process. Tables 3.2 – 3.5 list the default parameters for England, Wales, Scotland and Northern Ireland which are used as defaults for 2000 – 2010.

Waste Composition Editor

1980's - 2010 waste streams   Rename Add Delete Import Export

		Domestic	Civic Amenity	Commercial	Industrial	
Paper/Card	Newspapers (%)	SINGLE(11.38)	SINGLE(10.0)	SINGLE(10.0)	SINGLE(0.0)	SINGL
	Magazines (%)	SINGLE(4.87)	SINGLE(11.0)	SINGLE(0.0)	SINGLE(0.0)	SINGL
	Other paper (%)	SINGLE(10.07)	SINGLE(0.0)	SINGLE(50.1)	SINGLE(0.0)	SINGL
	Liquid cartons (%)	SINGLE(0.51)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGL
	Card packaging (%)	SINGLE(3.84)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGL
	Other card (%)	SINGLE(2.83)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGL
	Wood (%)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGL
Textiles	Textiles (%)	SINGLE(2.36)	SINGLE(3.0)	SINGLE(0.0)	SINGLE(0.0)	SINGL
Miscellaneous combustible	Disposable nappies (%)	SINGLE(4.35)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGL
	Other misc. combustibles (%)	SINGLE(3.6)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGL
Putrescible	Garden waste (%)	SINGLE(2.41)	SINGLE(22.0)	SINGLE(0.0)	SINGLE(0.0)	SINGL
	Other putrescible (%)	SINGLE(18.38)	SINGLE(0.0)	SINGLE(15.0)	SINGLE(0.0)	SINGL
Fines	10mm fines (%)	SINGLE(7.11)	SINGLE(15.0)	SINGLE(0.0)	SINGLE(0.0)	SINGL
Sewage sludge	Sewage sludge (%)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGL
Compost	Composted organic material (%)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGL
Ash	Incinerator ash (%)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGL
Non-Degradable	Non degradable (%)	SINGLE(28.86)	SINGLE(39.0)	SINGLE(24.6)	SINGLE(0.0)	SINGL

Stream Names   Degradation   C and I Calculator   OK   Cancel   Help

GASSIM

The commercial and industrial waste composition can now be specified on the basis of different commercial and industrial sectors (ERM 2006) (Tables 3.6 and 3.7). The percentages of each sector can be altered to reflect the different composition of industrial/commercial waste received at an individual landfill site. The defaults represent the average industrial and commercial waste composition for England. The user defined columns are editable and intended for use if the user knows the specific waste composition or if the waste comes from sectors which are not otherwise specified.

'Composition Data' for each waste stream is defined by using the drop down menu under 'project'. This will display the default waste compositions. Waste stream names and composition available can be edited within the 'Composition Editor' dialogue box.

The 'Waste Composition Editor' defines the relative proportions of different materials within the waste streams along with percentages for 'Water Content', 'Cellulose', 'Hemi-Cellulose' and 'Decomposition' for each waste fraction/material (use the scroll bar to access these columns). The proportion of the waste in different fractions has been determined from literature sources (see Chapter 5 for details). However, the user can edit these using site-specific information by clicking on the percentage that they wish to change and then selecting the button with three dots, which brings up a PDF input screen. The 'Waste Composition' is used to calculate the quantity of carbon that is available for slow, moderate and fast degradation and thus the quantity and rate of LFG production.

It should be noted that changing the 'Name' of the composition in the 'Waste Composition Editor' dialogue box will not cascade through and change the 'Composition' selected in the table. Therefore the new composition will have to be selected as described below.

The 'Waste Composition Editor' screen also provides the user with the option to Export their own composition files and Import previously saved and other default compositions. To do this you must change the name of the waste composition by clicking the Rename button at the top of the dialogue box and then export the file (which has the file extension .wst). To exit the waste composition screen click the Ok button or the cross in the top right hand corner of the box. If a PDF is used to describe uncertainty in one or more of the waste components then the percentage will no longer equal 100%. To avoid losing or gaining degradable carbon unintentionally, the figures are normalised back to 100% on each iteration of the model. As with waste type, if single values are used, ensure that the sum of single values in each column should be 100% or the normalisation process will introduce an error in the gas forecast.

Once waste inputs and timescales with respect to capping for each phase have been input into the model, GasSim2.5 can determine the quantity of the LFG available for utilisation, as GasSim2.5 assumes that LFG generated in the uncapped/operational area will only be emitted to the atmosphere and not collected.

Table 3.2 Waste Composition for England 2000-2010

	Domestic	Civic Amenity	Commercial	Industrial	Inert	Liquid Inert	Sewage Sludge	Composted Organic Material	Incinerator Ash	Residue from MRF	Recycling Schemes	Chemical Sludge	Industrial Liquid Waste	Water (%)	Cellulose (%)	Hemi-Cellulose (%)	Decomposition (%)
Newspapers	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	SINGLE(48.5)	SINGLE(9)	SINGLE(35)
Magazines	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	SINGLE(42.3)	SINGLE(9.4)	SINGLE(46)
Other Paper	SINGLE(19.8)	SINGLE(3.3)	SINGLE(28.8)	SINGLE(8.8)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	SINGLE(87.4)	SINGLE(8.4)	SINGLE(98)
Liquid Cartons	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	SINGLE(57.3)	SINGLE(9.9)	SINGLE(64)
Card Packaging	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	SINGLE(57.3)	SINGLE(9.9)	SINGLE(64)
Other Card	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	SINGLE(57.3)	SINGLE(9.9)	SINGLE(64)
Wood	SINGLE(3.0)	SINGLE(11.2)	SINGLE(3.3)	SINGLE(5.0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(20)	SINGLE(21)	SINGLE(11)	SINGLE(75)
Textiles	SINGLE(3.3)	SINGLE(2.3)	SINGLE(1.1)	SINGLE(0.3)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(25)	SINGLE(20)	SINGLE(20)	SINGLE(50)
Disposable Nappies	SINGLE(3.3)	SINGLE(2.9)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(20)	SINGLE(25)	SINGLE(25)	SINGLE(50)
Other Misc. Combustibles	SINGLE(0.3)	SINGLE(4.2)	SINGLE(10.4)	SINGLE(17.7)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(20)	SINGLE(25)	SINGLE(25)	SINGLE(50)
Garden Waste	SINGLE(16)	SINGLE(32.1)	SINGLE(9.8)	SINGLE(4.7)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(65)	SINGLE(25.7)	SINGLE(13)	SINGLE(62)
Other Putrescible	SINGLE(25.6)	SINGLE(14.8)	SINGLE(10.4)	SINGLE(6.8)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(65)	SINGLE(55.4)	SINGLE(7.2)	SINGLE(76)
10mm Fines	SINGLE(4.1)	SINGLE(1.2)	SINGLE(1.9)	SINGLE(0.5)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(40)	SINGLE(25)	SINGLE(25)	SINGLE(50)
Sewage Sludge	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(100)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(70)	SINGLE(14)	SINGLE(14)	SINGLE(75)
Composted Organic Material	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(100)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	UNIFORM (7.47, 9.59)	UNIFORM (7.47, 9.59)	SINGLE(57)
Incinerator Ash	SINGLE(0)	SINGLE(0)	SINGLE(0.2)	SINGLE(25.5)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(100)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	TRIANGULAR (0.5, 0.7, 1.5)	TRIANGULAR (0.5, 0.7, 1.5)	SINGLE(57)
Non Degradable	SINGLE(24.6)	SINGLE(28.0)	SINGLE(34.1)	SINGLE(30.7)	SINGLE(100)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)

Table 3.3 Waste Composition for Wales 2000-2010

	Domestic	Civic Amenity	Commercial	Industrial	Inert	Liquid Inert	Sewage Sludge	Composted Organic Material	Incinerator Ash	Residue from MRF	Recycling Schemes	Chemical Sludge	Industrial Liquid Waste	Water (%)	Cellulose (%)	Hemi-Cellulose (%)	Decomposition (%)
Newspapers	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	SINGLE(48.5)	SINGLE(9)	SINGLE(35)
Magazines	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	SINGLE(42.3)	SINGLE(9.4)	SINGLE(46)
Other Paper	SINGLE(21.0)	SINGLE(3.3)	SINGLE(28.8)	SINGLE(8.8)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	SINGLE(87.4)	SINGLE(8.4)	SINGLE(98)
Liquid Cartons	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	SINGLE(57.3)	SINGLE(9.9)	SINGLE(64)
Card Packaging	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	SINGLE(57.3)	SINGLE(9.9)	SINGLE(64)
Other Card	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	SINGLE(57.3)	SINGLE(9.9)	SINGLE(64)
Wood	SINGLE(2.8)	SINGLE(11.3)	SINGLE(3.3)	SINGLE(5.0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(20)	SINGLE(21)	SINGLE(11)	SINGLE(75)
Textiles	SINGLE(1.8)	SINGLE(2.3)	SINGLE(1.1)	SINGLE(0.3)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(25)	SINGLE(20)	SINGLE(20)	SINGLE(50)
Disposable Nappies	SINGLE(2.3)	SINGLE(2.9)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(20)	SINGLE(25)	SINGLE(25)	SINGLE(50)
Other Misc. Combustibles	SINGLE(7.0)	SINGLE(4.2)	SINGLE(10.4)	SINGLE(17.7)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(20)	SINGLE(25)	SINGLE(25)	SINGLE(50)
Garden Waste	SINGLE(12.7)	SINGLE(32.1)	SINGLE(9.8)	SINGLE(4.7)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(65)	SINGLE(25.7)	SINGLE(13)	SINGLE(62)
Other Putrescible	SINGLE(17.8)	SINGLE(14.8)	SINGLE(10.4)	SINGLE(6.8)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(65)	SINGLE(55.4)	SINGLE(7.2)	SINGLE(76)
10mm Fines	SINGLE(5.2)	SINGLE(1.2)	SINGLE(1.9)	SINGLE(0.5)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(40)	SINGLE(25)	SINGLE(25)	SINGLE(50)
Sewage Sludge	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(100)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(70)	SINGLE(14)	SINGLE(14)	SINGLE(75)
Composted Organic Material	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(100)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	UNIFORM(7.47, 9.59)	UNIFORM(7.47, 9.59)	SINGLE(57)
Incinerator Ash	SINGLE(0)	SINGLE(0)	SINGLE(0.2)	SINGLE(25.5)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(100)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(30)	TRIANGULAR(0.5, 0.7, 1.5)	TRIANGULAR(0.5, 0.7, 1.5)	SINGLE(57)
Non Degradable	SINGLE(29.4)	SINGLE(28.0)	SINGLE(34.1)	SINGLE(30.7)	SINGLE(100)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)

Table 3.4 Waste Composition for Scotland 2000-2010

	Domestic	Civic Amenity	Commercial	Industrial	Inert	Liquid Inert	Sewage Sludge	Composted Organic Material	Incinerator Ash	Residue from MRF	Recycling Schemes	Chemical Sludge	Industrial Liquid Waste	Water (%)	Cellulose (%)	Hemi-Cellulose (%)	Decomposition (%)
Newspapers	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	SINGLE (48.5)	SINGLE (9)	SINGLE (35)
Magazines	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	SINGLE (42.3)	SINGLE (9.4)	SINGLE (46)
Other Paper	SINGLE (25.0)	SINGLE (9.3)	SINGLE (28.8)	SINGLE (8.8)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	SINGLE (87.4)	SINGLE (8.4)	SINGLE (98)
Liquid Cartons	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	SINGLE (57.3)	SINGLE (9.9)	SINGLE (64)
Card Packaging	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	SINGLE (57.3)	SINGLE (9.9)	SINGLE (64)
Other Card	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	SINGLE (57.3)	SINGLE (9.9)	SINGLE (64)
Wood	SINGLE (1.2)	SINGLE (12.6)	SINGLE (3.3)	SINGLE (5.0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (20)	SINGLE (21)	SINGLE (11)	SINGLE (75)
Textiles	SINGLE (4.8)	SINGLE (2.2)	SINGLE (1.1)	SINGLE (0.3)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (25)	SINGLE (20)	SINGLE (20)	SINGLE (50)
Disposable Nappies	SINGLE (3.8)	SINGLE (0.3)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (20)	SINGLE (25)	SINGLE (25)	SINGLE (50)
Other Misc. Combustibles	SINGLE (3.7)	SINGLE (13.7)	SINGLE (10.4)	SINGLE (17.7)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (20)	SINGLE (25)	SINGLE (25)	SINGLE (50)
Garden Waste	SINGLE (6.7)	SINGLE (18.0)	SINGLE (9.8)	SINGLE (4.7)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (65)	SINGLE (25.7)	SINGLE (13)	SINGLE (62)
Other Putrescible	SINGLE (21.4)	SINGLE (3.2)	SINGLE (10.4)	SINGLE (6.8)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (65)	SINGLE (55.4)	SINGLE (7.2)	SINGLE (76)
10mm Fines	SINGLE (0.5)	SINGLE (0.8)	SINGLE (1.9)	SINGLE (0.5)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (40)	SINGLE (25)	SINGLE (25)	SINGLE (50)
Sewage Sludge	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (100)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (70)	SINGLE (14)	SINGLE (14)	SINGLE (75)
Composted Organic Material	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (100)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	UNIFORM(7.47, 9.59)	UNIFORM(7.47, 9.59)	SINGLE (57)
Incinerator Ash	SINGLE (0)	SINGLE (0)	SINGLE (0.2)	SINGLE (25.5)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (100)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	TRIANGULAR (0.5, 0.7, 1.5)	TRIANGULAR (0.5, 0.7, 1.5)	SINGLE (57)
Non Degradable	SINGLE (32.9)	SINGLE (39.9)	SINGLE (34.1)	SINGLE (30.7)	SINGLE (100)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)

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Table 3.5 Waste Composition for Northern Ireland 2000-2010

	Domestic	Civic Amenity	Commercial	Industrial	Inert	Liquid Inert	Sewage Sludge	Composted Organic Material	Incinerator Ash	Residue from MRF	Recycling Schemes	Chemical Sludge	Industrial Liquid Waste	Water (%)	Cellulose (%)	Hemi-Cellulose (%)	Decomposition (%)
Newspapers	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	SINGLE (48.5)	SINGLE (9)	SINGLE (35)
Magazines	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	SINGLE (42.3)	SINGLE (9.4)	SINGLE (46)
Other Paper	SINGLE (18.2)	SINGLE (3.3)	SINGLE (28.8)	SINGLE (8.8)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	SINGLE (87.4)	SINGLE (8.4)	SINGLE (98)
Liquid Cartons	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	SINGLE (57.3)	SINGLE (9.9)	SINGLE (64)
Card Packaging	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	SINGLE (57.3)	SINGLE (9.9)	SINGLE (64)
Other Card	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	SINGLE (57.3)	SINGLE (9.9)	SINGLE (64)
Wood	SINGLE (2.8)	SINGLE (11.2)	SINGLE (3.3)	SINGLE (5.0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (20)	SINGLE (21)	SINGLE (11)	SINGLE (75)
Textiles	SINGLE (1.8)	SINGLE (2.3)	SINGLE (1.1)	SINGLE (0.3)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (25)	SINGLE (20)	SINGLE (20)	SINGLE (50)
Disposable Nappies	SINGLE (2.3)	SINGLE (2.9)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (20)	SINGLE (25)	SINGLE (25)	SINGLE (50)
Other Misc. Combustibles	SINGLE (7.1)	SINGLE (4.2)	SINGLE (10.4)	SINGLE (17.7)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (20)	SINGLE (25)	SINGLE (25)	SINGLE (50)
Garden Waste	SINGLE (14.2)	SINGLE (32.1)	SINGLE (9.8)	SINGLE (4.7)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (65)	SINGLE (25.7)	SINGLE (13)	SINGLE (62)
Other Putrescible	SINGLE (19.8)	SINGLE (14.8)	SINGLE (10.4)	SINGLE (6.8)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (65)	SINGLE (55.4)	SINGLE (7.2)	SINGLE (76)
10mm Fines	SINGLE (5.4)	SINGLE (1.2)	SINGLE (1.9)	SINGLE (0.5)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (40)	SINGLE (25)	SINGLE (25)	SINGLE (50)
Sewage Sludge	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (100)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (70)	SINGLE (14)	SINGLE (14)	SINGLE (75)
Composted Organic Material	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (100)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	UNIFORM(7.47, 9.59)	UNIFORM(7.47, 9.59)	SINGLE (57)
Incinerator Ash	SINGLE (0)	SINGLE (0)	SINGLE (0.2)	SINGLE (25.5)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (100)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (30)	TRIANGULAR (0.5, 0.7, 1.5)	TRIANGULAR (0.5, 0.7, 1.5)	SINGLE (57)
Non Degradable	SINGLE (28.4)	SINGLE (28.0)	SINGLE (34.1)	SINGLE (30.7)	SINGLE (100)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)	SINGLE (0)

Table 3.6 Commercial Waste Compositions

Waste Composition	Commercial Industry Types							
	Default	Travel Agents, Other Business, Finance, Real Estate and Computer-Related Activities Sector	Transport, Storage and Communications Sector	Social Work and Public Administration Sector	Retail Sector	Hotels and Catering Sector	Education Sector	Miscellaneous Sector
Newspapers	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Magazines	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Other Paper	SINGLE(19.8)	SINGLE(27.8)	SINGLE(23.7)	SINGLE(31.0)	SINGLE(35.5)	SINGLE(17.0)	SINGLE(21.2)	SINGLE(21.8)
Liquid Cartons	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Card Packaging	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Other Card	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Wood	SINGLE(3.0)	SINGLE(2.6)	SINGLE(6.3)	SINGLE(1.8)	SINGLE(3.9)	SINGLE(2.1)	SINGLE(2.3)	SINGLE(1.8)
Textiles	SINGLE(3.3)	SINGLE(1.6)	SINGLE(1.4)	SINGLE(1.4)	SINGLE(1.0)	SINGLE(1.6)	SINGLE(1.7)	SINGLE(1.2)
Disposable Nappies	SINGLE(3.3)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Other Misc. Combustibles	SINGLE(0.3)	SINGLE(3.9)	SINGLE(7.6)	SINGLE(18.2)	SINGLE(14.3)	SINGLE(5.1)	SINGLE(10.8)	SINGLE(23.8)
Garden Waste	SINGLE(16)	SINGLE(10.1)	SINGLE(7.7)	SINGLE(9.3)	SINGLE(6.3)	SINGLE(11.1)	SINGLE(12.3)	SINGLE(8.0)
Other Putrescible	SINGLE(25.6)	SINGLE(12.9)	SINGLE(12.7)	SINGLE(12.1)	SINGLE(8.5)	SINGLE(16.5)	SINGLE(19.1)	SINGLE(14.2)
10mm Fines	SINGLE(4.1)	SINGLE(2.3)	SINGLE(1.8)	SINGLE(2.1)	SINGLE(1.3)	SINGLE(2.5)	SINGLE(2.6)	SINGLE(1.8)
Sewage Sludge	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Composted Organic Material	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Incinerator Ash	SINGLE(0)	SINGLE(0.7)	SINGLE(0.4)	SINGLE(0.1)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0.4)
Non Degradable	SINGLE(24.6)	SINGLE(38.1)	SINGLE(38.4)	SINGLE(24)	SINGLE(29.2)	SINGLE(44.1)	SINGLE(30.0)	SINGLE(27)

Table 3.7 Industrial Waste Compositions

Waste Composition	Default	Food, Drink and Tobacco	Furniture and Other Manufacturing	Manufacture of Basic Metals	Manufacture of Chemicals and Chemical Products	Manufacture of Fabricated Metal Products	Manufacture of Machinery and Equipment	Manufacture of Motor Vehicles and Other Transport Equipment	Manufacture of Office Machinery, Media and Medical Equipment	Manufacture of Pulp, Paper and Paper Products	Manufacture of Textiles and Other Apparel	Manufacture of Non-Metallic Mineral Products	Production of Coke, Oil, Gas, Electricity and Water	Publishing, Printing and Recording Sector	Wood and Wood Products sector
Newspapers	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Magazines	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Other Paper	SINGLE(8.8)	SINGLE(5.4)	SINGLE (15.5)	SINGLE (0.8)	SINGLE (5.6)	SINGLE (5.9)	SINGLE (10.1)	SINGLE (7.0)	SINGLE (23.4)	SINGLE (23.0)	SINGLE (5.9)	SINGLE (2.7)	SINGLE (0.5)	SINGLE (65.8)	SINGLE (3.8)
Liquid Cartons	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Card Packaging	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Other Card	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Wood	SINGLE (5.0)	SINGLE (1.6)	SINGLE (28.7)	SINGLE (0.3)	SINGLE (1.7)	SINGLE (2.1)	SINGLE (4.4)	SINGLE (6.4)	SINGLE (3.9)	SINGLE (1.8)	SINGLE (1.5)	SINGLE (1.4)	SINGLE (0.1)	SINGLE (1.4)	SINGLE (78.4)
Textiles	SINGLE (0.3)	SINGLE (0.2)	SINGLE (1.3)	SINGLE (0.1)	SINGLE (0.5)	SINGLE (0.4)	SINGLE (0.5)	SINGLE (0.5)	SINGLE (1.0)	SINGLE (0.2)	SINGLE (1.9)	SINGLE (0.2)	SINGLE(0)	SINGLE (0.6)	SINGLE (0.4)
Disposable Nappies	SINGLE (0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	DISPOSE(0)	SANGLE(0)
Other Misc. Combustibles	SINGLE (17.7)	SINGLE (38.6)	SINGLE (2.7)	SINGLE (71.5)	SINGLE (45.8)	SINGLE (14.3)	SINGLE (3.8)	SINGLE (6.0)	SINGLE (3.9)	SINGLE (39.6)	SINGLE (24.7)	SINGLE (43.7)	SINGLE (2.8)	SINGLE (6.0)	SINGLE (2.0)
Garden Waste	SINGLE (4.7)	SINGLE (2.0)	SINGLE (9.1)	SINGLE (0.5)	SINGLE (2.3)	SINGLE (3.0)	SINGLE (3.6)	SINGLE (3.4)	SINGLE (6.3)	SINGLE (1.5)	SINGLE (4.0)	SINGLE (1.3)	SINGLE (0.3)	SINGLE (4.2)	SINGLE (2.8)
Other Putrescible	SINGLE (6.8)	SINGLE (16.1)	SINGLE (10.3)	SINGLE (0.6)	SINGLE (2.8)	SINGLE (3.8)	SINGLE (4.7)	SINGLE (4.0)	SINGLE (7.1)	SINGLE (1.9)	SINGLE (5.8)	SINGLE (1.5)	SINGLE (0.3)	SINGLE (4.6)	SINGLE (3.1)
10mm Fines	SINGLE (0.5)	SINGLE (0.4)	SINGLE (2.0)	SINGLE (0.1)	SINGLE (0.5)	SINGLE (0.7)	SINGLE (0.8)	SINGLE (0.8)	SINGLE (1.4)	SINGLE (0.3)	SINGLE (0.9)	SINGLE (0.3)	SINGLE (0.1)	SINGLE (0.9)	SINGLE (0.6)
Sewage Sludge	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Composted Organic Material	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)	SINGLE(0)
Incinerator Ash	SINGLE (25.5)	SINGLE (0.2)	SINGLE (0.2)	SINGLE(9)	SINGLE (0.4)	SINGLE (1.7)	SINGLE(0)	SINGLE (5.9)	SINGLE(0)	SINGLE (3.5)	SINGLE(0)	SINGLE (6.6)	SINGLE (90.4)	SINGLE(0)	SINGLE (0.1)
Non Degradable	SINGLE (30.7)	SINGLE (35.5)	SINGLE (30.2)	SINGLE (17.1)	SINGLE (40.4)	SINGLE (68.1)	SINGLE (72.1)	SINGLE (66)	SINGLE (53)	SINGLE (28.2)	SINGLE (55.3)	SINGLE (42.3)	SINGLE (5.5)	SINGLE (16.5)	SINGLE (8.8)

GasSim2.5 can simulate landfills that are left uncapped or partly capped for a number of years prior to full capping by extending the operational life of the landfill, and entering zero tonnes of disposed waste each year. Waste can also recommence filling after such a period, simulating surcharging (or a new overlapping cell can now be constructed, if the surcharging is only over part of a cell). If a temporary cap has been installed, GasSim2.5 assumes the cap is removed and then reinstated once filling is complete.

Waste compositions are defined for specific sites and years. If you wish to represent a particular waste stream, you do so in the waste composition editor. Only one waste composition (comprising many waste streams) can be selected in any one year. As waste compositions evolve, through changes in individual waste streams, this can be represented by different waste compositions. You define which waste compositions apply for each year in the waste composition screen. The percentage fraction of which waste streams may be found in which cells is defined in the waste inputs which are on a cell by cell basis.
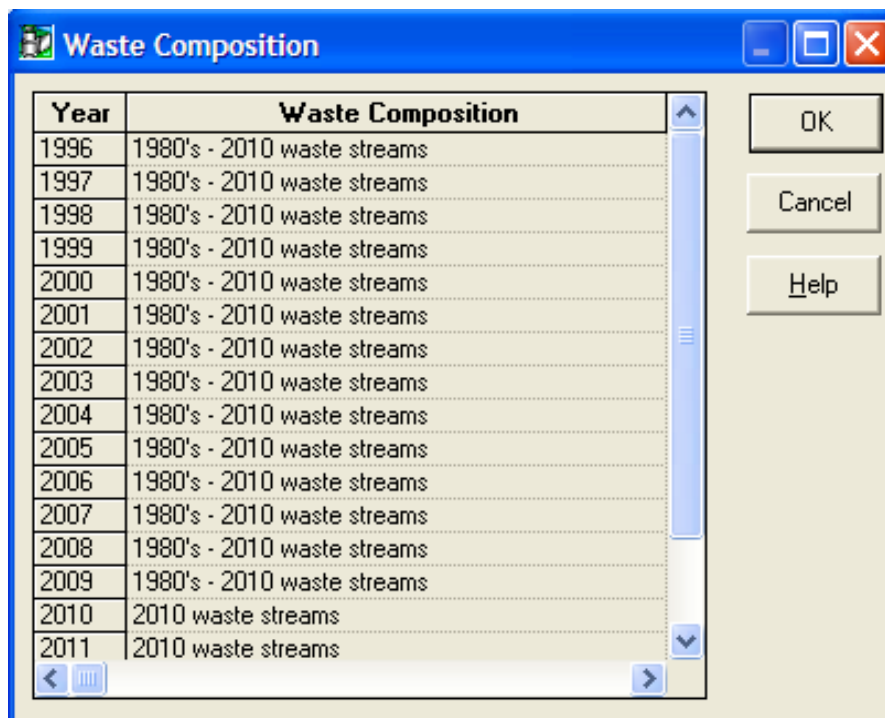
Waste Moisture Content and Waste Degradation Rates

The 'Degradation rates for Waste Moisture Conditions' for 'Dry', 'Average', 'Wet' and 'Saturated' waste, for 'Slow', 'Moderate' and 'Fast' degrading carbon determines the initial rate of degradation of waste. The users can now specify two more user defined types 'User Defined 1' and User Defined 2'. Clicking the Use Defaults button will set the simulated values to the default values provided on the right hand side of the table. Alternatively, by clicking on the required box on the left hand side of the table and selecting the button containing an arrow allows user defined PDF's of these values to be entered. These values should be altered with care as they determine the rate of waste decay and thus the generation of LFG. You should vary these degradation rates to calibrate the landfill model against reported abstraction data. They need not be single values.

You are required to select the 'Degradation rate – Filling Phase' of the waste using the drop down menu. You can select 'Moisture Content' as 'Dry', 'Average', 'Wet', 'Saturated', 'User Defined 1' or 'User Defined 2" moisture contents or specify 'Calculate' so that GasSim2.5 will calculate the moisture content based upon the input parameters you define. However, the estimation of the waste moisture content should be carried out with care, as this is a key factor controlling the waste degradation and thus LFG production, by determining the waste degradation constants. It is better to use observations of abstraction data to determine the most appropriate degradation rates. In a few cases, such as in specially designed bioreactor landfill cells, degradation rates faster than those provided for GasSim2.5's 'Wet' scenario may be required. You should determine these degradation rates very carefully. No defaults are provided for these conditions in the model.

Different degradation rates for different periods in a cell can be input into the model using the drop down menu in 'Degradation rate – after change' and the users are required to define 'Year of deg rate change' and 'Month of deg rate change'. It is intended that the rates which you input into 'User Defined 1' or 'User Defined 2" are used here, so that the main waste degradation parameters, 'Dry', 'Average', 'Wet', and 'Saturated', can remain unchanged. You should note that data on post-closure waste degradation rates are limited, and you should research your Site before selecting any parameters. This functionality works best in single cell models.

Waste Moisture Content and Waste Degradation Rates

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Degradation rate - Filling Phase	Wet	Wet	Wet	Average	Average	Average
Year of deg rate change	1999	2002	2005	2008	2011	2015
Month of deg rate change	January	January	January	January	January	January
Degradation rate - after change	Wet	Wet	Wet	Average	Average	Average
Waste Density (t/m3)	UNIFORM(0.8, 1.	UNIFORM(0.8, 1.	UNIFORM(0.8, 1.	UNIFORM(0.8, 1.	UNIFORM(0.8, 1.	UNIFORM(0.8, 1.
Effective Porosity (%)	UNIFORM(1.0, 2	UNIFORM(1.0, 2	UNIFORM(1.0, 2	UNIFORM(1.0, 2	UNIFORM(1.0, 2	UNIFORM(1.0, 2
Leachate Head (m)	UNIFORM(2.5, 4.	UNIFORM(2.5, 4.	UNIFORM(2.5, 4.	UNIFORM(0.2, 1.	UNIFORM(0.2, 1.	UNIFORM(0.2, 1.
Conductivity (m/s)	LOGUNIFORM(1.	LOGUNIFORM(1.	LOGUNIFORM(1.	LOGUNIFORM(1.	LOGUNIFORM(1.	LOGUNIFORM(1.
Adsorptive Capacity (%[v/v])	UNIFORM(1.0, 5.	UNIFORM(1.0, 5.	UNIFORM(1.0, 5.	UNIFORM(1.0, 5.	UNIFORM(1.0, 5.	UNIFORM(1.0, 5.
Leachate Recirculation (m3/hr)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)	SINGLE(0.0)

Name to give first user defined moisture in this model: User Defined 1
Name to give second user defined moisture in this model: User Defined 2

Degradation Rates for Waste Moisture Conditions (y-1)

	Dry	Average	Wet	Saturated	User Defined 1	User Defined 2
Slow	SINGLE(0.013)	SINGLE(0.046)	SINGLE(0.076)	SINGLE(0.013)	SINGLE(0.046)	TRIANGULAR(0.046, 0.076, 0.076)
Moderate	SINGLE(0.046)	SINGLE(0.076)	SINGLE(0.116)	SINGLE(0.046)	SINGLE(0.116)	TRIANGULAR(0.076, 0.116, 0.116)
Fast	SINGLE(0.076)	SINGLE(0.116)	SINGLE(0.694)	SINGLE(0.076)	SINGLE(0.694)	SINGLE(0.694)

Use Defaults

Default Degradation Rates for Waste Moisture Conditions (y-1)

	Dry	Average	Wet	Saturated	User Defined 1	User Defined 2
Slow	SINGLE(0.013)	SINGLE(0.046)	SINGLE(0.076)	SINGLE(0.013)	TRIANGULAR(0.013, 0.046, 0.046)	TRIANGULAR(0.046, 0.076, 0.076)
Moderate	SINGLE(0.046)	SINGLE(0.076)	SINGLE(0.116)	SINGLE(0.046)	TRIANGULAR(0.046, 0.076, 0.076)	TRIANGULAR(0.076, 0.116, 0.116)
Fast	SINGLE(0.076)	SINGLE(0.116)	SINGLE(0.694)	SINGLE(0.076)	SINGLE(0.116)	SINGLE(0.694)

OK   Cancel   Help

Calculation of the waste moisture content requires inputs from the 'Waste Density', the 'Effective Porosity', the 'Leachate Head', 'Hydraulic Conductivity' of the waste, Adsorptive Capacity' and volume of 'Leachate Recirculation', along with the 'Infiltration' rate (defined from the cap and liner dialogue box). GasSim2.5 assumes that the water is derived from infiltration, rate of leachate recirculation, the waste hydraulic properties, and the leachate level.

The 'Effective Porosity', 'Adsorptive Capacity' and 'Leachate Recirculation' are only used to calculate the waste moisture content and therefore these are disabled unless the 'Calculate' option has been selected. The 'Waste Density', 'Leachate Head' and 'Hydraulic Conductivity' are required by other modules and therefore must be defined here.

GasSim2.5 does not allow for daily or seasonal variations in infiltration or leachate head. The model will default to capping year timescales, however; it is possible to model the impact of draining the site or recirculating leachate by changing the degradation rate after a particular year and month.

Trace Gas Inventory

The trace gas database for each cell can be accessed by using the pull down menu as well as via the waste input screen for each cell. Selection of the trace gas database produces the following dialogue box:

The trace gas database is cell-specific. This means that users can represent a different trace gas composition in each cell that is created, should that level of detail be available. This functionality is intended to enable, for example, a different H_2S concentration to be represented in individual cells, reflecting the co-disposal of sulphate waste with household waste in a particular cell.

GasSim2.5 contains databases with default distributions of trace gas concentrations for PI (reporting requirements), Odour, and Global Impact. The distributions of the default species have been determined from literature (see Chapter 5), which has resulted in a combination of log triangular, log normal, triangular, normal and single value distributions. The source concentrations of trace gases can be edited by selecting the 'Concentration [mg/m^3]' of the gas of interest and redefining the PDF by selecting the button with an arrow. It should be noted that selecting 'Reset List' will reset trace gas concentrations to the GasSim2.5 default values, and overwrite any user-defined values.

The species in the inventory can be viewed by scrolling up and down through the list. The gases are listed in alphabetical order. You are required to select the 'Gas' species that you wish to simulate, whether these are species present within the LFG or present only as combustion products from flares and engines. Some combustion products can be determined from their Parent Species within the LFG, i.e. HF from F and HCl from Cl. Where this is the case, the parent product should be selected. To alter the trace gases to be included in the simulation, click on the 'Select' box to the left of the species to pick or remove a gas from the simulation. A tick appears in the box to indicate that it has been selected. Additionally all species displayed can be selected by clicking the Select All button, and all species can be deselected by clicking the Clear All button.

Specifying which trace gas species are present in the LFG (which includes the Parent Species) is carried out by clicking the box to the right of the species required, in the 'Raw Gas' column, so that a tick appears. These species will then require a 'Concentration [mg/m^3]' to be input. Species that are not selected as present in 'Raw Gas' will be defined as combustion products, the concentration of which will be defined in the Gas Plant dialogue box. When a parent product is used to define a combustion product you are also required to define the 'Molecular Ratio', i.e. the ratio of the Parent to the Daughter Species based on the molecular weights, e.g. total F to HF is 1.05.

The GasSim2.5 trace gas inventory contains species frequently considered as important in LFG risk assessment. However, the list is far from comprehensive. Therefore it is possible to add a new species by clicking the new button and entering the name of the new species in the dialogue box and clicking 'OK'. The new species will then appear at the bottom of the trace gas list.

Species that you have entered can be deleted by clicking the Delete button. However, default gases cannot be deleted; they can only be deselected by clicking on the box to the left of the species to remove the tick or clicking the Clear All button to remove all trace gases from the simulation.

Site-specific data are preferable to default data and may be a requirement for assessment of existing sites. The default data may not necessarily represent the range of concentrations found on the landfill you are simulating. Trace gas composition varies a great deal between sites and the default values cover a very wide range. The concentration of trace gases at an individual site may be considerably lower or higher than the defaults.

A further option on the 'Trace Gas Inventory' dialogue box enables you to define a declining source term in each phase for the trace gases by entering a 'Trace gas Half-life [years]'. This allows all the trace gases to decay at the rate defined by the PDF. If you wish to run the simulation where the concentration of trace components effectively remains constant, you should enter a very large half-life i.e. 100,000 years.

Gas Plant

The 'Gas Plant' option allows the gas flaring and utilisation by engines details at the site to be defined. GasSim2.5 uses this information, along with the LFG source/generation results, to calculate the emissions from flares, engines, the cap and through the liner. Clicking the words 'Gas Plant' on the splash screen or Edit 'Gas Plant' from the pull down menu allows access to this option and the following dialogue box will be displayed:

The 'Gas Plant' dialogue box allows you to define the number and capacity of the flares and spark ignition engines. You enter engines and flares by clicking the Add button to add engines/flares, and Remove to remove them for each type of gas plant you should select whether it is a 'Flare', 'Spark Ignition Engine' or 'Dual Fuel Engine' by clicking the 'Type' box and using the pull down menu. If a gas plant has already been drawn out on the cell layout domain, the coordinates will be shown. You must then define the 'Year and month Commissioned' and 'Year and month Decommissioned' for each flare/engine, by clicking in the boxes and typing the year and month. The cells from which gas is received by the gas plant is determined within the 'Cell details' dialogue box where 'combustion emissions' can be checked if required.

This table allows the 'Downtime' of the individual engines and flares to de defined to allow the yearly capacity to be calculated for PI reporting. The 'Downtime' accounts for the percentage of time the engines/flares are not in operation due to routine maintenance and breakdowns. Downtime should only be used in long-term atmospheric impact assessments. Downtime should be set to 0 for short-term atmospheric impact assessments, since these will be assessed when the plant in question is operating at full capacity.

The minimum and maximum capacity i.e. the operational range of the flare/engine needs to be entered in the subsequent columns.

The next set of engine or flare-specific inputs required are the 'Air to Fuel Ratio', 'Stack Height', 'Orifice Diameter' and 'Temperature' of the relevant flare/engine. The Flare 'Orifice Diameter' is the diameter of the flare stack, as GasSim2.5 assumes that all flares are enclosed to reflect best practice. These parameters are used in the atmospheric dispersion model to calculate the release height and rate of release of the gases from each source. The air to fuel ratio is also used to determine the trace gas emissions of combustion products.

Combustion within flares and engines results in the destruction of the bulk gases methane and hydrogen, and the creation of carbon dioxide. You enter the 'Destruction Efficiency', i.e. the proportion of methane and hydrogen that are destroyed in the engine and the flare, by clicking the relevant input box and entering the values or the range using a PDF. However, these should not be set at 100%, as it is unrealistic that any flare or engine will be 100% efficient. The generation of carbon dioxide is determined from the destruction of methane and undifferentiated VOCs.

There are various options that allow you to define the 'Order' that the engines and flares will be utilised, as described below:

- Commission the engine and flares in the order that they are displayed on the screen ('user defined');
- Commission the engines first with gassim2.5 determining the optimum order, with excess LFG being flared ('engines first');
- Commission the flares first with gassim2.5 determining the optimum order, with excess LFG being utilised by the engines ('flares first'); and
- Run the simulation without gas utilisation by selecting ('no flares or engines').

It should be remembered that GasSim2.5 will only use engines and flares that are available each year. Care should be taken when ordering the engines and flares as GasSim2.5 uses the available gas utilisation capacity to determine the quantity of gas that is combusted and thus the quantity of gas that is emitted uncontrollably. Where multiple flares/engines have been defined GasSim2.5 will commission additional flares/engines when sufficient LFG is available. The decommissioning date determines the last date that the flare/engine will be operated, however the model will remove the engine/flare if the LFG generation is below the minimum capacity. GasSim2.5 will also trim the flaring operation to follow the gas production curve.

In this dialogue box you also determine the 'Proportion to CO_2 [%]' (carbon dioxide) and 'Proportion to CH_4 [%]' (methane), which allows the user to define the LFG composition anticipated over the simulation period. These inputs can be entered (as percentages) either as single values or PDFs. The proportions are normalised to 100% for each iteration. These values are usually obtained from gas abstraction data. If abstracted gas includes entrained air, you should normalise the concentrations and flow rates of LFG to only the LFG component, and you should exclude entrained nitrogen and oxygen (which are normally present in the ratio 5:1 or thereabouts).

The 'Gas Plant' dialogue box has a link to the 'Trace Gas Plant' dialogue box. Selecting this option will open the following box:
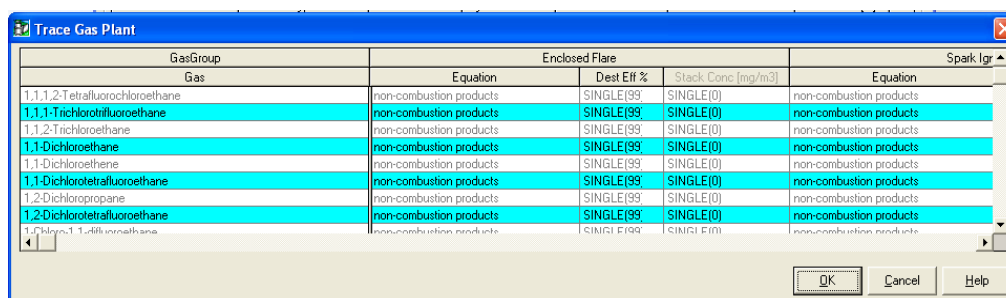
Trace gases can be destroyed or created by the combustion process, with some trace gases like PAHs undergoing both processes, due the breakdown of PAHs entering the flare/engine and the formation of PAHs by the breakdown of other compounds. Therefore the emissions of these species have to be calculated using different equations and parameters. Emissions of species that are destroyed by the combustion process are determined in a similar way to methane and hydrogen. However, the emissions of combustion products (those formed in the flare or engine) require the input of either the concentration of the species emitted to be monitored, or the concentration of the parent substance destroyed to form the daughter species, e.g. chlorine forms hydrogen chloride.

The default species have been defined with equations depending on their behaviour during combustion, described in Chapter 5. Additionally the emissions of VOCs, hydrogen chloride, hydrogen fluoride and sulphur dioxide can be defined using different equations depending on the parameters entered (see Table 3.8). If you enter additional species, GasSim2.5 requires you to determine the equation that will be used to calculate the emissions after combustion by selecting the relevant equations for each trace gas in the 'Equation' column. The additional inputs that you require depend on the equation selected (a list of equations and parameters required) is provided in Table 3.8.

Table 3.8: Combustion Equations and Input Parameters Required

Equation Used	Species	Parameters Required
'non-combustion products'	All non-combustion products, i.e. vinyl chloride, hydrogen sulphide etc.	Destruction efficiency, LFG concentration specified in the source model.
'carbon dioxide generation'	Carbon dioxide only.	Destruction efficiency of methane and where present, VOCs. Methane and VOC concentrations specified in the source model.
'combustion products'	Combustion products, i.e. hydrogen chloride, hydrogen fluoride, dioxins & furans, nitrogen oxides, sulphur dioxide, nitric acid, total phosphates, carbon monoxide, PAHs and Total non-methane VOCs.	Engine and/or flare Air/Fuel Ratio. Flare stack and/or engine exhaust concentration.
'combustion products from parent species'	Combustion products formed from Parent LFG species hydrogen chloride, hydrogen fluoride and sulphur dioxide.	Destruction efficiency, Molecular weight correction, LFG concentration or Parent Species generated in the source model, i.e. chlorine, fluorine, sulphur.

The source concentrations of the non-combustion product trace gases or the parent trace gases and the 'Molecular Ratios' are determined by the 'Waste Input', 'Trace Gas Inventory' dialogue box as described above. This ratio

correctly balances the mass of the 'Parent' and 'Daughter' species. You are required to enter the 'Destruction Efficiencies' for these species, as PDF's in the 'Trace Gas Plant' 'Engine Destruction Efficiency' and Flare 'Destruction Efficiency' columns. The destruction efficiency determines the proportion of the species that is destroyed in the flare/engine, which can be determined by on-site monitoring, or the proportion of a 'Parent' species that is converted into a 'Daughter' species.

The 'Destruction Efficiency' should be defined for VOCs, when these are simulated, even if these species are defined as 'Combustion Products' to allow the quantity of carbon dioxide to be calculated.

GasSim2.5 determines the emissions of trace gas combustion products using data from the 'Engine Exhaust Concentration' and/or 'Flare Stack Concentration' and the Air/Fuel Ratio. Therefore if the 'Combustion Products' equation has been selected you will be required to enter the 'Engine Exhaust Concentration' and/or Flare Stack Concentration', as a PDF in mg/Nm^3, in the relevant column for each species. These concentrations can be obtained from on-site monitoring and used to determine the emissions of 'Combustion Products' based on the quantity of exhaust leaving the flare or engines.

GasSim2.5's database is designed to work from normalised engine and flare emissions data. These are the values collected for stack emissions reporting. These values will have been collected at actual emission conditions (O_2 rich, wet, hot) but are normalised to dry gas, STP and 3% O_2 (flares) or 5% O_2 (gas engines) for inter-comparison purposes with standards and other gas plant.

Environmental Transport

Tier 1 Screening

The Tier 1 screening module provides a list of gases whose emissions are low enough that detailed modelling is not required. The 'Tier 1 screening' dialogue box is only active after the source and emissions modules have been simulated. GasSim2.5 has been coded in this way to optimise the running time of the model and to prevent the requirement for excessive information for simple simulations. It can be accessed either by the "Tier 1 Screening" text on the main screen, or by the option via the Simulate menu. The module requires only minimal data in order to give a simple assessment of the likely risk of all of the modelled trace elements.

An input screen is displayed, and the following inputs are required:

- 'Screen All Years' for all years or 'Year of interest' for a single year;
- When 'Year of interest' being selected, the user may choose 'Yearly Average' or a specific 'Month of interest'
- Use dxf map receptors or user defined distances to receptors; and
- Long-term background concentration for each gas.

For short-term (hourly) impacts, the main areas of concern are those close to the site boundary, such as public footpaths. The current Environment Agency interpretation of EU air quality limit values (such as short-term air quality objectives for nitrogen dioxide, from the year 2010 onwards) is that compliance is required at all off-site locations. Therefore the shortest distance to the site boundary, as well as the distance to the nearest receptor of relevant public exposure, must be specified for:

- The gas engine(s);

- The flare(s); and

- The operational area.

However, pollutants whose Environmental Assessment Levels ('EALs') are not driven by EU legislation may be considered screened out as insignificant provided that they are deemed so at the distance of the nearest receptor where there is relevant public exposure.

Selecting the map receptors option allows the dispersion model to be used to define the distances between the site and the receptors automatically.

The default Environmental Quality Standards ('EQS') and Environmental Assessment Levels ('EAL') values are provided as defaults in this module, although the user is able to enter their own. If no EAL or EQS is known for a trace element, the value "0" can be entered; gases without an EAL/EQS cannot be screened by this model. Note that default EALs/EQSs are not provided for all gases.

Non-zero background concentrations must be entered for those few pollutants, such as carbon monoxide, nitrogen dioxide and sulphur dioxide, which are normally present in the atmosphere at concentrations of a similar order of magnitude to their EQSs or EALs. Note that it is the background for nitrogen dioxide, not total oxides of nitrogen that should be entered for nitrogen oxides.

Pressing the Calculate button evaluates four sets of rules for each gas in the trace gas database, as described in the previous two sections. The first pair of rules determines whether the impact is insignificant or not, over the short-term (1 hour) or long-term (annual) assessment period. The second pair of rules determines whether the impact requires detailed modelling or if GasSim2.5 is sufficient. The rules are discussed in Chapter 6.

The 95%ile emission rate for emissions from the flare, gas engine and surface emission rate are used. The flare and gas engine height as entered in the Gas Plant module are used with the lookup tables (see below) to produce a concentration due to each process at the boundary or receptor in $\mu g/m^3$.

GasSim2.5 provides an emissions converter to allow the user to revert to actual conditions that are required for dispersion purposes in Tier 1 and Tier 2 modelling. The user provides normalised data from the site (or relies on the defaults provided), and also provides the stack emission conditions that applied at the time of testing (or uses representative values).

The calculate function key determines a distribution of results, and the user chooses a percentile from that distribution (normally the 95th) to arrive at a single value which can be used in the Tier 1 and Tier 2 modelling. Previously, GasSim users had to adjust normalised PDF's to actual PDF's, taking into account oxygen and moisture content differences, outside of GasSim, and overwrite the PDF's manually. GasSim2.5 now allows those PDF's to be overwritten with actual site data using the overwrite function key.

## Tier 2 Atmospheric Dispersion

The 'Atmospheric Dispersion' module is only active after the source and emissions modules have been simulated (via Simulate – Source Gases). Note, do not resave at any point within the source and emissions modules following a simulation as this will retime-stamp the files and inhibit you for loading the results. If you are reopening an existing model then only the Landfill Characteristics and Gas Plant modules will appear active (white type). If the source module has already been run then these results can be loaded via: File - Load Results from the main screen. Once the statistics have loaded, all modules of GasSim2.5 become active. GasSim2.5 has been coded in this way to optimise the running time of the model and to prevent the requirement for excessive information for simple simulations.

GasSim2.5 simulates the atmospheric dispersion of the gases emitted from engines, flares and the cap (landfill surface – fugitive emissions) of the landfill using the USEPA's AERMOD model.   AERMOD (**A**merican Meteorological Society and **E**nvironmental Protection Agency **R**egulatory **MOD**el) is a Gaussian plume model and is described in Chapter 6. The Tier 2 Atmospheric Dispersion module of the GasSim2.5 model is not probabilistic. The specific gas being simulated can however be modelled at one of a variety of confidence levels or percentiles taken from the emissions module.

AERMOD Inputs – Receptors

Clicking on the cartoon or selecting the option from 'Simulate' on the main menu bar accesses the 'Tier 2 Atmospheric Dispersion' module. A screen with the site plan of the landfill being modelled will be displayed. In the first instance, this site plan is that displayed under the Landfill Characteristics module. This screen can be used to deploy the receptors to be considered within the atmospheric dispersion by using the eight interactive buttons below the menu bar.

The first four buttons define receptor types: the first button to the far left is for a discrete receptor (a building, for example), the next is for a Cartesian Grid Receptor (these may be used for area coverage and for producing contour maps), the third is for a Polar Grid Receptor (these are commonly used for emissions from a point source), and the fourth is for Site Boundary Receptors (these follow the site boundary at a specified spacing). The later four buttons are to aid viewing and manoeuvring within the window being in turn from left to right, Zoom In, Zoom Out, Zoom All and Toggle Pan Mode. Zooming out of the screen shot is often required in the deployment of grid receptors over a sufficiently wide area, as the screen does not actively scroll once in the process of placing grid receptors.
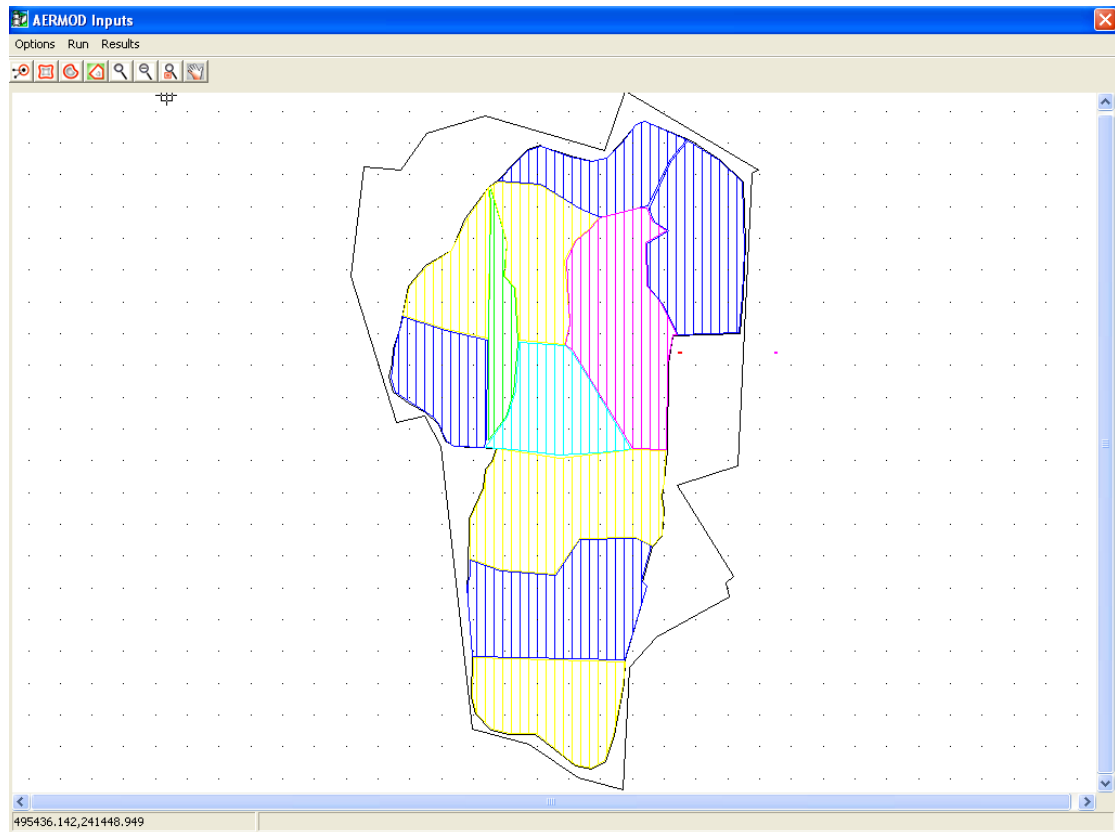
Click on the receptor button of interest and then onto the map to place the receptor in its required location. In the case of receptor grids the first click onto the map provides the starting point for the grid and you can drag the mouse to define the maximum extent. A double click is required to deploy the grid receptors.

The insertion of any receptor type leads to the activation of the receptor table screen. This can also be accessed directly via the menu – Options – Receptors. As the details of receptors can be changed via this table it is often useful to initiate them via the map in approximate positions and then edit the finer positional details in the table. Receptors can be added and removed directly from the receptor table screen. To delete a receptor take care to select only the receptor for deletion as there is no undo function. Note, if the map does not update following edits of receptor positions via the table, close the map screen and reopen.

The Receptors table screen allows you to Describe/name all the receptors for ease of recognition. Position, spacing of points for Grid receptors, and spacing of boundary receptors can all be edited. The default spacing is set at 50 m following Environment Agency guidance. Cartesian and Polar, can be turned On or Off via a click button adjacent to the Grid Receptors title. Both grid receptor types also have independently the option for on-site receptors to be removed. Again, this option is activated by click boxes this time below the grid receptor details of interest. Two site boundary receptors are available for activation via click boxes under the Include column. BR001 tends to be the boundary around the landfill cells, and BR002 tends to be the landfill site boundary.

Use of polar grids can significantly reduce run times, and is generally acceptable to the Environment Agency, provided the receptor grid spacing is no more than about 50 m in the vicinity of the site boundary. The use of discrete receptors or the disabling of on-site receptors is only considered advisable when you have sufficiently high level of confidence in your meteorological data. If the prevailing wind direction is not precise, hot spots may not actually fall on receptors of interest.

AERMOD Inputs – Emissions

Investigation and selection of the emissions for simulation in the Atmospheric Dispersion module are viewed under the menu Options – Simulation Parameters. Selection of this launches the following screen.

Substances of interest, year of interest, and percentile of the emission rate, can be viewed via the drop down menu at the top of the screen. As changes are made to these options so the tables of Sources data will update. The

Source tables illustrate the emission rate and, if a point source, exit velocity for the chosen substance and year. Both the emission rate and exit velocity have been temperature corrected to the operating conditions of the plant. The inclusion of various point and fugitive sources are made via the click boxes under the include heading of the tables.

The point sources available for selection in this screen are taken from those input within the Gas Plant module of GasSim2.5. Fugitive emission sources are based on the number of cells making up the landfill site in the model. Any changes required to the number or type of sources requires the details in the Gas Plant (for point sources) and/or the Landfill Characteristics (for fugitive sources) to be edited and the Source Gases module rerun. Similarly, it is within the Gas Plant that the list of species being considered is first illustrated (see click box for Trace Gases). If no trace gases, or those required, are not present then these need to be selected back in the Landfill Characteristics Module. From the site layout plan screen either right click in a landfill cell to bring up the options list, or go to the Menu – Cells. Within the Waste Inputs option there is a Trace Gases button which can be used to select either all trace gases, or those of interest. Note, the selection of trace gases in one landfill cell is applied to all cells and so needs only to be undertaken once. Again, if any changes are made to the trace gases then the Source Gases module will need to be rerun.

Background concentration levels for a substance of interest in an area can be taken into account in the air dispersion modelling and associated results. Background concentration levels should be added during Tier 1 screening.

AERMOD Inputs – Meteorology

Meteorological data for use in the Atmospheric Dispersion model are selected via the click box meteorology halfway down the Simulation Parameters screen. The following screen is launched to allow selection of either a generic Area meteorology file (relating to one of the Agency Areas in England and Wales) or a site-specific, AERMOD compatible file. The Environment Agency Area meteorology files cover 30 Areas (or parts of Areas). Site-specific files would usually have been pre- processed via AERMET (or equivalent). GasSim2.5 is able to import site-specific surface (.sfc) meteorology files via the Browse option. Note, the site-specific profile file (.pfl) must have the same name, just different suffix, and be in the same location as the surface file for GasSim2.5 to locate.

The generic meteorological data sets that are provided for certain areas of England and Wales are unlikely to give as good predications as meteorological data that have been selected and processed (with appropriate surface roughness length, etc.) specifically for the site in question. Hence, these should not be relied upon to predict concentrations at discrete receptor locations. If 1 year of data is used (whether from generic data sets provided or site-specific), the user is advised to select "Simulate 5 years meteorological data" which applies a safety factor of 1.3 to all predictions (prior to adding on the background) in order to account for inter-annual variability.

Once a meteorological file is selected the station details are automatically imported along with the data period. The data period for the simulation can be edited if required to specify a particular year within a multi-year meteorological file.

Finally, in the Simulation Parameters section the Air Quality Objectives to which the dispersion concentration results are to be compared must be selected via the click boxes.

At any time during the AERMOD inputs it is possible to save the model using the menu Options – Save. This save option under the inputs screen does not retime-stamp the Source Gases files and so the results can still be reloaded. If a model were closed and reopened following saving during the AERMOD inputs, the Source Gases results would have to be reloaded to activate the Air Dispersion module. On entering the Atmospheric module screen the site plan would now include all the receptors previously added. Note, these receptors do not appear on the site plan map within the Landfill Characteristics.

AERMOD Inputs – Run

To run the Atmospheric Dispersion module either select Run from the AERMOD inputs screen or Simulate Tier 2 Atmospheric Dispersion from the main GasSim2.5 starting screen. A dialogue box is launched which details the processing of data for the various days of the year selected for the simulation.
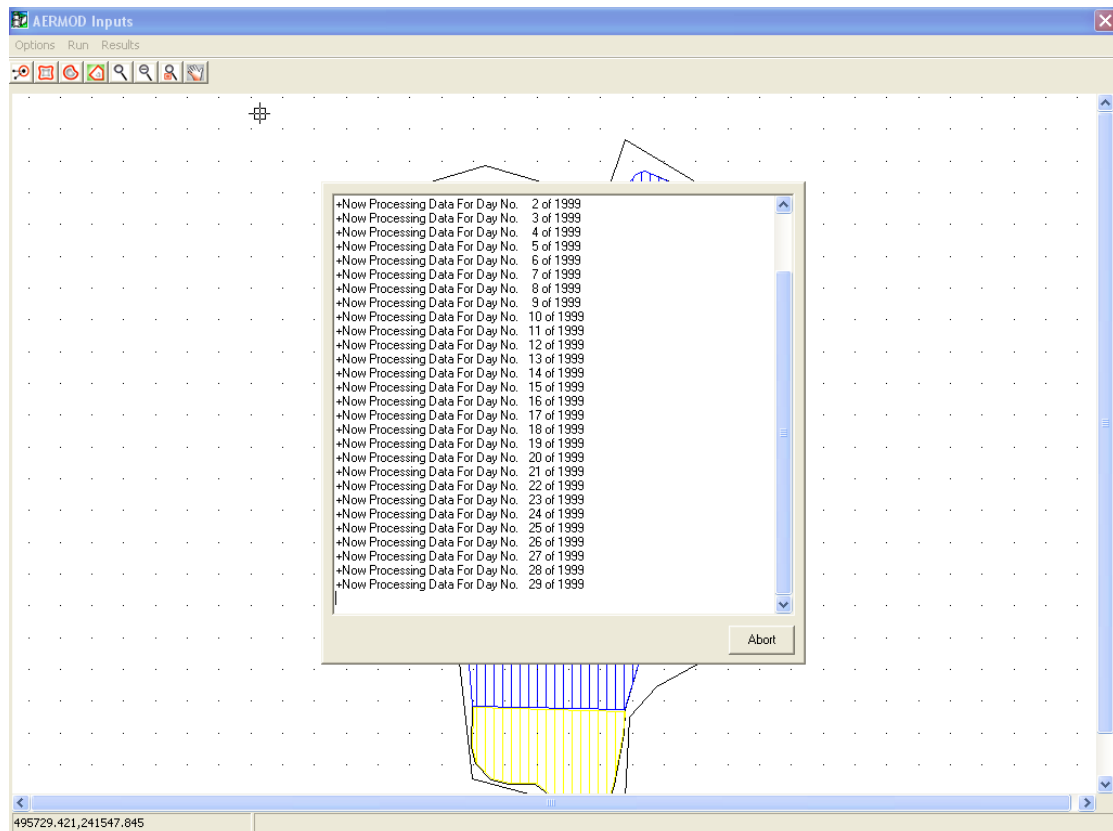
Following a simulation the air dispersion results are automatically shown on the site plan map using colour coded receptors. Red receptors illustrate a breach in air quality standards at a particular location. Grey indicates no standard applies, and black indicates compliance with the standard. Results can be viewed via a table or exported to a file (filename.csv) for plotting using a specialist graphics package such as Surfer. All results options are accessed via the menu Results – Load Results/View Results/Export.

To exit the Atmospheric module click the red cross in the top right hand corner of the screen. Once back in the main GasSim2.5 screen DO NOT save at any time before closing the model.
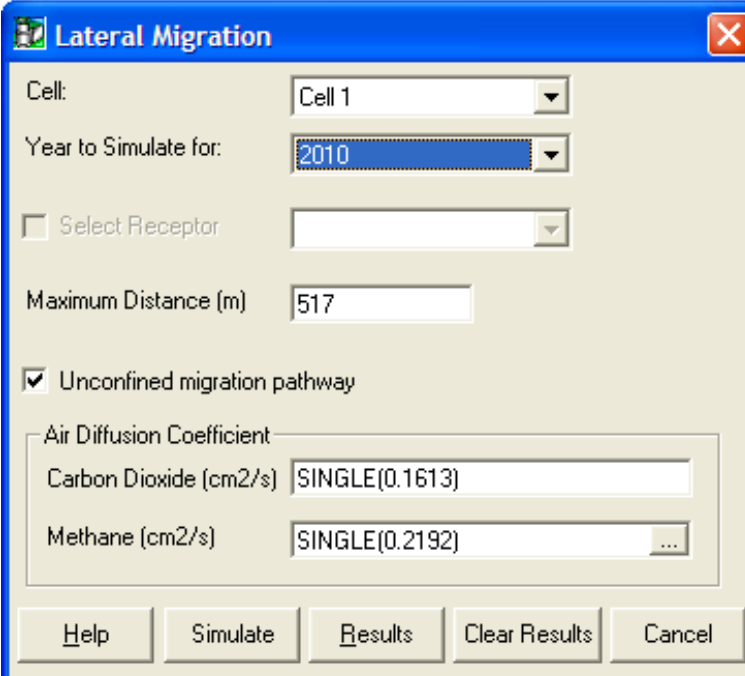
The information and interpretation of the data within the air dispersion results are discussed in Chapter 4.

Lateral Migration

The 'Lateral Migration' dialogue box is only active after the source and emissions modules have been simulated, as discussed above. GasSim2.5 simulates lateral migration using a 1-dimensional flow model, which is emitted uniformly from all external surfaces of the cell, using an advection and dispersion equation to simulate the migration of gas through the cell liner. The model assumes that gas flow through geological material is governed by both advection and dispersion, while flow through a geomembrane is governed by diffusion only. Clearly if the geomembrane has been significantly compromised and contains a large number of defects this assumption will no longer be valid and the user should amend the liner or capping details as appropriate. The advection term is determined by the velocity in the geosphere, which calculated from the proportion of gas moving through the liner,

discussed in more detail in Chapter 6. The dispersion is calculated using the air diffusion coefficient and the effective porosity, which is determined from the geosphere porosity and moisture content.

Clicking on the cartoon text or selecting the option under Simulate on the main menu accesses the 'Lateral Migration' dialogue box. The information requested in this box contains all the information required to simulate the lateral migration of gases emitted through the cell liner. You first have to select the 'Cell' you wish to simulate followed by the 'Year to Simulate for', using the pull down boxes. 'Year to simulate for' must be after the cell temporary capped year. You then need to indicate whether you want to select a specific receptor using the tick box. If you choose to select a receptor, use the pull down menu to choose between those you have included in the model. If a receptor is not selected, the 'maximum distance' over which you wish GasSim2.5 to simulate lateral migration is required. This allows the model to cease its calculations at a defined point to optimise the running time.

The 'Air Diffusion Coefficient' comprising carbon dioxide, methane and hydrogen requires you to define the dispersivity of the bulk gases in air to allow GasSim2.5 to calculate the dispersivities in soil.

The dialogue box also requires the selection of whether the model will simulate a confined migration pathway. If confined, this will prevent air exchange at the surface via the geological formation and therefore plug flow only will be accounted for within the model.

Soil breathing is considered to be mainly controlled by the variations of atmospheric pressure. When atmospheric pressure is high, air enters the soil. The air forced into the soil will mix with the migrated gases. In contrast, as the pressure becomes lower the mixture of air and migrated gases will be released to atmosphere. The process will

continue to dilute the initial concentration of migrated gases. After 1 year of soil breathing, approximately 16% of the initial concentration of migrated gases remains below the ground surface.

To run a lateral migration simulation click on the 'Simulate' button, and then the 'Results' button to view the results, discussed in Chapter 4. Selecting the 'Clear Results' option will remove the saved results from previous model runs.

If you do not have air diffusion coefficients for all of the trace gases then the model will still run, but those gases that are missing input data will not be simulated.

Global Impacts

There have been major changes to the Global Impacts screen since GasSim v1.5. To support this there have been corresponding changes to the results saved during a simulation, and new code to calculate appropriate statistics from this data according to the options selected by the user. Various new parameters have been added to aid reporting, including the CH_4 burnt in engines and flares, and the Global Warming Potentials (GWP) reduction associated with this combustion; Bulk LFG composition; and the methane generation potential of waste deposited (L_0). The emissions of carbon dioxide and methane have been subdivided to show the results for surface emissions, engine emissions and flare emissions separately. In some cases new results files have been generated during the Gas Generation calculation to support this.

Using the Global Impacts Model

Once you have run the Source Gases simulation (or reloaded the results from an earlier simulation) you can enter the Global Impact Results screen by clicking on Global Impact on the main screen or selecting Global Impact on the Simulate menu. Before the Global Impact Result Screen appears the raw result data needed for calculating the Global Impacts is loaded into memory. This may take a few minutes depending on the size of the model, and a progress screen is displayed during this process.

Once the Global Impact Results screen appears you can select the year of interest from the drop down list at the top of the screen, or select 'Sum of all years'. You will see the figures updating as you change your selection.

The user can select which trace gases to include in the model in following two ways:

- You can select which gases you wish to include in the various totals displayed in the bottom half of the screen. To do this simply clicks on the check boxes in the 'include' column at the right hand side of the table. Again you will see the figures updating as you change your selection of gases; and

- To select which gases are included is to use the 'Gas Inclusion' drop down list. For example if you select IPCC from this list the check boxes in the table will change to include only IPCC gases.

Selection of the DEFRA option for trace gas inclusion is equivalent to the 'Default' option on previous versions of GasSim. The 'IPCC' option allows users to select trace gas components which are appropriate for reporting emissions following the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The 'IPCC + Montreal' option adds emissions of trace gases included within the Montreal Protocol and subsequent Amendments to the IPCC guidelines.

The printing of global impact results has also been updated, and the grid has been changed to allow copying of the data; and a copy button has also been added which copies various other fields to the clipboard as well as the values shown in the grid. The trace gas screen has been amended to allow copy and paste in the grid.

The percentile on which all the figures are based is indicated in the title bar of the 'Global Impact Results' screen. You can change this by clicking on the 'Options' button. This will show a screen on which you can select which percentile is used and also allows you to set GWP and Ozone depletion Potentials (ODP) values for the three bulk gases (carbon dioxide, methane and hydrogen).

The 'Trace Gases' button on this screen takes you to another screen where you can set GWP and ODP for trace gases.

The Default button here reverts these trace gas figures to the defaults for GWP and ODP provided by GasSim2.5 (see the earlier table for the actual values – trace gases not listed will have default GWP and ODP values of zero).

The ODP and GWP of bulk and trace gases have been amended where appropriate using the data provided in the *Scientific Assessment of Ozone Depletion*, 2006, published by the World Meteorological Organisation and the IPCC Fourth Assessment Report, *Climate Change 2007* (Table 3.9).

Table 3.9: Summary of Default GWP and ODP Values

Name	Global Warming Potential	Ozone depletion Potential
Carbon Dioxide	1	
Methane	25	
Acetalehyde (ethanal)	1.3	
Acetone	0.5	
Bromodichloromethane	1,300	1,890
Butane	4	
Carbon tetrachloride (tetrachloromethane)	1,400	0.73
1-Chloro-1,1-difluoroethane	2,310	0.07
Chlorodifluoromethane	1,810	0.05
Chloroform (trichloromethane)	30	
Chlorotrifluoromethane	14,400	
Dichlorodifluoromethane	10900	1
Dichlorofluoromethane	210	
Dichloromethane (methylene chloride)	9	
1,1-Dichlorotetrafluoroethane	10,000	0.94
Ethane	5.5	
Ethylene	3.7	
Fluorotrichloromethane	4,750	1
Freon 113	6,130	1
Methyl chloride (chloromethane)	146	
Propane	3.3	
1,1,1,2-Tetrafluorochloroethane	609	0.02
Toluene	2.7	
Trichlorofluoromethane	4,750	1
Trichlorotrifluoroethane	6,130	1
1,1,1-Trichlorotrifluoroethane	6,130	1

Once you have made all your selections so that the Global Impact Results screen is displaying the figures you require, you can use the Print button to print a report containing these results. Or you can use the Copy button to copy the figures to the clipboard so that you can subsequently paste then into a spreadsheet.

European Pollutant Emission Register (PI) Reporting

The PI Reporting screen has been improved in several ways. The list of the species has been changed to more closely match that expected for current PI Reporting. A new column has been added containing the CAS number of the species. Gases not modelled now have a reported value of 'n/a' rather than 'Not Modelled'. Figures can now be copied from the grid and a new 'Copy' button copies the entire grid to the clipboard so that it can subsequently be pasted into a spreadsheet. The grid now resizes when the form is resized by the user.

The printing has been altered to reflect the changes to the grid.

The current list of PI gases, their associated CAS numbers and the reporting thresholds are provided in Table 3.10, below.

Table 3.10: PI Reporting Thresholds

Gas	CAS	Threshold
Inorganics		
Ammonia	7664-41-7	1.00 t
Asbestos	1332-21-4	1.00 kg
Carbon Dioxide	124-38-9	10,000.00 t
Carbon disulphide	75-15-0	1.00 t
Carbon monoxide	630-08-0	100.00 t
Hydrogen chloride	7647-01-0	10.00 t
Hydrogen cyanide	74-90-8	100.00 kg
Nitrous oxide	10024-97-2	10.00 t
Phosgene	75-44-5	10.00 kg
Sulphur hexafluoride	2551-62-4	10.00 kg
Organics		
Acetaldehyde [Ethanal]	75-07-0	100.00 kg
Acrolein	107-02-8	10.00 kg
Acrylamide [2-Propenamide]	79-06-1	10.00 kg
Acrylonitrile [2-Propenenitrile]	107-13-1	1.00 t
Aldrin	309-00-2	1.00 kg
Allyl alcohol [2-Propen-1-ol]	107-18-6	10.00 kg
Amitrole [3-Amino-1,2,4-triazole]	61-82-5	1.00 kg
Aniline [Benzeneamine]	62-53-3	10.00 kg
Anthracene	120-12-7	10.00 kg

Gas	CAS	Threshold
Benzene	71-43-2	1.00 t
Benzo(a)pyrene	50-32-8	1.00 kg
Benzo(b)fluoranthene	205-99-2	1.00 kg
Benzo(g,h,i)perylene	191-24-2	1.00 kg
Benzo(k)fluoranthene	207-08-9	1.00 kg
Benzo butyl phthalate (BBP)	85-68-7	10.00 kg
Benzyl chloride	100-44-7	10.00 kg
Bromoethene	593-60-2	10.00 kg
Butadiene [1,3-Butadiene]	106-99-0	100.00 kg
Butene - all isomers	-	1.00 t
Carbon tetrachloride [Tetrachloromethane]	56-23-5	10.00 kg
Chlordane	57-74-9	1.00 kg
Chlordecone	143-50-0	1.00 kg
Chlororethane	75-00-3	10.00 kg
Chloroform [Trichloromethane]	67-66-3	100.00 kg
Chloroprene	126-99-8	10.00 kg
Chrysene	218-01-9	10.00 kg
Crotonaldehyde	4170-30-3	10.00 kg
Cumene hydroperoxide	80-15-9	10.00 kg
Dibutyl phthalate	84-74-2	10.00 kg
p-Dichlorobenzene [1,4-Dichlorobenzene]	106-46-7	1.00 kg
Dichlorodiphenyltrichloroethane (DDT)	50-29-3	1.00 kg
Dichloromethane (DCM) [Methylene chloride]	75-09-2	1.00 t
Dieldrin	60-57-1	1.00 kg
Diethyl aniline [N,N-Diethyl benzeneamine]	91-66-7	10.00 kg
Di(2-ethylhexyl)phthalate (DEHP)	117-81-7	10.00 kg
Diethyl ether	60-29-7	10.00 kg
Diisopropyl ether	108-20-3	10.00 kg
Dimethylaniline [N,N-Dimethyl benzeneamine]	121-69-7	10.00 kg
Dimethyl sulphate	77-78-1	1.00 kg
Dimethylformamide	68-12-2	1.00 t
Dimethyl-o-toluidine	609-72-3	10.00 kg
Dimethyl-p-toluidine	99-97-8	10.00 kg
Dioxane	123-91-1	10.00 kg
Diphenylamine	122-39-4	10.00 kg
Endrin	72-20-8	1.00 kg
2-Ethoxyethanol [Ethyleneglycol ethylether]	110-80-5	10.00 kg
2-Ethoxyethyl acetate [Ethyleneglycol ethylether acetate]	111-15-9	1.00 kg
Ethyl acrylate	140-88-5	10.00 kg
Ethyl benzene	100-41-4	100.00 kg
Ethyl bromide [Bromoethane]	74-96-4	10.00 kg
1-Ethyl-3,5-dimethylbenzene	934-74-7	10.00 kg
Ethylene [Ethene]	74-85-1	1.00 t
Ethylene dichloride [1,2-Dichloroethane]	107-06-2	1.00 t
Ethylene oxide [1,2-Epoxyethane]	75-21-8	1.00 t
Ethyl toluene - all isomers	25550-14-5	10.00 kg
Fluoranthene	206-44-0	1.00 kg
Formaldehyde [Methanol]	50-00-0	10.00 kg
Heptachlor	76-44-8	1.00 kg
Hexabromobiphenyl	36355-1-8	100.00 g
Hexabromocyclododecane	25637-99-4	10.00 kg
Hexachlorobenzene	118-74-1	1.00 kg

Gas	CAS	Threshold
Hexachlorocyclohexane - all isomers	608-73-1	1.00 kg
Hexane	110-54-3	10.00 kg
1-Hexene	592-41-6	10.00 kg
Indeno(1,2,3-cd)pyrene	193-39-5	1.00 kg
Iodomethane	74-88-4	10.00 kg
Isophorone	78-59-1	10.00 kg
Isophorone diisocyanate	4098-71-9	1.00 kg
Isoprene	78-79-5	10.00 kg
Lindane	58-89-9	1.00 kg
Maleic anhydride	108-31-6	10.00 kg
Methane	74-82-8	10.00 t
Methanol	67-56-1	100.00 kg
2-(Methoxyethoxy)ethanol	111-77-3	10.00 kg
2-Methoxyethanol	109-86-4	10.00 kg
2-Methoxyethyl acetate	110-49-6	10.00 kg
Methyl bromide [Bromomethane]	74-83-9	100.00 kg
2-Methyl-2-butene	513-35-9	10.00 kg
3-Methyl-1-butene	563-45-1	100.00 kg
Methyl chloride [Chloromethane]	74-87-3	1.00 t
Methyl chloroform [1,1,1-Trichloroethane]	71-55-6	10.00 kg
4,4'-Methylene-bis(2-chloroaniline)	101-14-4	1.00 kg
4,4'-Methylene dianiline	101-77-9	10.00 kg
4,4'-Methylenediphenyl diisocyanate	101-68-8	1.00 kg
Methyl isocyanate	624-83-9	1.00 kg
Mirex	2385-85-5	1.00 kg
Naphthalene	91-20-3	100.00 kg
Nitrobenzene	98-95-3	10.00 kg
2-Nitropropane	79-46-9	1.00 kg
Pentachlorobenzene	608-93-5	1.00 kg
Pentachlorophenol	87-86-5	1.00 kg
Pentane	109-66-0	100.00 kg
Pentene - all isomers	25377-72-4	1.00 t
Phenol	108-95-2	10.00 kg
Propylbenzene	103-65-1	10.00 kg
Propylene	115-07-1	10.00 t
Propylene oxide	75-56-9	100.00 kg
Styrene	100-42-5	100.00 kg
Tetrachloroethane [1,1,2,2-Tetrachloroethane]	79-34-5	10.00 kg
Tetrachloroethylene	127-18-4	100.00 kg
Tetrafluoroethylene	116-14-3	10.00 kg
Toluene	108-88-3	100.00 kg
Toluene diisocyanate - all isomers	-	10.00 kg
Toxaphene	8001-35-2	1.00 kg
Trichlorobenzene - all isomers	12002-48-1	1.00 kg
Trichloroethylene	79-01-6	1.00 t
Trichlorotoluene	98-07-7	10.00 kg
Trimellitic anhydride	552-30-7	1.00 kg
Trimethylbenzene - all isomers	25551-13-7	10.00 kg
Vinyl acetate	108-05-4	10.00 kg
Vinyl chloride	75-01-4	1.00 t
Xylene - all isomers	1330-20-7	1.00 t
Metals and compounds		

Gas	CAS	Threshold
Antimony	7440-36-0	1.00 kg
Arsenic	7440-38-2	1.00 kg
Beryllium	7440-41-7	1.00 kg
Boron	7440-42-8	1.00 t
Cadmium	7440-43-9	1.00 kg
Chromium	7440-47-3	10.00 kg
Copper	7440-50-8	10.00 kg
Lead	7439-92-1	100.00 kg
Manganese	7439-96-5	10.00 kg
Mercury	7439-97-6	1.00 kg
Nickel	7440-02-0	10.00 kg
Selenium	7782-49-2	100.00 kg
Vanadium	7440-62-2	10.00 kg
Zinc	7440-66-6	100.00 kg
Other Substances		
Brominated diphenylethers - penta, octa and deca	-	10.00 kg
Chlorine and total inorganic compounds - as HCl	7782-50-5	10.00 t
Chlorofluorocarbons (CFCs)	EDF-079	1.00 kg
Dioxins and furans (PCDDs/PCDFs) - I-TEQ	-	0.01 g
Dioxins and furans (PCDDs/PCDFs) - WHO-TEQ	-	0.01 g
Fluorine and total inorganic compounds - as HF	7782-41-4	1.00 t
Halons	-	1.00 kg
Hydrobromofluorocarbons (HBFCs)	-	10.00 kg
Hydrochlorofluorocarbons (HCFCs)	-	1.00 kg
Hydrofluorocarbons (HFCs)	-	100.00 kg
Nitrogen oxides - NO and NO2 as NO2	-	100.00 t
Non-methane volatile organic compounds (NMVOCs)	-	10.00 t
Particulate matter - PM2.5	-	1.00 t
Particulate Matter - PM10	-	1.00 t
Particulate Matter - total	-	10.00 t
Perfluorocarbons (PFCs)	-	10.00 kg
Polychlorinated biphenyls (PCBs)	1336-36-3	100.00 g
Polychlorinated Biphenyls (PCBs) - as WHO TEQ	1336-36-3	0.01 g
Sulphur oxides - SO2 and SO3 as SO2	-	100.00 t

Preparing to Run the Model

If values are invalid or if there are still input parameters that GasSim2.5 needs before a model can be run, then a list of parameters where additional data inputs are required will be shown.

Before running the source and generation module you should select or check the number of iterations required for the simulation in the 'Project Details' dialogue box, accessed by Edit on the main menu bar then selecting Project Details. The number of iterations selected will affect the accuracy of the predictions made by GasSim2.5 and will also increase the time required to run the simulation. The number of iterations used for the Monte Carlo simulation determines the numbers of times that the model is run and thus the number of scenarios that are tested. The lateral migration module will be simulated for the same number of iterations as the source and emissions module.

If the results of the modelling are being examined at a specific confidence level, there are a theoretical minimum number of iterations that should be made. For instance, if the results are being examined at a 95% confidence level, then for each output 10 values must occur above the 95% confidence level to ensure that these high values are representative.

By definition, there will also have to be 190 values below the 95% confidence level. To obtain reasonable results at the 95% confidence level, therefore, more than 200 iterations should be specified. If the results are to be examined at the 99% confidence level then the same argument applies and the landfill should be simulated more than 1000 times. The following table gives the theoretical minimum number of iterations required for other confidence levels (Table 3.11):

Table 3.11: Number of Iterations Required

Confidence Level (%)	Theoretical Minimum Number of Iterations
1	1001
5	201
10	101
50	21
90	101
95	201
99	1001

To optimise running time it is recommended that the source and emissions results are reviewed before running the 'Lateral Migration' modules. In some cases it may be appropriate to run the generation and emissions module through a large number of iterations, but to reduce the number of iterations needed for lateral migration.

Running the Model

Once you have selected the options you wish you can then run the model by selecting Simulate from the main menu bar and then selecting the module that you wish to simulate:

- Source Gases;
- Tier 1 Screening;
- Tier 2 Atmospheric Dispersion;
- Lateral Migration; and
- Global Impact.

Alternatively, to simulate the source gases you can simply press the F5 key. If the model has been recently edited and not yet saved you will be prompted to allow GasSim2.5 to save the file prior to running using the current file name. If you wish to change the file name you can abort the run process by pressing the 'No' button and use the File menu to save the file to a new name using the Save As option. If you are happy to continue press the 'OK' button.

The message that appears gives a brief summary of the model run and gives details of the model's progress through the requested number of iterations for the simulated years. On completion of the model run the Results menu will become available. The type and extent of results available will depend on the options selected when the model was run. Model output is discussed in a Chapter 4.

Other Model Output

As well as the graphical and statistical output that will be discussed in Chapter 4, there are other options relating to model output that need to be briefly discussed at this point. It is possible to export certain results and import results from GasSim2.5 runs that you have previously carried out, these options are also discussed in Chapter 4.

Printing Your Model

GasSim2.5 has been developed around the concept that printed output should be suitable for immediate inclusion as an appendix to a risk assessment report or for attachment to a memorandum recording a decision. To this end, considerable effort has been spent on print layout and quality assurance issues. You can define the printer and its set up under the Printer Set-Up option.

The Print Model option on the File menu allows you to send details of the model construction and the results of the landfill simulation to a printer. Records of this type are essential to document your work and for quality assurance purposes.

Traceability and Quality Assurance

Because GasSim2.5 has been designed for use in a quality assured environment, you will have to save a model before printing a record and save a record of your model before you can run a simulation. By ensuring all your printed output is linked to the time and date stamp of the saved model, this feature provides an audit trail where output corresponds to input. Obviously, once you have run a simulation for a decision you should not overwrite your saved data file and you should back it up securely.

Information relating to the project should be entered in the 'Project Details' dialogue box described previously.

GasSim2.5 prompts for justification by displaying the 'Justifications' dialogue window every time a parameter is changed (this usually appears when the 'OK' button is selected on a data input). This box allows the source of any parameter values entered into the model to be referenced. Information entered into the justification text box will appear in the 'Justifications' section of the model summary report attached to the relevant parameter. You should make your description clear. Think of this text as a note to an auditor. Rather than just giving the name of a report, give a figure number, page number or reference to a table to facilitate review. The parameter justifications can also be viewed and edited by selecting View and Justifications.

During the initial stages of a GasSim2.5 desk study a considerable amount of site-specific data may be collected from a variety of sources. It is recommended that the source of data is fully documented. The justification boxes should assist you in this process.

CHAPTER 4: INTERPRETING THE RESULTS

4.   INTERPRETING THE RESULTS

This chapter will explain what GasSim2.5 predicts, the results and outputs formats available and gives some guidance on their interpretation.

What GasSim2.5 Predicts

The GasSim2.5 output can be split into eight groups:

- Carbon degradation and LFG generation (cell by cell or total site values);
- Engine and flare emissions (totals), and surface emissions (cell by cell or total site values);
- Tier 1 Atmospheric Screening;
- Tier 2 Atmospheric Dispersion (including odour);
- Lateral migration (including vegetation stress);
- Global atmospheric impact (GWP and ODP); and
- PI reporting.

The type of graphical output of the model varies depending upon what is being examined (Table 4.1).

Table 4.1: Summary of Graphical Outputs Available

Output Parameter	Detail	Probabilistic	By Cell	By Total Site	Presentation
LFG Generation	Bulk Gas	✓	✓	✓	Time Series (m^3/hr)
	Trace Gas	✓	✓	✓	Time Series (g/hr)
Emissions	Bulk Gas	✓	✓	✓	Time Series (m^3/hr)
	Trace Gas	✓	✓	✓	Time Series (g/hr)
Lateral Migration	Bulk Gas	✓	✓	✗	Distance vs mg/m^3 or Distance vs %
	Trace Gas	✓	✓	✗	Distance vs mg/m^3
Vegetation Stress	CO2 and CH4	✓	✓	✗	Distance vs %
Tier 1 Screening	Trace Gas	✗	✗	✓	Table only
Tier 2 Atmospheric Dispersion	Trace or Bulk, plus odour units	✗	✗	✓	Tables, exportable data for plotting
Global Atmospheric Impact	All Gases	✗	✗	✓	Table only
PI Reporting	All Gases	✗	✗	✓	Table only

Probabilistic output will only be available if a number of realisations or iterations have been run. Running a single iteration should be avoided unless all of the inputs have been defined as single values.

The LFG generation outputs are intended to help you understand the behaviour of the waste degradation and thus the gas production within the landfill. These results should be studied first to ensure that the simulation is responding correctly. Only then should you use the pathway and receptor modules of the model.

The emissions module outputs the gas concentrations from flares, engines, the cap, and laterally through the liner. The lateral migration, atmospheric dispersion and global impact modules then use these results.

Getting to Your Results – Graphical Output

When a simulation has been run, the results can be viewed by clicking the 'Results' option on the main menu GasSim toolbar. The first option in the drop down menu is 'graphs' which allows you to view the results for a number of options in graphical form on a cell specific basis, or for the site as a whole. A maximum of eight items will be visible, depending on the options that have been selected during the simulation set up. Other options will be greyed out and will not respond to the mouse, i.e. if the simulation has been run without engines and/or flares the emissions from these will not be visible. The items available under 'Graphs' are:

- Generated gases;
- Residual gases;
- Spark ignition engine output;
- Duel fuel engine output;
- Other engine output;
- Flare output;
- Surface emissions; and
- Lateral emissions.

Other items available under the 'Results' option are:

- Statistics;
- Lateral Migration;
- Pi Reporting; And
- Multiple Graphs.

Results Menu – Graphs- Generated Gases

Available Carbon by Year

This reports the quantity of carbon that is available to degrade from waste deposited in each operational year. The amount will vary with the waste input rate and the waste characteristics. GasSim reports the quantity of carbon available for degradation each operational year and the decline of this tonnage in subsequent years. The degradation of carbon from subsequent years can be investigated by selecting any year of the operational life from the menu under Plot.

Total Available Carbon

This details the total carbon that is available to degrade per year. This combines the available carbon for each operational year.

Degraded Carbon by Year

This reports the quantity of carbon that is degraded each year. This will vary with the waste input rate and the waste characteristics. GasSim reports the quantity of carbon available for degradation each operational year of each cell and the degradation of this can be investigated by changing the simulation years through the menu under Plot.

Total Degraded Carbon

This reports the total carbon that is degraded per year and this combines the degraded carbon for each operational year.

Total Bulk LFG

This reports the total amount of bulk gas (CH_4, CO_2, H_2) that is generated in order to provide an indication of how much gas is available to be collected and flared/utilised. Note that there are also three options under the 'Generated Gases' results that report the total amount of CH_4, CO_2 and H_2 individually, and the combine bulk LFG. These graphs show the amount of gas which should be managed/controlled to minimise the environmental impact, and viewing these graphs will allow engines and flare to be sized.

Trace Gases

Also listed within the 'generated gases' menu are a number of trace gases. The rate of generation of each of these selected trace gases may be seen in graphical format by clicking on the arrows to scroll up and down and selecting the trace gas of interest.

Results Menu –Graphs- Residual Gases

The quantity of gas that is generated and not collected by engines and flares may be seen graphical by selecting 'Residual Gases' results. This is the quantity of gas that will be emitted through the surface and laterally.

Results Menu – Graphs - Engine Output and Flare Output

Total combusted LFG and the emissions of unburned bulk and trace gases emitted from all engines or all flares per year, depending on those types entered during simulation setup, are shown graphically by selecting the appropriate gas from the drop down menus under 'Graphs'. The quantity of gas collected is determined by the amount of waste in place, the degree of capping, the collection efficiency, the downtime and capacity of the gas plant. The reported emissions have been corrected for the destruction of non-combustion products and the formation of combustion products. A comparison of the engines and flare emissions graphs with the generated gases allows an assessment of the quantity of gas that is generated and is not controlled (available via the 'multiple graphs' option). If these graphs are blank then the engines or flares are not being utilised for some reason. This may be due to a number of factors, but one of the most common is the collection efficiency. The collection efficiency if controlled by the presence or absence of different degrees of engineered cap, and the presence or absence of gas collection systems, whether temporary or permanent.

Results Menu – Graphs- Surface Emissions and Lateral Emissions

Gas that is not collected and utilised by engines or flares will be lost uncontrollably through the surface and/or the side of the cell (i.e. by allowing surface and lateral emissions). These emissions are proportioned depending on the cap and liner construction. Uncontrolled release of gas may be a result of insufficient engine and flare capacity. These results should therefore be examined before proceeding to the Impact modules to ensure that the gas collection/management system has been optimised.

Results Menu - Lateral Migration

Plotting the concentration of bulk or trace gases for the selected cell, year and percentile against distance assesses the extent of lateral migration caused by the uncontrolled release through the liner. These results are utilised in the assessment of vegetation impact. The vegetation impact is determined using the 'Vegetation Stress' module where the vegetation stress limit defined is shown as a horizontal line on a graph of the sum of CO_2+CH_4 expressed as a percentage against distance. The 'Lateral Migration' dialogue box also has buttons which enable the user to plot a 'Graph' or 'Print' the results. The dialogue box is exited by clicking 'OK'. Additional screening levels of 1% methane v/v and 5% methane v/v are also plottable.

Results Menu – Statistics

The results for generated gases, emissions from engines and flares, surface and lateral emissions can also be viewed as statistics. The statistics at the 5%ile, 20%ile, 25%ile, 50%ile, 75%ile, 90%ile and 95%ile can be viewed by selecting 'Results' – 'Statistics' and then selecting the cell and result of interest in the drop down menus. The 'Statistics' dialogue box also has buttons which enable the user to plot a 'Graph' or 'Print' the results. The dialogue box is exited by clicking 'OK'.
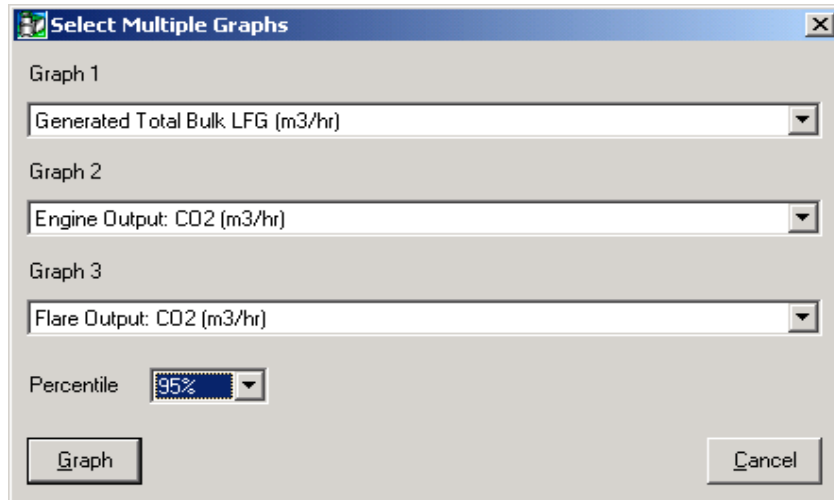
Results Menu – PI Reporting

The emissions for PI reporting from flares, engines and the surface, i.e. the whole landfill, are listed as 25%ile, 50%ile and 75%ile for the selected year of the simulation. The table also lists the PI reporting threshold for each species. These results are viewed by selecting 'Results'– 'PI Reporting' and then selecting the year of interest from the drop down menu.

If results for a particular year and month are below the reporting threshold, GasSim2.5 will output "brt". If the result is above the reporting threshold, a 25%ile and 75%ile is reported, if the reporting of this value is not required, GasSim2.5 will output "n/a".

Results Menu – Multiple Graphs

GasSim2.5 will allow up to three outputs of the gas generation and emissions modules to the plotted on the same graph. There is a restriction that the selection should have the same units and users must specify a percentile to plot. Selecting two or more outputs with different units will generate a warning message but a graph will still be generated but the units being plotted will not be applicable to all of the outputs. It is not necessary to plot three outputs, plotting just two is a valid option.
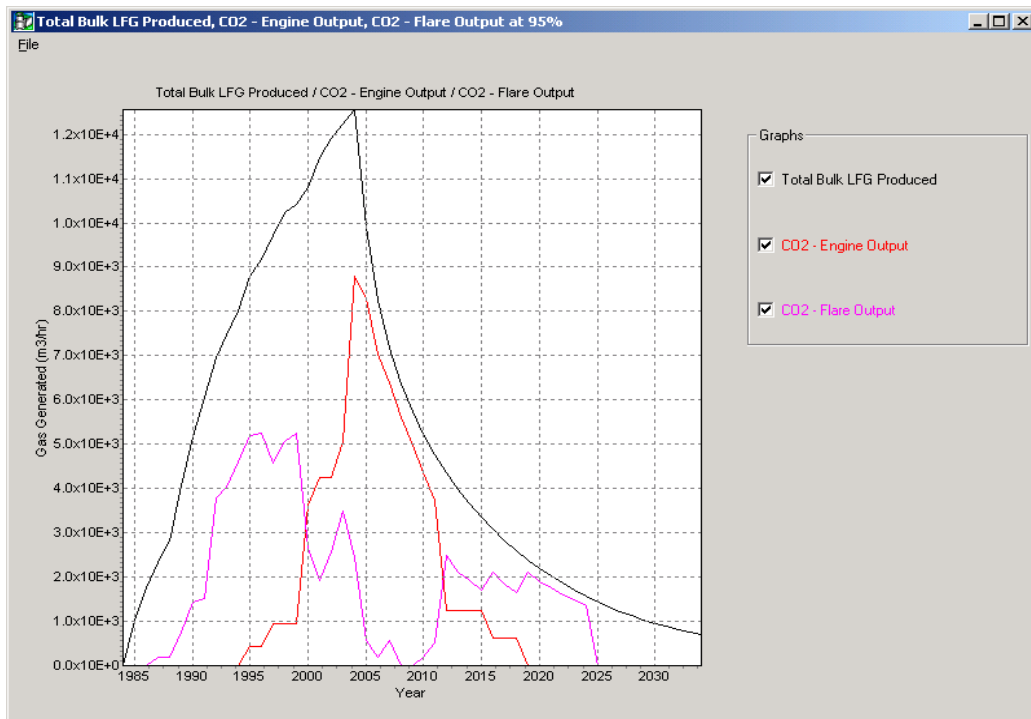
Other Results

Once the gas generation model has been run, the other pathways/receptor modules become accessible. These modules rely on the existence of a valid results file. For a model that has previously been run during an earlier session, it should be possible to re-load the results to avoid the need to re-run the model.

The results of these additional modules are not made available through the results menu (with the exception of the lateral migration results). Rather, they are available directly from the individual modules themselves (as is lateral migration).

NOTE: if any changes are made to the model that might affect the LFG generation and emissions results (i.e. changing waste inputs, trace gas concentrations or landfill characteristics, etc.), it will be necessary to re-run the source term model prior to running any of the impact modules. The model should warn you if this situation arises.

Results - Tier 1 Screening

This part of the model determines whether further modelling of the emission of a gas is required.

The results screen's "Print" button will produce a list of the inputs to, and outputs from, the screening module, as well as a list of the gases that were not modelled.

	Year	Short Term				Long Term			
		Predicted Boundary Concentration µg/m3	Predicted Nearest Receptor Concentration µg/m3	Is the emission rate Insignificant?	Is detailed modelling required?	Predicted Boundary Concentration µg/m3	Predicted Nearest Receptor Concentration µg/m3	Is the emission rate Insignificant?	Is detailed modelling required?
1,1-Dichloroethane - surface	2015	75.6442	47.2776	Yes	No	1.56016	0.425498	Yes	No
Acetalehyde (ethanal) - surface	2015	0.47775	0.298594	Yes	No	0.00985359	0.00268734	Yes	No
Acetone - surface	2015	0.0614662	0.0384163	Yes	No	0.00126774	0.000345747	Yes	No
Acrylonitrile - surface	2015	0.26722	0.167013	Yes	No	0.00551141	0.00150311	Yes	No
Benzene - surface	2015	0.179274	0.112046	Yes	No	0.00369752	0.00100841	Yes	No
Benzo(a)pyrene - engine	2015	0.0172916	0.00707385	No EAL	No EAL	0.00094318	0.000727035	No	Yes
Benzo(a)pyrene - flare	2015	7.21494e-005	1.89867e-005	No EAL	No EAL	2.87513e-006	1.62743e-006	Yes [at	No
Butadiene (modelled as	2015	0.0941148	0.0588217	Yes	No	0.00194112	0.000529395	Yes	No
Butane - surface	2015	1.5269	0.954312	Yes	No	0.0314923	0.00858881	Yes	No
Carbon disulphide - surface	2015	0.0387248	0.024203	Yes	No	0.0007987	0.000217827	Yes	No
Carbon monoxide - engine	2015	666.12	272.503	Yes	No	36.3338	28.0073	No EAL	No EAL
Carbon monoxide - flare	2015	214.876	56.5462	Yes	No	8.56272	4.84682	No EAL	No EAL
Carbon monoxide - surface	2015	8.72316	5.45198	Yes	No	0.179915	0.0490678	No EAL	No EAL
Carbon tetrachloride	2015	0.189318	0.118323	Yes	No	0.00390467	0.00106491	Yes	No
Chlorobenzene - surface	2015	16.8301	10.5188	Yes	No	0.34712	0.0946691	Yes	No

Not Modelled:
1,1,1,2-Tetrafluorochloroethane
1,1,1-Trichlorotrifluoroethane
1,1,2-Trichloroethane
1,1-Dichloroethene
1,1-Dichlorotetrafluoroethane
1,2-Dichloropropane
1,2-Dichlorotetrafluoroethane
1-Chloro-1,1-difluoroethane
2-Chloro-1,1,1-trifluoroethane
2-Propanol
Bromodichloromethane
Butene isomers

Results - Tier 2 Atmospheric Dispersion

GasSim2.5 reports the predicted environmental concentration ('PEC') at ground level. For long-term emission results the PEC comprises the process contribution ('PC') from the sources at the site plus the long-term background. For short-term emissions the PEC comprises the process contribution ('PC') from the sources at the site plus the twice long-term background. The methodology of comparing the PEC and not the PC to the relevant environmental standards may not be appropriate outside the UK.

Several short-term air quality standards stipulate a number of times the standard can be breached within a year. For example the UK hourly NO_2 standard is 200 $\mu g/m^3$, not to be exceeded more than 18 times per year. GasSim2.5 accounts for this number of exceedences by generating the modelled results at a number of different percentiles.

In the example of NO_2 above, the 18 highest hours are allowed to exceed, therefore the hour of interest is the 19th highest hour result. It is this 19th highest hour result which needs to be directly compared the standard for NO_2 of 200 $\mu g/m^3$.

The equivalent percentile to the 19th highest hour is calculated in the following way:
As the NO_2 emission standard has an hourly averaging period, first calculate the number of hours in a year (8760):

Percentile required = 100-((18/8760) x 100) = 99.79%

The same methodology can be applied to calculate the appropriate results percentile for other standards. For ease of reference, Table 4.2 below contains the most commonly used standards, and the appropriate percentiles.

Table 4.2: Short-Term Air Quality Standards and Appropriate Percentiles

Emission	Short-Term Averaging Period	Air Quality Standard	Appropriate Results Percentile to Use
NO_2	1 hour	1 hour mean, 18 exceedences	99.79
SO_2	15 minutes	15 minute mean not to be exceeded more than 35 times a year	99.90
SO_2	1 hour	1 hour mean not to be exceeded more than 24 times a year	99.73
SO_2	24 hour	24 hour mean not to be exceeded more than 3 times a year	99.18
PM_{10} (UK)	24 hour	24 hour mean, 35 exceedences	90.41
PM_{10} (Scotland)	24 hour	24 hour mean, 7 exceedences	98.08

Results – Global Impact

The 'Global Impact Results' can be viewed using the 'Global Impact Results' dialogue box, which reports the Global Warming Potential ('GWP') and Ozone Depletion Potential (ODP) for each simulated gas for each year and the sum of all simulated years. GasSim allows the reporting of:

- GWP for each of the bulk and trace gases (as tonnes of carbon dioxide); and

- ODP for each of the bulk and trace gases (as tonnes of trichlorofluoromethane);

- Total ODP for the site (as tonnes of trichlorofluoromethane), which is the sum of the bulk and trace gases (reported to 3 significant figures); and

- Total GWP for the site (as tonnes carbon dioxide), which is the sum of the selected bulk and trace gases (reported to 3 significant figures), by allowing the user to select the bulk and trace gases that they wish to include in the determination of the GWP. This is carried out by the user selecting the trace gases by checking the individual boxes for each gas in the column 'Included in GWP', or using the 'Gas Inclusion' drop down list (details in Chapter 3).

Loading (Importing) Results without Running the Model

After you have carried out a simulation once, the results will be saved and it is not necessary to re-run the simulation to view the results. Therefore, assuming that you have not altered any of the input parameters, the results can be imported into the model by selecting 'File' – 'Load Results' from the main menu bar.

If you have changed any input values (or exited input screens by clicking 'OK' rather than 'Cancel'), GasSim will prompt you to save the file before closing the model. If you save the file with the same name, by changing the input values, you will no longer be able to load results from previous model runs with the same name, due to GasSim2.5's internal traceability and quality assurance system (see Chapter 3 for details).

Customising Your Results – Graphs

GasSim provides a number of options for viewing and printing your graphs. These are accessed through 'File' on the menu bar, which is present in the top left hand corner of each graph.

By clicking and holding the left mouse button on a graph, cross hairs appear and the co-ordinates of the cross point are displayed at the top of the graph. This feature is extremely useful for determining the probability of particular values.

Zoom

Selecting 'File' – 'Zoom' – 'Window' allows you to specify a particular area of the graph to examine in more detail, by clicking and holding the left mouse button in the top left hand corner of the area you are interested in, dragging the window outline until you have covered the desired area, and then releasing the button. You can return to the full graph using ('File' – 'Zoom' – 'All'). You can display the last view before the current view using 'File' – 'Zoom' – 'Previous'.

You can also zoom in on a particular area, using 'File' – 'Zoom' – 'Scale'. This option allows you to change the scale of the graph axes. This option produces an additional dialogue box:
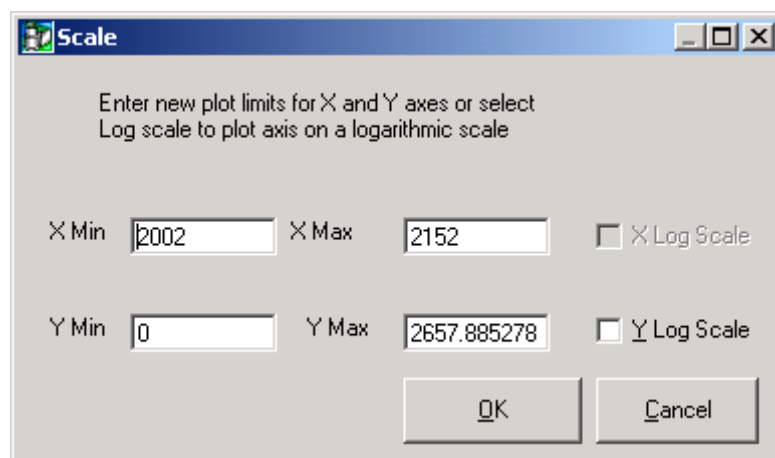
You should type in the maximum and minimum axis values you require, and when each value has been set, click on the 'OK' button. The graph will immediately be rescaled. To exit the dialogue box without making changes you can click on 'Cancel' or click on the button marked 'x' in the top right hand corner of the box. Built-in error checks prevent values being entered that are outside of the capabilities of the code.

Individual axes can be altered, in the same way, by double-clicking (left mouse button) on the axis you wish to edit. You are also given the option to plot using a log scale, on the y-axis, which you can use if the results span a large range. This facility is useful for determining the emissions during the operational period or the years just after the operational period when the gas generation peaks.

Options

Under this sub-menu you can turn the graph grid lines on and off 'File' – 'Options' – 'Grid'.

Copy

This option allows you to put a copy of the current graph on the clipboard as a bitmap so that it can be incorporated in another Windows application such as Microsoft Word or Excel. You can also copy the current graph or active Window to the clipboard by pressing the Alt and PRINT SCREEN (PrtSc) keys together. Older keyboards may not recognise Alt + PRINT SCREEN, so try Shift + PRINT SCREEN instead. To paste information from the Clipboard into a Windows application, start the destination application and place the insertion point where you want the information from the Clipboard to appear. Choose Paste from the destination application's Edit menu, and Windows will copy the information automatically to the insertion point. To capture the entire screen (not just the current graph or active window) press the PRINT SCREEN key on the keyboard. Older keyboards may require you to use Alt + PRINT SCREEN or Shift + PRINT SCREEN. Refer to your Microsoft Windows manual for more general tips on editing the clipboard contents.

Print

This option allows you to print the current graph.

Export

In some instances you may wish to retain your results in text format rather than in graphical or statistical format. 'Export Data' allows results to be saved as a .csv file.

Percentiles

The percentile selection boxes on the right hand-side of the dialogue box allows the option to show the curves for the calculations at different percentiles. Selecting the desired percentile will draw the line on the graph for this percentile and a tick will appear in the box. To deselect click the box again.

Exit

Clicking 'File – Exit' closes the current graph.

Interpreting Your Results

Since some or all of the input parameters to the analytical equations are used in a probabilistic calculation it is not possible to provide a single value that truly represents all possible outcomes. It may be suggested that it is appropriate to compute a 'worst case' outcome, or an 'average' by selecting values from within the input ranges, but this does not follow the philosophy of a risk assessment - taking full account of all outcomes, both positive and negative.

The solution most commonly adopted, and which is employed within GasSim, is known as the 'Monte Carlo' approach (discussed in Chapter 2). In this method, the calculations are carried out many times, and each time the value for each input parameter is selected randomly from within the specified range. If the calculation (or iteration) is carried out 100 times there will be 100 results, and these 100 results may be represented on a frequency histogram, just like the input distributions.

Format of the Results

GasSim shows the calculated vales at the different percentiles and report these either as a written summary in the 'Statistics' dialogue box or illustrates them as different coloured lines on the graphs, as described above.

Confidence

Confidence in the Results

The output results from a GasSim assessment show the results for all iterations in a single simulation. Results for subsequent simulations may be slightly different, particularly at extremely high or low percentiles. This is due to the random number generator 'seed value' used in model runs.

Using a large number of iterations and not concerning yourself with absolute extreme values will minimise any problems associated with the different random number seeds used in GasSim. It is important to remember the percentiles available to view are determined by the number of iterations run (see Chapter 3 for details).

Confidence in Decision Making

GasSim generates result distributions, which incorporate the underlying uncertainties. Typically, when making a decision most people will take account of these uncertainties by using the 95th percentile (for example, giving you 95% confidence that contaminant concentrations will be lower than an acceptable maximum limit). Demanding increased confidence over a 90% or 95% level is not free of additional risks or penalties. Increased confidence means greater costs - increased spending on containment design, for example, and requires greater run-times to create stable (reproducible) results at the extremes of confidence limits. However, the increased engineering required to meet more stringent performance criteria will also provide better environmental protection and a reasonable balance should be found between an acceptable level of uncertainty in the risk assessment and

attempting to engineer away hazards. The Environment Agency commonly expects a 95%ile to be a reasonable assessment level in a GasSim2.5 assessment.

Because it explicitly allows for uncertainties when estimating landfill performance, GasSim moves debate away from how the landfill will behave and on to questions about appropriate standards of care and management options, and so on. You should be aware that while using GasSim is likely to focus debate, it will not provide a solution to contentious issues and is only a tool to aid in your deliberations.

Understanding Modelling Errors

Potential Causes of Error

GasSim uses a variety of mathematical techniques to calculate ultimate gas concentration distributions over time. The program combines analytical and semi-analytical models of gas generation with analytical models of environmental (lateral and atmospheric) transport. The latter in turn represent the movement of gas in the environment between the source and receptor. Each of the models implemented in GasSim is derived from either established theory, or on empirical relationships that are based on analysis of field data.

There are several reasons why model results may be erroneous. In general these fall into the following groups:

- The model is incorrect;
- The mathematical implementation of the model is incorrect;
- The model is inappropriate for the problem to which it is applied; and
- The parameterisation of the model is inappropriate or wrong.

For the specific models used in GasSim, the first of these potential problems is partially addressed in the chapters outlining the theory and use of equations and in the associated references. Every effort has been made to ensure that the models used in GasSim are valid, although the best validation of a model arises from its widespread use and comparison with various datasets. Equally, the mathematical and computational implementation in GasSim has been subjected to appropriate verification and validation – (see Chapter 7 for further details).

The GasSim model actually consists of several individual calculations, which are computed in sequence. Any one of the component calculations may be inaccurate because it is not a valid representation of your system. In particular, some equations may have a limited range of applicability. It is your responsibility to ensure that the models and equations used in GasSim are appropriate for your system.

The final bullet point listed above relates to the parameterisation of the model. GasSim checks that physical parameters are generally reasonable, but it allows a necessarily wide range of values. You should therefore recognise that it is possible for a well-constructed, physically sensible model to give absurd results if its parameters are assigned inconsistently.

Approach to Model Checking

Given the possibilities noted above (that a part of the model may be inappropriate or that the parameterisation may be inconsistent), it is important that you should make yourself aware of the results of each stage in the simulation, and check that they are reasonable when compared with known validation data and with prior expectations.

Most importantly, the predictions of the source and emissions models should be checked before the lateral migration, atmospheric dispersion and impact calculations can be believed. Both gas generation and emissions rates should lie within reasonable ranges; unrealistically high or low values are probably diagnostic of the model's inapplicability or incorrect parameterisation. While modelling checks may help with model verification, the ultimate responsibility for choosing the right model and checking against site-specific information rests with you.

CHAPTER 5: DEFAULT VALUES AND SUGGESTED INPUTS

5.   DEFAULT VALUES AND SUGGESTED INPUTS

Introduction

Each time a new model is created in GasSim2.5 default values are assigned to certain parameters. Adopted default values are saved as part of the model and are over-written when an existing model is retrieved. This chapter explains the basis on which default values have been assigned to various parameters and also provides a reference source for other suggested input values.

Assumptions and Limitations of Default Parameters

Generally the defaults and suggested input values have been derived from UK and US sources. Consequently, the uncertainty representing some of the suggested input ranges may extend over a number of orders of magnitude. The default and suggested input parameters are not intended to be mean values that may be applied to a site, but rather a range of values that may be narrowed (or even widened) with site-specific knowledge and data. For these reasons, it is emphasised that wherever possible site-specific values should be used as input parameters.

Default Values

Broadly, there are three classes of defaults in GasSim:

- Values which are project-specific and which you will change in every instance;

- Values of chemical and physical constants that will rarely (if ever) need to be changed; and

- Values for which you are unlikely to have any better information.

Examples from the classes are as follows. Project-specific parameters include the landfill dimensions, the cap thickness and engine or flare capacities. Properties such as molecular weights, gas densities and viscosities have been taken from reliable sources so there should be little need to change these. Parameters for which you are unlikely to have better information might include deposition velocities and air diffusion coefficients.

Project Details

The 'Project Details' dialogue box requires information on the project and the client, the **'**Start' date that the waste deposition commences, the 'Operational Period' of the number of years for which deposition continues, the 'Simulation Period' of the number of years for which that you wish to run the simulation, and the number of 'Iterations'. This information should also be changed for each new model using information obtained from the Site Operator and the task to be undertaken.

Cell Layout

The landfill geometry including the geometry of each individual cell is defined by drawing out the shape of the landfill and the individual cells using the mouse on a plain scaled plotting screen or overlying an importing plan of the site (using Autocad™ dxf or drawing exchange files). These are specific to each simulation and should normally be obtained from the Site Operator. The area and depth of the landfill are calculated as described in Chapter 3.

Landfill Characteristics

Infiltration

Infiltration through the cap should be determined from the effective rainfall (obtained for the site) and the capping type and status. This information on rainfall should be obtained from an on-site weather station, the Meteorological Office or literature sources. GasSim2.5 allows uncapped and capped infiltration to be simulated. A default assumption is that capped infiltration is 10% of uncapped infiltration.

Cap and Liner Properties

The design and construction of the engineered barriers including the 'Cap Thickness' and 'Liner Thickness' should be obtained from the Site Operator. The 'Cap' and 'Liner Hydraulic Conductivity' should be defined on a site-specific basis depending on their age, level of compaction, the moisture content, and the level of engineering competence employed in construction, i.e. the use of CQA. GasSim requires the definition of the hydraulic conductivities, i.e. the permeability of the strata to water, as currently very little research has been undertaken to determine the gas permeability of natural materials. The gas conductivities are calculated from the hydraulic conductivities within the code, using the relative density and viscosity of gas and water.

The hydraulic conductivity of mineral caps and liners should be fully characterised at the material source and placed to achieve a design specification, with subsequent in-situ testing. A range of typical hydraulic conductivities for mineral liners have been obtained from LandSim version 2 (Environment Agency, 2001) and are listed in Table 5.1. The hydraulic conductivities of welded membrane liner systems should be provided in the manufacturer's specifications. Where the liner is lapped, rather than welded, it is recommended that the influence of the liner is reduced, as gas will be emitted through the lapped areas.

Table 5.1: Hydraulic Conductivities of the Cap and Liner

Material	Range of Hydraulic Conductivities (m.s^{-1})
Clay is normally engineered to a specification of a maximum hydraulic conductivity of	1×10^{-9}
Bentonite Enriched Sand (BES) is normally engineered to a specification of	1×10^{-10} – 1×10^{-11}
Dense Asphaltic Lining (DAC) system is normally engineered to a specification of	1×10^{-11} – 1×10^{-14}
Geomembrane liner (without defects)	1×10^{-14} - 1×10^{-16}
Typical geomembrane	1×10^{-12} – 1×10^{-14}

Gas Collection Efficiency

Details for the dates of installation for the capping of individual cells and their corresponding gas collection systems should be obtained from the Site Operator. An estimate of the 'Gas Collection Efficiency' can be obtained from the Site Operator. However, where this is not the case GasSim recommends default values from Table 5.2 below.

Table 5.2: Gas Collection Efficiency Estimates

	No Cap	Temporary Cap	Permanent Cap
Sacrificial Gas Collection System	Triangular (10.30.50)	Triangular (40,50,60)	Triangular (55,65,75)
Permanent Gas Collection System	Triangular (50,60,70)	Triangular (75,85,95)	Triangular (90,95,97.5)

These have been derived from a confidential full site surface flux survey of a large (>200Ha) landfill with various combinations of cap and gas collection infrastructure and the overall predicted surface flux has been validated by comparison with whole site gas generation forecasts (within GasSim) and site gas abstraction data. The gas collection efficiency estimates are therefore internally consistent with GasSim gas generation and surface emission forecasts.

Biological Methane Oxidation

Methane emissions can be reduced as they pass through the landfill cap by microbial processes. The proportion of the methane that is converted to carbon dioxide in the cap is calculated by the 'Biological Methane Oxidation' term. This can be simulated without or without fissures. Simulating this reduction without fissures requires a percentage of 'Biological Methane Oxidation', which should be defined on a site-specific basis, as the quantity of methane oxidation is dependent on a number of factors including the cap thickness and permeability. Alternatively this can be defined using the default of 10%, which is based on IPCC guidelines.

'Biological Methane Oxidation' can also be simulated with fissures and a soil cap by calculating the methane oxidation rates for different cover materials, based on the knowledge that caps generally have a maximum capacity for oxidation, and beyond that methane is released. The maximum capacity is a PDF developed from lab and field measurements. This is moderated by an efficiency term, which is a default triangular PDF of between 10 - 46% with a mean of 25%. This calculation method also requires further inputs by the user to define the 'Soil Depth' above the cap and the '% of Area Occupied by Fissures'. Both of these parameters are site-specific and therefore information should be obtained from the Site Operator or by investigation. Where site-specific information relating to the proportion of gas escaping from fissures is not available, this module should not be used and the PCC default should be used.

Waste Inputs

The dates on which the waste deposition commences and the number of years for which deposition continues for each cell are used by GasSim2.5 to produce a matrix in which the yearly 'Waste Input', i.e. deposition rate (in tonnes), must be defined. These should be obtained from the Site Operator, and therefore no defaults have been provided. Where this information is not known, an estimate of the filling rate each year should be made even if this is simply dividing the total waste mass filled by the filling time (and making appropriate use of PDFs to account for the uncertainty). However, the use of estimations will affect the outputs and therefore should be taken into account when interpreting the data.

Waste Composition

The nature of the waste deposited should be defined by the proportion of the waste from each stream i.e. percentage of domestic, inert, industrial waste etc. This influences the quantity of carbon available for degradation and therefore a default is not provided. This information should be available from the Site Operator.

Separate waste composition files have been created to reflect the difference between the composition of waste in each of the four Devolved Administrations using data compiled by ERM (2006) (described see Chapter 3 for details). The domestic waste data for England was compiled using Parfitt (2002), for Wales using NAW (2003), for Scotland using SEPA (2005) and for Northern Ireland using EHSNI (2005) and ERM (2005). The Civic Amenity data for England was also taken from Parfitt (2002) and for Wales from NAW (2003). For Northern Ireland and Wales, Civic Amenity data was not available so consequently the data for England was used. Likewise for commercial and industrial waste, data was only available for England and hence the data for each constituent country uses the information available for England, originally taken from Environment Agency (2003).

The waste compositions for subsequent years are obtained using government proposed targets for reducing biodegradable domestic waste (Waste Strategy 2000). In each year the biodegradable domestic waste of each country was reduced by the government reduction targets. The percentage of non-biodegradable domestic waste was then calculated as being the surplus, thus making 100%. All compositions for the remaining categories of waste remain unchanged throughout the time periods.

Commercial and Industrial Waste Composition Calculator

The commercial and industrial waste composition can now be specified on the basis of different commercial and industrial sectors (ERM 2006) (see Chapter 3 for details). The percentages of each sector can be altered to reflect the different composition of industrial/commercial waste received at an individual landfill site. The defaults represent the average industrial and commercial waste composition for England. The user defined columns are editable and intended for use if the user knows the specific waste composition or if the waste comes from sectors which are not otherwise specified.

GasSim2.5 provides defaults for the percentages 'Water Content', 'Decomposition', 'Cellulose' and 'Hemi-Cellulose' for each waste fraction (Gregory *et al*, 1999). Additionally GasSim is highly flexible and allows you to redefine or edit a waste stream, using site-specific data, by altering the PDF's defining the fractionation of the material and percentages for the 'Water Content', 'Decomposition', 'Cellulose' and 'Hemi-Cellulose' for each waste fraction.

GasSim contains six waste streams, which are not defined due to their site specific nature and require defining using this process in order to use them in a simulation: 'Industrial Waste', 'Liquid Inert', 'Residues from a MRF', 'Recycling Schemes', 'Chemical Sludges', and 'Industrial Liquid Waste'. Three additional waste streams are available for site-specific uses, and the labelling of the waste streams can be modified by the user to suit site-specific conditions.

Moisture Content and Waste Degradation Rates

The 'Waste Moisture Content' can be entered a 'Dry', 'Average', 'Wet' or 'Saturated', 'User Defined 1' and 'User Defined 2' or can be calculated using the inputs of 'Infiltration', 'Waste Density', 'Effective Porosity', 'Leachate Head', waste 'Hydraulic Conductivity', 'Adsorptive Capacity' and 'Leachate Recirculation'. These data are cell-specific.

The volume of 'Leachate Recirculation' will be cell-specific and should be obtained from the Site Operator, if this operation occurs at the site. GasSim assumes that this rate is constant for the simulation period.

The depth of the 'Leachate Head' is cell-specific and therefore should also be obtained from the Site Operator. However, in practice the leachate head is normally maintained at 1m, therefore this value has been suggested as a default.

'Effective Porosity', 'Adsorptive Capacity', 'Waste Density 'and waste 'Hydraulic Conductivity' should all be obtained on a cell-specific basis. However, suggested ranges have been tabulated (Table 5.3).

Table 5.3: Source Model Default Input Parameters (from Gregory *et al*., 1999)

Parameter	Default Range
Waste Density [t/m^3]	0.8 – 1.2
Effective Porosity [% (v/v)]	1 – 20
Hydraulic Conductivity [m/s]	$1 \times 10^{-5} – 1 \times 10^{-9}$
Adsorptive Capacity [%(v/v)]	1 – 5

In our experience it is difficult simulate a wet or saturated site by calculating the waste moisture content without having a high leachate head. Therefore we recommend simulating a wet site by selecting the 'Wet' option.

The default decay constants are used to determine the degradation of carbon for the three different waste moisture levels and the three rates of degradability (rapid, k_1, moderate, k_2, and slow, k_3). These values are listed in Table 5.4 and have been obtained from the HELGA framework (Gregory *et al*., 1999) and more recent work for GasSim2.5 by Gregory and Browell (2011).

Very wet (i.e. waterlogged or saturated) landfills where the moisture content is probably >80% are simulated with the same decay rate as a dry landfill because under such conditions, degradation is actually retarded and gas generation can be slowed significantly. Similar retardation of degradation rates have been observed after capping but this mechanistic approach is not specifically considered in GasSim2.5. Recirculation of leachate can also enhance degradation rates and the user is recommended to calibrate the model with site-specific data in these cases. GasSim2.5 has been calibrated against 10 UK landfills of varying sizes and we have found that varying the cellulose decay rates between the wet and dry extreme values allows the model to accurately represent all of the sites examined. Anecdotal evidence in regard of managed bioreactor landfills or landfills where leachate recirculation is practiced efficiently suggests that the half-life could be as much as half that represented in GasSim for a wet landfill. GasSim2.5 users should not feel constrained by the single values supplied as defaults. Uniform

and other distributions are equally plausible and will help the user in calibrating the model. There is limited research on post closure waste degradation rates, and the defaults given below should only be used with justification.

Table 5.4: Degradation Rate Constants for three Fractions of Degradable Cellulose in Waste (from Gregory *et al.*, 1999 and Gregory and Browell, 2011)

Waste Moisture Level (driven primarily by water filled porosity)	Degradation Rate Constants	Degradation Half-Lives, $t\frac{1}{2}$
Dry. Less than 30% (v/v) moisture	$k_1 = 0.076$ $k_2 = 0.046$ $k_3 = 0.013$	$t \frac{1}{2}_{(1)} = 9$ $t \frac{1}{2}_{(2)} = 15$ $t \frac{1}{2}_{(3)} = 53$
Average. Greater than 30% (v/v) and less than 60% (v/v) moisture	$k_1 = 0.116$ $k_2 = 0.076$ $k_3 = 0.046$	$t \frac{1}{2}_{(1)} = 6$ $t \frac{1}{2}_{(2)} = 9$ $t \frac{1}{2}_{(3)} = 15$
Wet. Greater than 60% (v/v) moisture and less than 80% (v/v) moisture	$k_1 = 0.694$ $k_2 = 0.116$ $k_3 = 0.076$	$t \frac{1}{2}_{(1)} = 1$ $t \frac{1}{2}_{(2)} = 6$ $t \frac{1}{2}_{(3)} = 9$
Saturated. Greater than 80% (v/v) moisture	$k_1 = 0.076$ $k_2 = 0.046$ $k_3 = 0.013$	$t \frac{1}{2}_{(1)} = 9$ $t \frac{1}{2}_{(2)} = 15$ $t \frac{1}{2}_{(3)} = 53$
Super-wet Waste (e.g. very high infiltration or Bioreactor)	$k_1 = 0.694$ $k_2 = 0.116 – 0.694$ $k_3 = 0.076 – 0.116$	$t \frac{1}{2}_{(1)} = 1$ $t \frac{1}{2}_{(2)} = 1 – 6$ $t \frac{1}{2}_{(3)} = 6 – 9$
Post Closure Rates for Average Sites	$k_1 = 0.076 – 0.116$ $k_2 = 0.046 – 0.076$ $k_3 = 0.046$	$t \frac{1}{2}_{(1)} = 6 – 9$ $t \frac{1}{2}_{(2)} = 9 – 15$ $t \frac{1}{2}_{(3)} = 15$
Post Closure Rates for Wet Waste Sites	$k_1 = 0.116 – 0.694$ $k_2 = 0.076 – 0.116$ $k_3 = 0.046 – 0.076$	$t \frac{1}{2}_{(1)} = 1 – 6$ $t \frac{1}{2}_{(2)} = 6 – 9$ $t \frac{1}{2}_{(3)} = 9 – 15$

Trace Gases Inventory

Trace gas concentrations should be defined on-site by monitoring. However, default concentrations have been defined a list of species (Table 5.5). Where it is expected that the trace gas is routinely found in LFG and is on the PI list, default data have been supplied. Additionally default concentrations have been provided for substances that are likely to result in odour problems (Table 5.6), or impact the global atmosphere by global warming or ozone depletion (Table 5.7). The default trace gas concentrations have been derived from performing statistical analysis on the data gathered by a number of authors (AERC draft database, 2001; Derwent *et al.*, 1996; and Stoddart *et al.*, 1999) and have been supplanted by data from Parker *et al* (2002). These default concentrations are anticipated to vary on a site by site basis according to the age of the waste, the composition, and whether the site is capped or uncapped. Therefore site-specific data should be used when available, rather than relying on assumptions based upon literature sources. Hydrogen sulphide is problematic odorous species, and reported data may come disproportionately from investigative work on sites with high concentrations of this trace gas. Hence, the default values provided for this substance in particular, should be reviewed in the light of any site-specific information.

The 'Trace gases Half-life' has been derived by examining the emissions of VOCs in landfill gas from a number of studies, described in Chapter 6, which provide a normal distribution for the half-life of 4.11 years with a standard deviation of 1.56 years. However, the half-life is anticipated to vary with the LFG composition and the nature of the waste, so use site-specific information where available. The source concentration of VOCs should be defined even when you are simulating the emissions of these as a 'Combustion Product' as GasSim simulates their breakdown to produce carbon dioxide.

The trace gas database reflects the PI reporting thresholds. From the trace gas list, it is possible to highlight the Priority trace gas components as defined by the Environment Agency (2004a). The distributions of these priority trace components are also in accordance with Environment Agency R&D Technical Report P1-491/TR Environment Agency (2004c). The list of trace components with specific impact on odour has likewise been refreshed in review of Environment Agency guidance (2010a).

Table 5.5: Trace Gas Default Values for General components of Raw LFG (mg/m^3)

Species	Distribution and Values
1,1,1,2-Tetrafluorochloroethane	LOGTRIANGULAR(0.002, 0.2, 2.0)
1,1,1-Trichlorotrifluoroethane	LOGTRIANGULAR(0.005, 0.4, 8.0)
1,1,2-Trichloroethane	LOGTRIANGULAR(0.004, 1.0, 10.0)
1,1-Dichloroethane	LOGTRIANGULAR(1.00E-03, 1.00E-01, 6.18E+04)
1,1-Dichloroethene	LOGTRIANGULAR(1.00E-03, 1.00E-02, 1.52E+03)
1,1-Dichlorotetrafluoroethane	LOGTRIANGULAR(0.05, 0.25, 6.4)
1,2-Dichloropropane	SINGLE(0.0)
1,2-Dichlorotetrafluoroethane	LOGTRIANGULAR(0.01, 9.8, 300.0)
1-Chloro-1,1-difluoroethane	LOGTRIANGULAR(0.04, 0.57, 31.0)
2-Chloro-1,1,1-trifluoroethane	LOGUNIFORM(0.05, 1.5)
2-Propanol	LOGTRIANGULAR(0.005, 2.0, 34.0)
Acetalehyde (ethanal)	LOGTRIANGULAR(0.1, 0.2, 52.0)
Acetone	LOGTRIANGULAR(0.005, 0.1, 50.0)
Acrylonitrile	LOGTRIANGULAR(0.02, 0.4, 38.0)
Benzene	LOGTRIANGULAR(1.00E-03, 1.00E-01, 1.14E+02)
Bromodichloromethane	SINGLE(0.0)
Butadiene (modelled as 1,3-Butadiene)	LOGTRIANGULAR(0.05, 1.45, 6.0)
Butane	LOGTRIANGULAR(0.19, 1.0, 709.0)
Butene isomers	LOGTRIANGULAR(1.00E-03, 2.00E-01, 1.80E+00)
Carbon disulphide	LOGTRIANGULAR(0.01, 0.1, 11.0)
Carbon monoxide	LOGTRIANGULAR(0.11, 1.1, 5000.0)
Carbon tetrachloride (tetrachloromethane)	LOGTRIANGULAR(2.00E-04, 2.00E-01, 1.52E+02)
Carbonyl sulphide	LOGTRIANGULAR(0.006, 0.2, 4.4)
Chlorobenzene	LOGUNIFORM(0.002, 3000.0)
Chlorodifluoromethane	LOGTRIANGULAR(0.005, 0.1, 9900.0)
Chloroethane	LOGTRIANGULAR(1.00E-03, 1.00E-02, 6.15E+03)
Chlorofluorocarbons (CFCs) (Total)	LOGTRIANGULAR(0.06, 102.3, 1230.0)
Chlorofluoromethane	LOGTRIANGULAR(0.008, 0.2, 110.0)
Chloroform (trichloromethane)	LOGTRIANGULAR(1.00E-03, 2.00E-01, 7.00E+01)
Chlorotrifluoromethane	LOGTRIANGULAR(0.1, 0.2, 49.0)
Dichlorodifluoromethane	LOGTRIANGULAR(0.01, 9.0, 790.0)
Dichlorofluoromethane	LOGTRIANGULAR(1.00E-03, 1.00E-02, 6.02E+02)
Dichloromethane (methylene chloride)	LOGTRIANGULAR(1.00E-03, 2.00E-02, 1.52E+03)
Diethyl disulphide	LOGTRIANGULAR(1.00E-03, 2.00E-02, 2.60E+00)
Dimethyl disulphide	LOGTRIANGULAR(1.00E-03, 2.00E-02, 4.00E+01)
Dimethyl sulphide	LOGTRIANGULAR(1.00E-03, 1.00E-02, 6.00E+01)
Ethane	LOGTRIANGULAR(0.005, 6.25, 200.0)
Ethanethiol (ethyl mercaptan)	LOGTRIANGULAR(0.01, 0.01, 41.9)
Ethanol	LOGTRIANGULAR(0.005, 0.2, 810.0)
Ethyl toluene (all isomers)	LOGTRIANGULAR(1.00E-03, 1.00E-02, 8.30E+00)
Ethylbenzene	LOGTRIANGULAR(1.00E-03, 1.00E-03, 8.75E+02)
Ethylene	UNIFORM(0.2, 5.8)
Ethylene dibromide	SINGLE(0.0)
Ethylene dichloride	LOGTRIANGULAR(0.006, 0.01, 1820.0)
Fluorotrichloromethane	LOGTRIANGULAR(1.00E-03, 1.00E-02, 1.00E+03)

Species	Distribution and Values
Formaldehyde (methanal)	LOGTRIANGULAR(0.2, 0.2, 52.0)
Freon 113	LOGTRIANGULAR(0.013, 4.8, 125.0)
Halons	SINGLE(0.0)
Hexachlorocyclohexane (all isomers)	SINGLE(0.0)
Hexane	LOGTRIANGULAR(1.00E-03, 9.60E+00, 4.40E+01)
Hydrochlorofluorocarbons (HCFCs) (Total)	LOGTRIANGULAR(0.02, 128.8, 916.2)
Hydrofluorocarbons (HFCs) (Total)	SINGLE(0.0)
Hydrogen sulphide	LOGTRIANGULAR(5.70E-04, 2.40E+00, 5.57E+03)
Limonene	LOGTRIANGULAR(1.00E-03, 1.00E-01, 2.40E+02)
Mercury	SINGLE(0.0)
Methanethiol (methyl mercaptan)	LOGTRIANGULAR(0.005, 0.01, 87.0)
Methyl chloride (chloromethane)	LOGTRIANGULAR(0.006, 0.2, 10.0)
Methyl chloroform (1,1,1-Trichloroethane)	LOGTRIANGULAR(1.00E-03, 1.80E+02, 1.60E+03)
Methyl ethyl ketone (2-butanone)	LOGTRIANGULAR(0.005, 0.005, 73.0)
Methyl isobutyl ketone	LOGTRIANGULAR(0.005, 0.2, 9.9)
Nitric acid	SINGLE(0.0)
Odour Units (Predicted)	TRIANGULAR(5.00E+04, 1.25E+05, 2.50E+05)
PAH (reported as Naphthalene)	LOGTRIANGULAR(1.00E-03, 2.00E-01, 1.70E+01)
para-Dichlorobenzene (modelled as 1,4-Dichlorobenzene)	LOGTRIANGULAR(0.006, 0.05, 2.7)
Pentane	LOGTRIANGULAR(0.02, 0.3, 105.0)
Pentene (all isomers)	LOGTRIANGULAR(1.00E-03, 2.00E-01, 1.10E+01)
Perfluorocarbons (PFCs) (Total)	SINGLE(0.0)
Phenol	SINGLE(0.0)
PM10s	SINGLE(0.0)
Propane	LOGTRIANGULAR(1.00E-03, 1.90E+00, 1.29E+01)
Propanethiol	LOGTRIANGULAR(0.2, 0.2, 2.1)
Sulphide, total simulations with H2S	LOGTRIANGULAR(1.00E-03, 2.40E+00, 5.58E+03)
Sulphide, total simulations without H2S	LOGTRIANGULAR(5.00E-04, 8.00E-03, 3.50E+00)
t-1,2-Dichloroethene	LOGTRIANGULAR(0.006, 1.0, 41.0)
Tetrachloroethane (modelled as 1,1,2,2-Tetrachloroethane)	LOGUNIFORM(1.00E-03, 5.00E+01)
Tetrachloroethylene (Tetrachloroethene)	LOGTRIANGULAR(1.00E-03, 1.00E-02, 7.70E+03)
Toluene	LOGTRIANGULAR(0.01, 0.1, 1250.0)
Total non-methane volatile organic compounds (NMVOCs)	LOGUNIFORM(0.05, 1473.0)
Trichlorobenzene (all isomers)	LOGTRIANGULAR(0.01, 0.01, 0.13)
Trichloroethylene (trichloroethene)	LOGTRIANGULAR(0.01, 2.0, 608.0)
Trichlorofluoromethane	LOGTRIANGULAR(1.00E-03, 1.00E-02, 1.00E+03)
Trichlorotrifluoroethane	LOGTRIANGULAR(1.00E-03, 4.80E+00, 2.40E+01)
Trimethylbenzene (all isomers)	LOGTRIANGULAR(1.00E-03, 1.00E-02, 1.87E+02)
Vinyl chloride (chloroethene, chloroethylene)	LOGTRIANGULAR(1.00E-03, 1.00E-02, 7.66E+03)
Xylene (all isomers)	LOGTRIANGULAR(1.00E-03, 1.00E-03, 6.18E+04)
Total volatile organic compounds (VOCs)	LOGUNIFORM(0.05, 1473.0)

Table 5.6: Trace Gas Default Inputs for Odorous Components of LFG (mg/m3)

Species	Distribution and Values
Carbon disulphide	LOGTRIANGULAR(1e-2, 0.1, 11)
Diethyl disulphide	LOGTRIANGULAR(0.001, 0.02, 2.6)
Dimethyl disulphide	LOGTRIANGULAR(0.001, 0.02, 40)
Dimethyl sulphide	LOGTRIANGULAR(1e-3, 0.01, 60)
Ethanethiol (ethyl mercaptan)	LOGTRIANGULAR(0.01, 0.0 1, 41.9)
Hydrogen sulphide	LOGTRIANGULAR(0.00057, 2.4, 5570)
Limonene	LOGTRIANGULAR(0.001, 0.1, 240)
Methanethiol (methyl mercaptan)	LOGTRIANGULAR(5e-3, 0.01, 87)
Odour Units (Predicted)	TRIANGULAR(50000, 125000, 250000)
Propanethiol	LOGTRIANGULAR(0.2, 0.2, 2.1)
Sulphide, total simulations with H2S	LOGTRIANGULAR(1e-3,2.4,5575)
Sulphide, total simulations without H2S	LOGTRIANGULAR(5e-4,8e-3,3.5)
Toluene	LOGTRIANGULAR(0.01, 0.1, 1250)
Xylene (all isomers)	LOGTRIANGULAR(0.001, 0.001, 61784)

Table 5.7 Trace Gas Default Inputs for Global Impact Species of LFG (mg/m3)

Species	Distribution and Values
1,1-Dichlorotetrafluoroethane	LOGTRIANGULAR(5e-2, 0.25, 6.4)
1,2-Dichlorotetrafluoroethane	LOGTRIANGULAR(1e-2, 9.8, 300)
1-Chloro-1,1-difluoroethane	LOGTRIANGULAR(0.04, 0.57, 31)
2-Chloro-1,1,1-trifluoroethane	LOGUNIFORM(5e-2, 1.5)
Chlorodifluoromethane	LOGTRIANGULAR(0.005, 0.1, 9900)
Chlorofluorocarbons (CFCs) (Total)	LOGTRIANGULAR(0.06, 102.3, 1230)
Chlorofluoromethane	LOGTRIANGULAR(8e-3, 0.2, 110)
Chlorotrifluoromethane	LOGTRIANGULAR(0.1, 0.2, 49)
Dichlorodifluoromethane	LOGTRIANGULAR(1e-2, 9, 790)
Dichlorofluoromethane	LOGTRIANGULAR(1e-3, 0.01, 602)
Hydrochlorofluorocarbons (HCFCs) (Total)	LOGTRIANGULAR(0.02, 128.8, 916.2)

GasSim2.5 allows the simulation of species that are produced by LFG combustion from parent species, e.g. fluorine (F). Concentrations can be defined to determine hydrogen fluoride (HF) emissions using the 'Combustion Product for Parent' equation. This determination requires a 'Molecular Ratio', the ratio based on the molecular weight of the daughter species compared to the parent species, e.g. F to HF is 1.05. A number of commonly used correction ratios are tabulated below (Table 5.8).

Table 5.8: Molecular Weight Correction Factor

Emission of Species	Species Concentration in LFG	Molecular Ratio
Hydrogen chloride (HCl)	Chloride (Cl)	1.03
Hydrogen fluoride (HF)	Fluoride (F)	1.05
Sulphur dioxide (SO$_2$)	Sulphur (S)	2.00

Gas Plant

The 'Proportion to CH_4' and 'Proportion to CO_2' generated by methanogenic decay has been set at a default of 50% for each. However, this ratio is site-specific and therefore the ratio measured at the site should be used, if available. It is recommend that this information is obtained from dynamic monitoring points, e.g. at the supply manifold to the gas plant, with the values obtained normalised to 100%, i.e. measurements should be taken from the gas collection system, and the composition corrected to exclude entrained air.

To determine the volume of hydrogen produced GasSim assumes that 1% of the carbon deposited in the year of deposition undergoes acetogenic decay to produce hydrogen and carbon dioxide. This assumed value has been validated during the HELGA framework (Gregory *et al*., 1999) and produces a maximum concentration of hydrogen in LFG of around 10%, which fits with the work of Farquhar and Rovers (1973). Acetogenic decay will also slightly increase the CO_2 generation.

Information relating to the number of flares and engines, the 'year and month Commissioned' and 'year and month Decommissioned', and the 'Order' in which they are operated is site-specific and therefore GasSim does not provide any defaults. This information should be obtained from the Site Operator.

The engines and flares are best entered directly on the plan of the site, to obtain the co-ordinates of the plant automatically. The engine and flare input data should be obtained from the flare specification or the Site Operator. The specification and its operation will affect the 'Minimum Capacity' and 'Maximum Capacity' and therefore this information should be obtained from the Site Operator. The 'Engine Capacity' will depend on a number of factors, including the type of engine used and the methane to carbon dioxide ratio of the LFG inputs. Therefore these values should be obtained from the operator or the engine specification.

Bulk gas 'Destruction Efficiency' (methane and hydrogen) should be determined on-site by monitoring the concentrations in landfill gas inputted and then emitted from the flare or engine. Emissions from the flare and engine will depend on the age, capacity, temperature, air to fuel ratio, residence time, and the level of maintenance that has been carried out on the flare or engine during its operation. Flares and engines often have high destruction efficiencies when installed but poor maintenance will cause their efficiency to decline. Where site-specific data is not available Table 5.9 provides recommended data. The ranges have been obtained from the following studies: Baldwin *et al*. (1993a and 1993b), Millican (1995), California State Air Resources Board (1986a and 1986b), and LQM (2002).

The Flare 'Air to Fuel Ratio', 'Stack Height' of flare, 'Temperature' and 'Orifice Diameter' should be obtained from the Site Operator or the flare specification. GasSim suggests a default air to fuel ratio of 11 for flares and a flare temperature of 1000ºC. The Engine 'Air to Fuel Ratio', 'Exhaust Height' of the emission stack, engine 'Temperature' and Exhaust 'Orifice Diameter' are also engine-specific and should be obtained from the Site Operator. However, where this information is not available, defaults of the 'Air to Fuel Ratio' of 7 and a 'Temperature' of 500ºC are recommended. In these instances, the fuel is defined as the landfill gas as a whole,

and not simply the methane component of the LFG. The air to fuel ratios can be calculated for different combustion temperatures for flares using the information in Appendix 4 of the Guidance on Landfill Gas Flaring (Environment Agency 2002a).

Table 5.9: Recommended Destruction Efficiency for Flares and Engines

Species	Minimum Reported Value (%)	Maximum Reported Value (%)	No. Of Samples	Recommended Destruction Efficiency
Benzene	4.6	99.6	12	99
Benzyl chloride (chlorobenzene)	92.8	92.8	1	99
Carbon tetrachloride (tetrachloromethane)	71.63	>99	5	99
Chloroform	83.3	99.92	7	99
Dichlorodifluoromethane	97.6	98.6	2	99
1,2-Dichloroethane	93.8	99.99	5	99
Dichloromethane	93.8	99.9	6	99
Hydrogen				99
Hydrogen sulphide	70.6	96.9	6	99
Methane	96.0	99.6	8	99
Tetrachloroethene	83.3	99.98	5	99
Toluene	92.0	99.99	12	99
Total VOCs				99
1,1,1-Trichloroethane	74.8	>99.99	7	99
Trichloroethylene (trichloroethene)	97.8	99.97	10	99
Trichlorofluoromethane	89.8	99.8	4	99
Trichlorotrifluoroethane	95.2	99.5	2	99
Trimethybenzene	99.1	99.9	7	99
Vinyl chloride (chloroethene)	89.3	>99.9	4	99
Xylene (all isomers)	92.0	99.96	14	99
Other Species				99

Trace Gas 'Destruction Efficiencies' should be determined on-site by monitoring of the actual trace LFG concentrations and the engine/flare emissions. These are required where the emissions of these species are being simulated using the 'Non-Combustion Products', 'Combustion Product from Parent' or 'Carbon Dioxide Generation' equations. However, where site-specific data is not available Table 5.9 provides recommended data. Additionally, when using the 'Combustion Product from Parent' equation, the 'Destruction Efficiency' relates to the destruction of the parent species and not the generation of the daughter species, i.e. Chlorine in LFG is destroyed by a 99% destruction efficiency to form hydrogen chloride.

Exhaust Concentrations are required for species that are generated by the combustion process, using the 'Combustion Product' equation. These concentrations should be determined on-site as the level of emissions will depend on the age, capacity, residence time, temperature, air to fuel ratio and level of maintenance. If site-specific data is not available, a number of recommended values are listed in Table 5.10 - 5.12. The ranges have been obtained from Valis (2000) and LQM (2002), and have been supplemented by Environment Agency research data. The data are given in normalised format. To convert the data to actual emission conditions, site-specific stack data are required, and these data are input in the Emissions Converter screen. When site-specific data or converted normalised data have been calculated, they can be pasted into the GasSim model overwriting the default values.

The destruction efficiency and source concentration of VOCs should be defined even when you are simulating the emissions of these as a 'Combustion Product', as GasSim simulates their breakdown to form carbon dioxide.

The flare and engine 'Downtime' is the percentage of time that the flare will not operate per year due to routine maintenance and breakdown. This information should be obtained from the Site Operator, alternatively where this information is not available a uniform distribution of 3 - 5% should be used as a default.

Table 5.10: Trace Gas Emissions for Enclosed Flares (mg/m^3)

Species	Distribution and Values
Benzo(a)pyrene	LOGUNIFORM(1E-6,0.0006)
Carbon monoxide	LOGTRIANGULAR (26, 294, 2178)
Dioxins and furans (modelled as 2,3,7,8-TCDD)	LOGTRIANGULAR (9e-9, 3.1e-8, 3.6e-7)
Nitrogen oxides	TRIANGULAR(43, 85, 149)
PM10s	UNIFORM(1,10)
Sulphur reduced (reported as SO2)	UNIFORM (0, 482)
Total chloride (reported as HCl)	LOGUNIFORM (0.5, 36)
Total fluoride (reported as HF)	LOG UNIFORM (0.4, 21)
Total non-methane volatile organic compounds (NMVOCs)	LOGUNIFORM(1,30)

Table 5.11: Trace Gas Emissions for Spark Ignition Engines (mg/m^3)

Species	Distribution and Values
Benzo(a)pyrene	LOG UNIFORM (1.1e-12, 9.6e-10)
Carbon monoxide	LOG TRIANGULAR (508, 1311, 1969)
Dioxins and furans (modelled as 2,3,7,8-TCDD)	LOG UNIFORM (7e-10, 2.3e-6)
Nitrogen oxides	LOG UNIFORM (330, 2132)
PM10s	TRIANGULAR (1.2, 4.6, 12.5)
Sulphur reduced (reported as SO2)	LOG UNIFORM (18,402)
Total chloride (reported as HCl)	LOG TRIANGULAR (0.0005, 10, 584)
Total fluoride (reported as HF)	LOG TRIANGULAR (0.0002, 7, 45)
Total non-methane volatile organic compounds (NMVOCs)	LOG TRIANGULAR(0.0118, 18.1, 90)

Table 5.12: Trace Gas Emissions for Dual Fuel Engines (mg/m³)

Species	Distribution and Values
Benzo(a)pyrene	LOG UNIFORM (1.1e-12, 9.6e-10)
Carbon monoxide	UNIFORM (1250, 2280)
Dioxins and furans (modelled as 2,3,7,8-TCDD)	LOG UNIFORM (7e-10, 2.3e-6)
Nitrogen oxides	UNIFORM (1200, 1800)
PM10s	UNIFORM (26.4, 39.6)
Sulphur reduced (reported as SO2)	UNIFORM (432, 648)
Total chloride (reported as HCl)	UNIFORM (1.36, 2.04)
Total fluoride (reported as HF)	UNIFORM (1.04, 1.56)
Total non-methane volatile organic compounds (NMVOCs)	UNIFORM (52.8, 79.2)

Tier 1 Screening

GasSim2.5 uses as the basis for Tier 1 screening the data from the Environment Agency guidance "Screening method for emissions to air from landfill sites" (Environment Agency, 2004b). This provides a number of tables that can be used to calculate a ground-level concentration of a gaseous emission at a receptor, based on the 95%ile emission rate from the process, its height, and the distance to the receptor. Separate tables are provided for short-term and long-term concentrations. The look-up tables have been developed to be conservative:

- The tables are not directional, so you do not need meteorological data;

- The tables are essentially based on the 100%ile;

- The tables are derived from a representative and not extreme windrose; and

- The tables evaluate the Environment Agency's H1 assessment equations.

The lookup tables (Tables 5.13 - 5.17) provide ground-level concentrations for discrete values of stack heights and distances. GasSim allows the user to define any stack height within a reasonable range, and linearly interpolates between the receptor concentrations provided in the tables.

Table 5.13: Maximum Hourly Ground Level Concentration Beyond a Given Distance from a Typical Landfill Gas Engine (µg/m³ per g/s emitted)

Shortest Distance from Engine to Site Boundary or nearest Sensitive Receptor	Height of Gas Engine Stack (m)											
	3.5	4	5	6	7	8	9	10	15	20	25	30
< 50 m	460	380	255	185	135	100	85	75	35	20	15	10
50 m	330	300	240	185	135	100	85	75	35	20	15	10
100 m	160	155	140	125	115	100	85	75	35	20	15	10
150 m	100	100	95	85	80	75	70	60	35	20	15	10
200 m	75	70	70	65	60	55	55	50	35	20	15	10
250 m	55	55	55	50	50	45	45	40	30	20	15	10
300 m	45	45	45	40	40	40	35	35	25	20	15	10
350 m	40	40	35	35	35	35	30	30	25	15	15	10
400 m	35	35	30	30	30	30	25	25	20	15	10	10
450 m	30	30	30	25	25	25	25	25	20	15	10	10
500 m	25	25	25	25	25	25	20	20	15	15	10	10

Table 5.14: Maximum Hourly Ground Level Concentration Beyond a Given Distance from a Typical Landfill Flare Stack (µg/m³ per g/s emitted)

Shortest Distance from Flare to Site Boundary or nearest Sensitive Receptor	Height of Flare Stack(m)							
	4	5	6	7	8	9	10	12
< 50 m	715	400	285	195	140	105	75	55
50 m	290	255	215	180	140	105	75	55
100 m	125	120	110	100	90	80	75	55
150 m	75	75	70	65	60	60	55	45
200 m	55	50	50	50	45	45	40	35
250 m	40	40	40	35	35	35	35	30
300 m	35	30	30	30	30	30	25	25
350 m	30	25	25	25	25	25	25	20
400 m	25	25	20	20	20	20	20	20
450 m	20	20	20	20	20	20	15	15
500 m	20	20	15	15	15	15	15	15

Table 5.15: Maximum Annual Mean Ground Level Concentration Beyond a Given Distance from a Typical Landfill Gas Engine (µg/m³ per g/s emitted)

Shortest Distance from Engine to Site Boundary or nearest Sensitive Receptor	Height of Gas Engine Stack (m)											
	3.5	4	5	6	7	8	9	10	15	20	25	30
< 50 m	19	17	13	11	9.5	8	7	6	3.5	2	1.5	1
50 m	19	17	13	11	9.5	8	7	6	3.5	2	1.5	1
100 m	15	14.5	13	11	9.5	8	7	6	3.5	2	1.5	1
150 m	10	10	9.5	9	8	7.5	7	6	3.5	2	1.5	1
200 m	7	7	7	6.5	6.5	6	5.5	5.5	3.5	2	1.5	1
250 m	5.5	5.5	5.5	5	5	5	4.5	4.5	3	2	1.5	1
300 m	4	4	4	4	4	4	3.5	3.5	3	2	1.5	1
350 m	3.5	3.5	3.5	3.5	3.5	3	3	3	2.5	2	1.5	1
400 m	3	3	3	3	3	2.5	2.5	2.5	2	1.5	1.5	1
450 m	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2	2	1.5	1	1
500 m	2	2	2	2	2	2	2	2	1.5	1.5	1	1

Table 5.16: Maximum Annual Mean Ground Level Concentration Beyond a Given Distance from a Typical Landfill Flare Stack (μg/m^3 per g/s emitted)

Shortest Distance from Flare Site Boundary or nearest Sensitive Receptor	Height of Flare Stack(m)							
	4	5	6	7	8	9	10	12
< 50 m	10.5	7.5	7	6	5.5	4.5	4	3
50 m	10.5	7.5	7	6	5.5	4.5	4	3
100 m	8.5	7.5	7	6	5.5	4.5	4	3
150 m	6	6	5.5	5	5	4.5	4	3
200 m	4.5	4.5	4.5	4	4	4	3.5	3
250 m	3.5	3.5	3.5	3.5	3	3	3	2.5
300 m	3	3	3	2.5	2.5	2.5	2.5	2.5
350 m	2.5	2.5	2.5	2.5	2	2	2	2
400 m	2	2	2	2	2	2	2	1.5
450 m	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
500 m	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5

Table 5.17 : Maximum Hourly and Annual Mean Ground Level Concentrations Beyond a Given Distance from a Typical Landfill Area Source (μg/m^3 per g/s emitted)

Shortest Distance from Sensitive Receptor to nearest Edge of Ground Level Area Source	Maximum Hourly Ground Level Concentration (μg/m^3 per g/s emitted)	Maximum annual Mean Ground Level Concentration (μg/m^3 per g/s emitted)
50 m	8,000	165
100 m	6,000	80
150 m	5,000	45
200 m	4,000	35
250 m	3,500	25
300 m	3,000	20
350 m	2,500	15
400 m	2,000	15
450 m	2,000	10
500 m	1,500	10

Gaseous emissions to air are considered insignificant, and therefore not to require more detailed modelling, if:

- Long-term ground-level contributions at the considered receptor are below 1% of the long-term Environmental Assessment Level (EAL) or Environmental Quality Standard (EQS);

- Short-term contributions are below 10% of the short-term EAL or EQS; and

- Where the ground-level contributions are calculated using the lookup-table method.

GasSim provides default values for EQSs/EALs for a number of gases, provided in Table 5.18, and the user is able to edit these values or add values to gases currently not attributed an EQS or EAL.

Table 5.18: Default EQSs/EALs used in GasSim2.5

Gas	Short-Term (mg/m^3)	Long-Term (mg/m^3)
Acetalehyde (ethanal)	9200	370
Acetone	362000	18100
Acrylonitrile	264	8.8
Arsenic (total inorganic arsenic in the PM10 fraction)	0.003	
Benzene		5
Benzo(a)pyrene		0.00025
Butadiene (modelled as 1,3-Butadiene)		2.25
Butane	181000	14500
Carbon disulphide	100	64
Carbon monoxide	10000	
Carbon tetrachloride (tetrachloromethane)	3900	130
Chloroform (trichloromethane)	2970	99
Dichloromethane (methylene chloride)	3000	700
Ethylbenzene	55200	4410
Ethylene dichloride	700	42
Formaldehyde (methanal)	100	5
Hexane	21600	720
Hydrogen chloride, or (Total chloride (reported as HCl))	750	
Hydrogen fluoride, or (Total fluoride (reported as HF))	160	16
Hydrogen sulphide	150	140
Mercury	7.5	0.25
Methyl chloride (chloromethane)	21000	1050
Methyl chloroform (1,1,1-Trichloroethane)	222000	11100
Methyl ethyl ketone (2-butanone)	89900	6000
Nitric acid	1000	52
Nitrogen oxides (NOx)	200	40
PAH (reported as Naphthalene)	8000	530
para-Dichlorobenzene (modelled as 1,4-Dichlorobenzene)	30600	1530
Phenol	3900	200
PM10s		40
PM10s - 24 hour	50	
Sulphur dioxide	350	
Sulphur dioxide - 15 min	266	
Sulphur dioxide - 24 hour	125	
Tetrachloroethylene (Tetrachloroethene)	8000	3450
Toluene	8000	1910
Trichlorobenzene (all isomers)	2280	76
Trichloroethylene (trichloroethene)	1000	1100
Trimethylbenzene (all isomers)	37500	1250
Vinyl chloride (chloroethene, chloroethylene)	1851	159
Xylene (all isomers)	66200	4410

Meteorological Data

There are two options of meteorological data to use within GasSim, default data or user-defined data, which are discussed below:

GasSim Default Meteorological Data

The default data sets have been produced by the Environment Agency Air Quality and Modelling Assessment Unit (AQMAU) using AERMET. A default dataset is available for most of the Environment Agency Areas in England and Wales. Figure 5.1 below identifies the Environment Agency Areas. Data are not provided for Areas where

complex terrain makes a default windrose difficult, so a number of the northern areas are not included, and the data for the Welsh Areas should only be used where simple terrain exists and the windrose appears representative.

The meteorological data is contained within two files, .sfc and .pfl files. The user is only asked to identify which .sfc file is required. The corresponding .pfl file is automatically loaded.

The windroses for each of the default meteorological datasets are shown in Figure 5.2 below.

User Defined Meteorological Data

In some cases it may not be appropriate to use the default data available within GasSim2.5. For example if the windrose in the vicinity of the site is not adequately represented by the default windrose for the area or if more appropriate site-specific data are available.

GasSim2.5 can accept user defined meteorological data that has been pre-processed using the AERMOD meteorological pre-processor AERMET. AERMET provides a meteorological pre-processor, which organises meteorological data suitable for import into GasSim. In order for site-specific meteorological data to be used, hourly data are required for input into AERMET. More information regarding AERMET can be found within the 'Users Guide for the AERMOD Meteorological pre-processor (AERMET)', USEPA, November 1998.

Background Air Quality Concentrations

Background air quality data, required by GasSim2.5, can be obtained direct from local authorities. Another useful source of air quality data is the DEFRA website (http://laqm.defra.gov.uk/). Other sources of background data may also be available. The user must verify that the background data are suitable prior to use within GasSim. GasSim2.5 requires background air quality concentrations to be input in $\mu g/m^3$.

Figure 5.1: Environment Agency Regions (England and Wales)

Anglian Region: Central
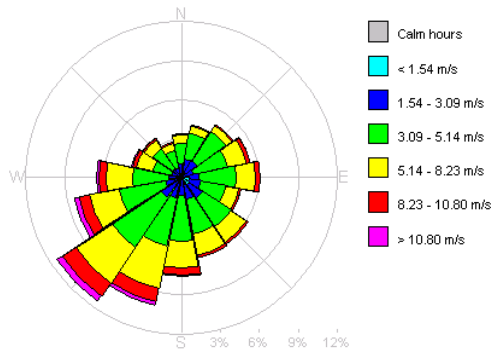
Anglian Region: Eastern
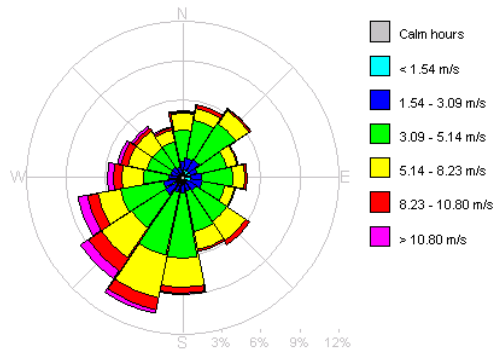
Anglian Region: Northern
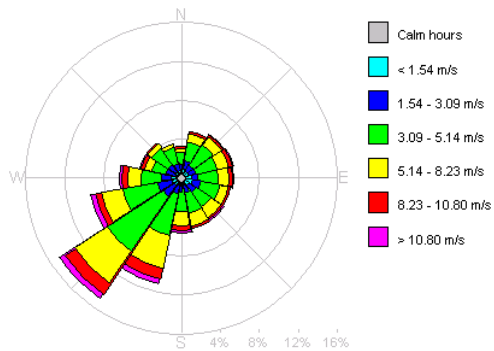
Midlands Region: Lower Severn
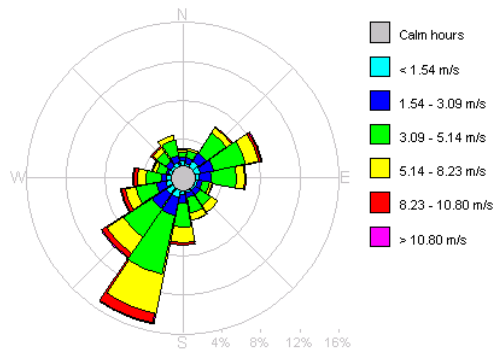
Midlands Region: Lower Trent
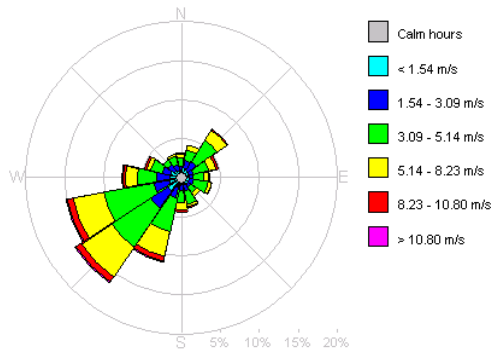
Midlands Region: Upper Severn
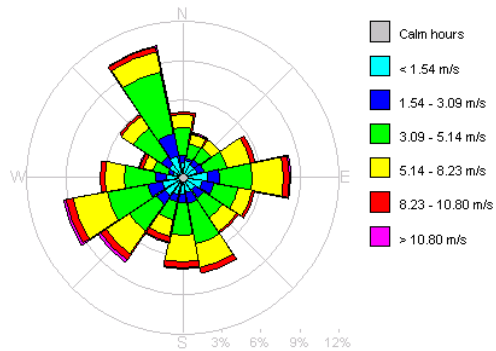
Midlands Region: Upper Trent
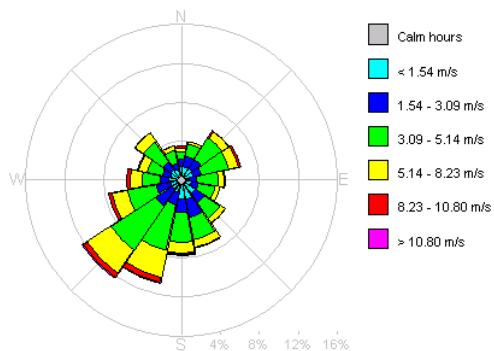
North East Region: Dales
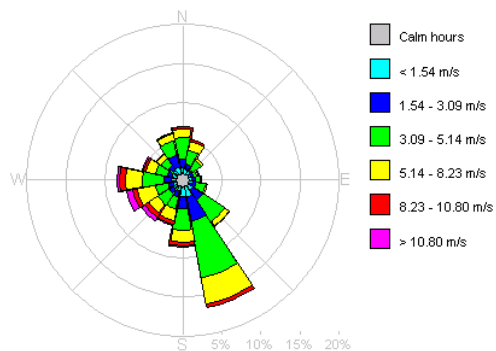
Figure 5.2: Windroses for Default Meteorological Datasets

North East Region: Northumbria
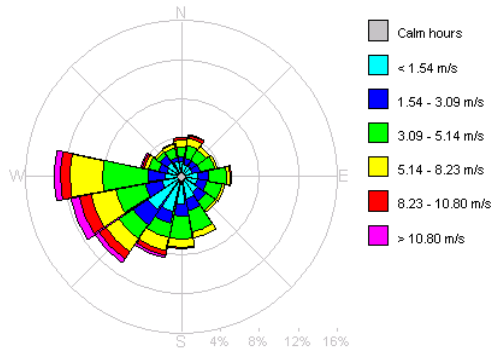
North East Region: Ridings (East)
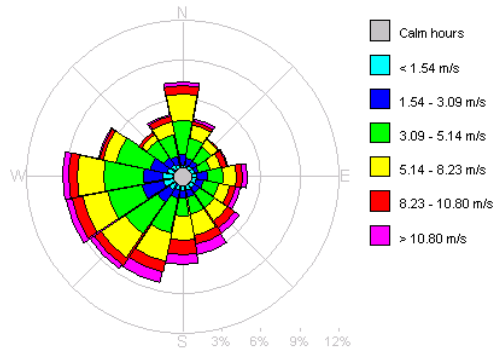
North East Region: Ridings (West)
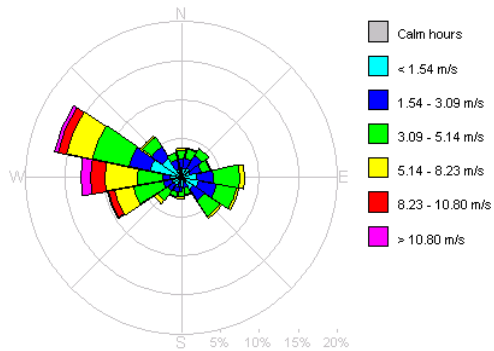
North West Region: South (West)
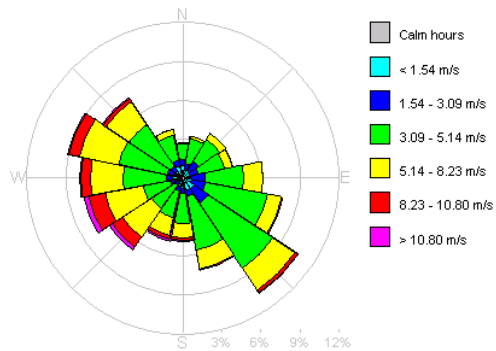
Southern Region: Hampshire
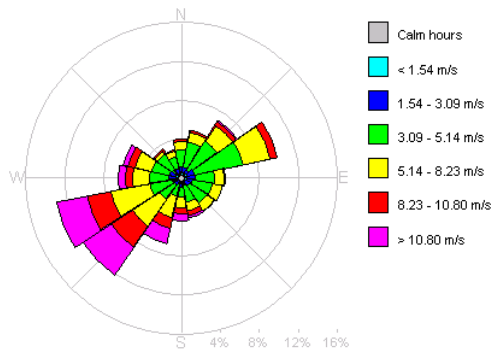
Southern Region: Kent
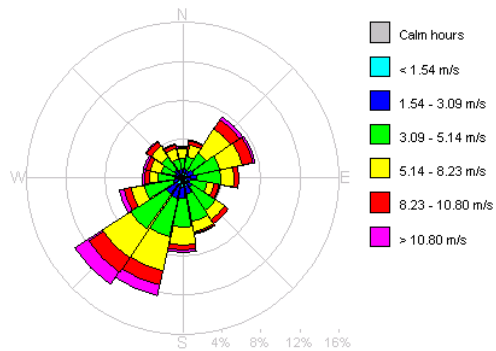
Southern Region: Sussex
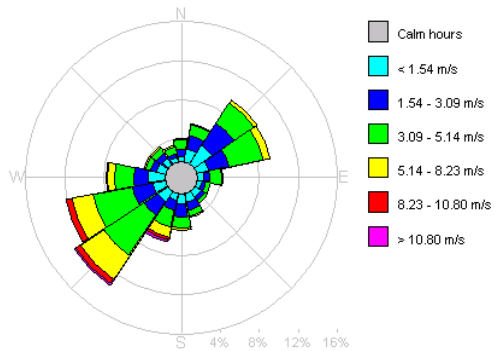
South West Region: Cornwall
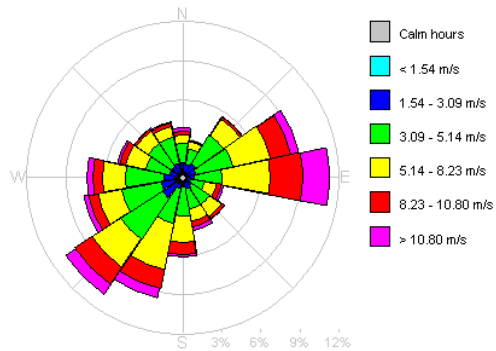
Figure 5.2: Windroses for Default Meteorological Datasets (continued)

South West Region: Devon (North)
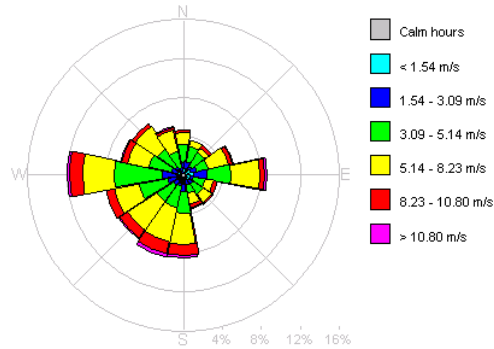
South West Region: Devon (South)
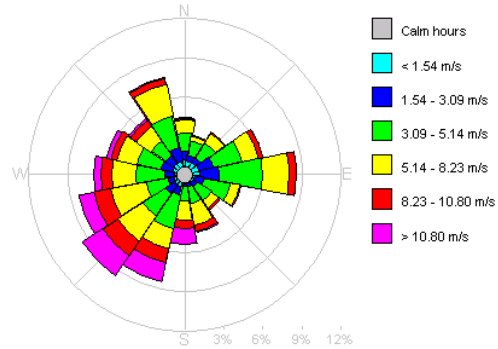
South West Region: North Wessex
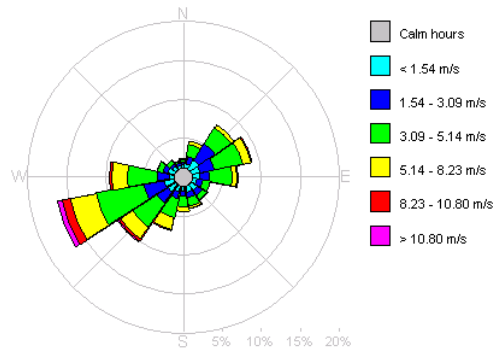
South West Region: South Wessex
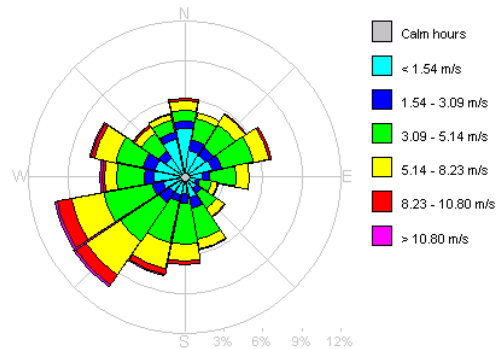
Thames Region: (North & South) East
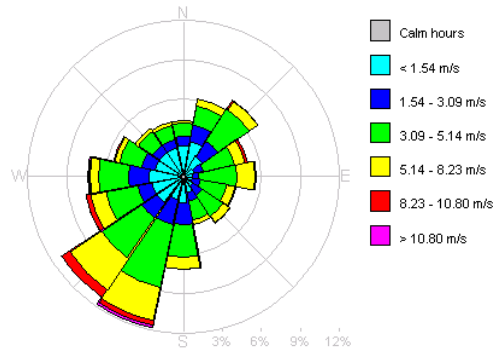
Thames Region: West
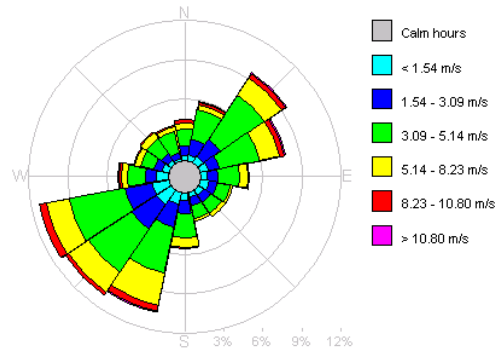
EA Wales: North (East)
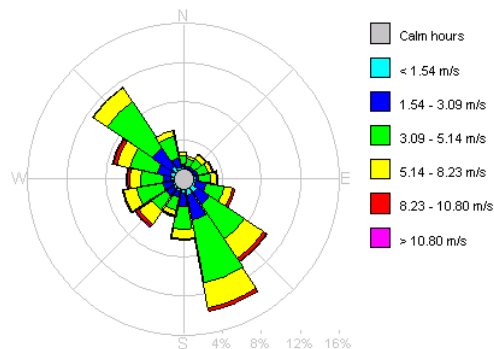
EA Wales: North (West)
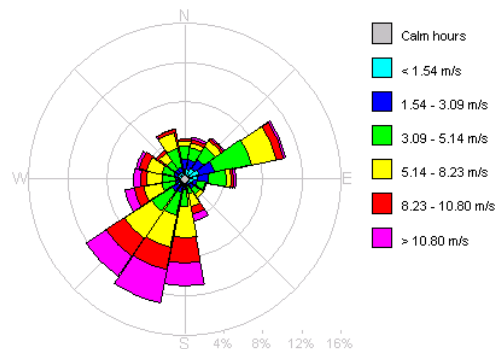
Figure 5.2:   Windroses for Default Meteorological Datasets (continued)

EA Wales: South East
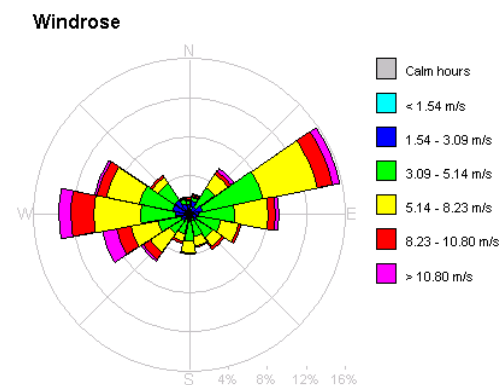
EA Wales: South West
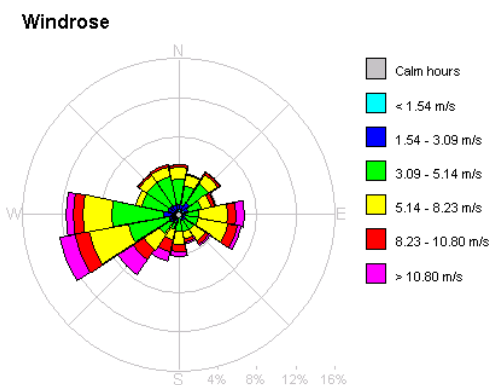
Windrose

Windrose

Figure 5.2: Windroses for Default Meteorological Datasets (continued)

Odour Modelling using the Atmospheric Dispersion Module

GasSim2.5 can simulate the dispersion of odour in two ways, by atmospheric dispersion of 1) individual odorous species and 2) the overall odour concentration, expressed in odour units per cubic metre. The odour threshold can be used to determine the point at which the odour is no longer detectable for the selected species. Values of the odour thresholds of the species of odorous trace gases in GasSim2.5 are provided in Table 5.19 below. These individual values have been taken from AEA Technology (1994), AERC (2000) and Devos *et al.* (1990). It should be noted that there are combinations of compounds that may exhibit either synergistic or antagonistic effects on the overall odour unit value. This factor has not been taken into account in the model, but is considered to be a relatively minor consideration with most landfill gas mixtures.

Table 5.19: Odour Thresholds for Odorous Trace Gases

Compound	Odour Thresholds* (mg/m^3)
Carbon disulphide	7.0×10^{-1}
Diethyl disulphide	3.0×10^{-4}
Dimethyl disulphide	4.0×10^{-3}
Dimethyl sulphide	3.7×10^{-3}
Ethanethiol	4.6×10^{-4}
Hydrogen sulphide	1.0×10^{-4}
Limonene	2.0×10^{-2}
Methanethiol	2.0×10^{-4}
Propanethiol	1.4×10^{-4}
Toluene	7.0×10^{-1}
Xylene	5.4×10^{-1}
Odour Units	1.0 (Ou)

* Odour Thresholds Best Estimate Reported Value (AEA, 1994 and 1997) Manual on Odour Assessment - AEA Technology 1997. Guidance on the emissions from different types of landfill gas flares. Report No. CWM 142/94A and Odour Measurement and Control an Update – AEA Technology 1994 (AEA/CS/REMA-038). Devos M., Patte F., Rouault J., Laffort P. & Van Gemert L.J. (1990) Standardized human olfactory thresholds. Oxford University Press.

GasSim also allows the dispersion of odour units. The source term contains an estimate of the quantity of odour units in LFG. This is destroyed at 99% efficiency in the gas management plant, but is not destroyed through surface emissions. An Odour Unit (as defined in the European standard: Air Quality – Determination of odour

concentration by dynamic olfactometry) is the amount of (a mixture of) odorants present in one cubic metre of odorous gas (under standard conditions), which can be detected by 50% of the members of an odour panel.

It should be noted that currently in the UK there are no statutory standards or objectives for assessing odour nuisance. On this basis, over all odour benchmark levels are typically based upon guideline documents of *Additional Guidance for H4 Odour Management – How to comply with your environmental permit* (Environment Agency March 2011).

GasSim2.5 uses a stringent 1 OU_E/m^3 for a default odour threshold in the modeling.

Lateral Migration

 'Lateral Migration' is simulated using an advection-diffusion equation, with the advection term calculated from the lateral emissions from the landfill, and diffusion from the limiting permeability of the liner, coupled with the 'Geosphere' 'Moisture Content' and 'Geosphere' 'Porosity' data inputted within the 'Landfill Characteristics' screen, and the 'Air Diffusion Coefficient' inputted on the lateral migration screen. The first three parameters depend on the medium through which the gas is travelling and therefore should be determined on a cell-specific basis or should be obtained for a hydrogeological textbook. The 'Air Diffusion Coefficient' for carbon dioxide and methane simulated by GasSim2.5 is provided in Table 5.20.

Table 5.20: Air Diffusion Coefficients for GasSim Species

Species	Air Diffusion Coefficient (cm^2/s)
Carbon dioxide	0.1613
Methane	0.2192

The selection of a receptor or the 'Maximum Distance' determines the extent at which GasSim2.5 will simulate lateral migration; increasing the distance will increase the simulation time. Should a receptor not be selected, we recommend that the maximum distance is initially set at 100 m and then refined once the initial simulation has been run.

Global Impact

The compounds used to determine the 'Global Warming Potential' (GWP) and 'Ozone Depletion Potential' (ODP) can be defined by the user. However, a number of GWPs and ODPs for species commonly of interest have been included as defaults (Table 5.21). The theory behind this is discussed in Chapter 6.

Table 5.21: Ozone Depletion and Global Warming Potentials

Species	CFC/HCFC No.	Ozone Depletion Potential	Global Warming Potential
Carbon dioxide			1
Methane			21
Chloroform			4
Dichloromethane (methylene chloride)			9
1-Chloro-1,1-difluoroethane	HCFC-142b	0.065	2300
Chlorodifluoromethane	HCFC-22	0.055	1900
Chlorofluoromethane	HCFC-31	0.020	
2-Chloro-1,1,1-trifluoroethane	HCFC-133a	0.060	
Chlorotrifluoromethane	CFC-13	1.0	14000
Dichlorodifluoromethane	CFC-12	1.0	10600
Dichlorofluoromethane	HCFC-21	0.040	
1,1,1,2-Tetrafluorochloroethane	HCFC-124	0.02-0.04	620
Trichlorofluoroethane (freon 113)	HCFC-131	0.007-0.050	
Trichlorofluoromethane	CFC-11	1.0	4600
Trichlorotrifluoroethane	CFC-113	0.8	6000
1,1,1- Trichlorotrifluoroethane	CFC-113	0.80	6000

From DTER – Climate Change -draft UK Programme (2000), Stoddart et al 1999 and WMO (1998)

CHAPTER 6: THEORY BEHIND GASSIM2.5 (CALCULATIONS)

6.   THEORY BEHIND GASSIM2.5

This chapter contains the assumptions made, the equations used and any simplifications adopted in the development of GasSim2.5.

Overview of the Model and Model Theory

General

A complete LFG risk assessment follows a source-pathway-receptor methodology that is simulated in GasSim2.5 by various modules (see Figure 6.1):

- Landfill characteristics (source term).
    - Infiltration;
    - Waste Source Term;
    - Landfill Cap And Liner Engineering;
    - Cap Oxidation Of Methane; And
    - Gas Management.
- Environmental transport (pathway).
    - Tier 1 screening;
    - Tier 2 atmospheric dispersion; and
    - Lateral migration.
- Environmental impact.
    - Local Impacts; and
    - Global Impact.

GasSim2.5 considers the uncertainty in processes, models and parameters, focusing on the impact of landfill gas on the identified receptors. GasSim2.5 does not simulate the catastrophic impacts associated with inundation of floodwater, earthquake or collapse of underlying mine workings. Additionally, GasSim2.5 environmental transport and environmental impact modules have a minimum time step of one year and therefore cannot simulate lateral migration associated with sudden drops in atmospheric pressure. GasSim2.5 does, however, assess short-term exposure by the atmospheric dispersion pathway.

In this chapter we discuss the processes and models that produce the equations coded into GasSim2.5. GasSim2.5 does not consider the movement of landfill leachate or LFG dissolved in water, only LFG generation, utilisation, movement and impacts are considered in the model. GasSim2.5 produces possible concentrations of species in LFG and simulates their transport.
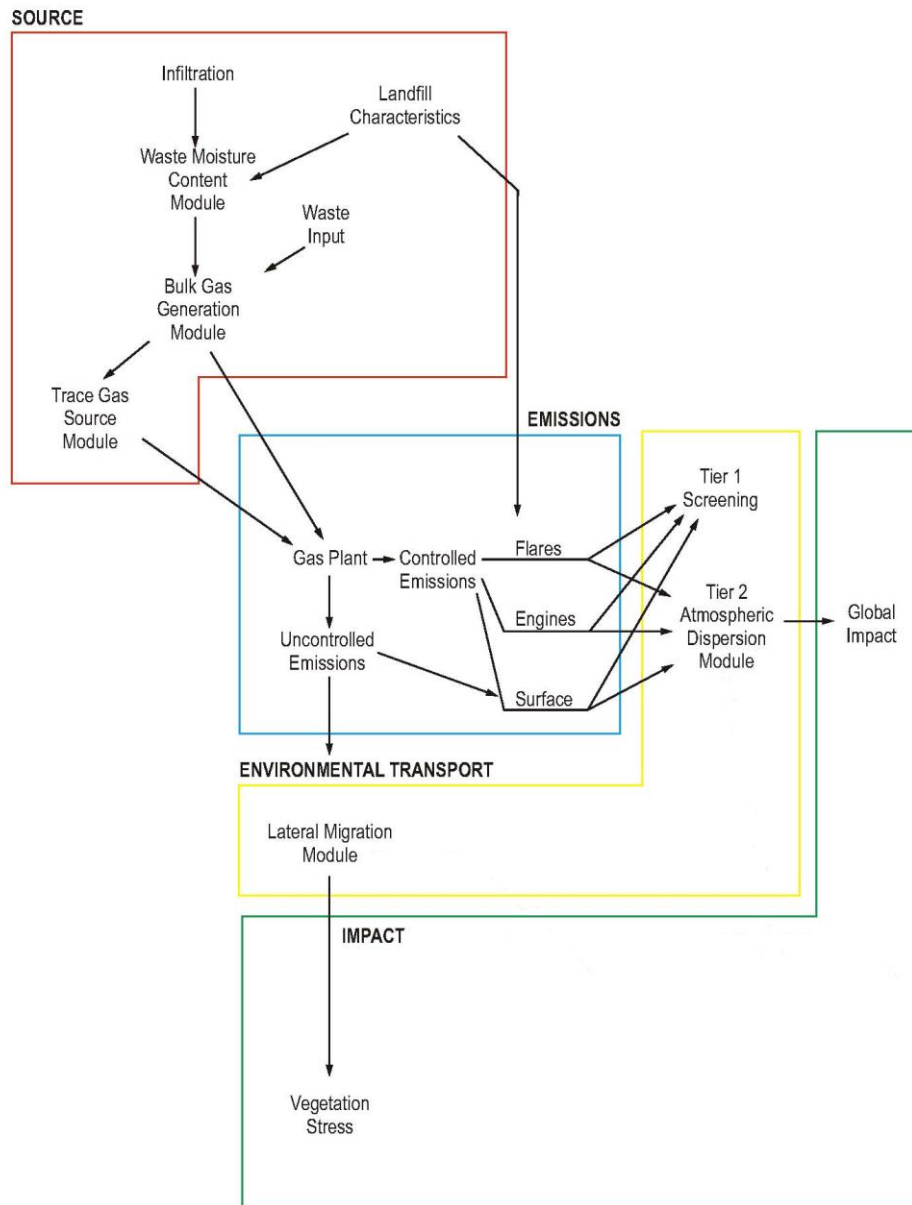
Figure 6.1: GasSim Modules

The GasSim2.5 modules are able to:

- Calculate the moisture content of the waste from the infiltration rate, leachate conditions, waste hydraulic properties and hydrogeological characteristics;

- Calculate the LFG generation rate for bulk gases (CH_4, CO_2, H_2) using the waste quantity, breakdown/composition, the rate of decay, moisture content and the emission ratio of CH_4 to CO_2;

- Calculate the trace gas concentrations by determining the volume of bulk gas generated, the concentration of trace gas monitored in 1 m^3 of LFG and the half-life of trace gases;

- Calculate the volume of gas that is utilised by flares and engines, and thus determine the emissions from these processes and the uncontrolled emissions through the liner and cap;

- Simulate biological methane oxidation, including or excluding the presence of fissures in the cap;

- Calculate the migration of the gas from lateral emissions through the unsaturated pathway;

- Determine the potential for vegetation stress adjacent to the landfill;

- Calculate the atmospheric dispersion of flare, engine and surface emissions;

- Determine the potential for the emissions of odorous compounds and odour units and their atmospheric dispersion;

- Determine the risk to the global atmosphere; and

- Estimate PI emissions.

Model Operation

GasSim2.5 considers the landfill as a series of cells. These can exhibit different gas generation properties due to different waste types and rates of filling as different emissions characteristics dependent upon capping, gas collection, and the relationship between adjacent cells.

The source term determines the generation of LFG for an individual site based on the mass of waste deposited and the waste composition of the waste stream or streams. The waste is degraded following a first-order decay model that calculates the LFG generation for up to 200 years using multi-phase equations. The emission model takes this output and uses it to calculate the LFG emission of bulk and trace gases to the environment after allowing for LFG collection, flaring, utilisation (energy recovery), and biological methane oxidation. This calculation is undertaken by using information on the site gas collection system, flare, engine, and engineered barriers (cap and liner), if present. It is assumed that LFG generated and not collected is in equilibrium and will be emitted from the landfill cap or liner at a steady state. Additionally, the model calculates the concentrations of other major and trace gases emitted from the landfill surface, landfill sides, flares and engines.

The environmental transport equations simulate the dispersion of emitted LFG via both atmospheric dispersion and lateral migration. Atmospheric dispersion is modelled to determine the concentration of the species in the air for a given hour or for an annual average exposure. GasSim2.5 simulates off-site dispersion using AERMOD, assessing the impact of emissions from engines, flares and the landfill surface.

Lateral migration simulates the transverse migration of landfill gas through the unsaturated subsurface by advection and diffusion. The geosphere has been simplified into one zone, which is simulated using a conservative 1-dimensional linear pathway to provide the maximum concentration at a given point. The gas concentrations along the pathway are then used to determine the potential for vegetation stress and the exposure to humans, including the migration into buildings.

The impact to the global atmosphere is assessed by determining the global warming potential and ozone depletion potential of the emissions.

Source Term

Waste Moisture Content

GasSim2.5 calculations begin with the determination of the waste moisture content. GasSim2.5 assumes that the waste moisture content is derived from infiltration through the landfill cap or uncapped landfill surface, leachate conditions, the waste hydraulic properties and hydrogeological characteristics (as detailed in Chapter 3). GasSim2.5 assumes that the infiltration rates and leachate levels are cell-specific. The determination of the effect of infiltration and drainage systems on the depth of the leachate head is beyond the scope of GasSim2.5 and therefore this should be determined before running GasSim2.5, perhaps using a model like LandSim. The infiltration rate through the landfill cap is dependent on the effective rainfall and cap design. The determination of the infiltration rate is also beyond the scope of GasSim2.5.

Precipitation, and therefore, infiltration through the capped and uncapped area of the landfill generally follow a normal distribution; therefore a mean value and a standard deviation are required to define the distribution. This information can be obtained from Meteorological Office records or the on-site meteorological station.

The waste moisture content, free void space and the effective saturation of the waste are determined by using a relatively simple water balance calculation (Figure 6.2).

The model then defines different categories of the waste moisture content:

- Saturated - greater than 80% v/v moisture;
- Wet - greater than 60% (v/v) moisture;
- Average - greater than 30% and less than 60% moisture; and
- Dry - less than 30% (v/v) moisture.

Alternatively, if the waste moisture content is known the moisture category can be entered directly. However, the determination of the waste moisture content should be carried out with care, as this is a key factor controlling the waste degradation and thus LFG production, as it is used to determine the waste degradation constants used.

This approach can be bypassed and the waste moisture content and hence waste degradation rates can be selected by the user. This is the typical way in which a GasSim2.5 model is calibrated against site data.

Figure 6.2: Waste Moisture Content Calculation

Landfill Gas Generation

Gas generation is determined using a multi-phase first order LFG generation equation, developed by the HELGA framework (Gregory *et al*., 1999) (Figure 6.3). This model was originally based on the scientific studies of the Agriculture and Food Research Council (1988), and models developed by Hoeks and Oosthoek (1981) and van Zanten and Scheepers (1996). However, the GasSim2.5 multi-phase equation is a significant improvement on these as it can:

- Define precisely the mix (breakdown), composition and moisture content of waste in the landfill site;
- Calculate LFG generation based on the degradation rates of the individual materials in the landfilled waste; and
- Calculate LFG generation on a cell-by-cell basis.

These additions make the GasSim2.5 multi-phase equation highly flexible and allow it to be tailored to individual landfill sites, taking account of specific waste streams, filling/deposition rates and environmental conditions.

The source model has two main processes that are initially identical, irrespective of the decay equation:

- Defining the waste in the landfill site; and
- Calculating carbon available for decay from a specified mass of waste.

Figure 6.3: Bulk Gas Source Term Model

Defining the Waste Mass and Volume

GasSim2.5 simulates the landfilling process by the user defining the month/year that deposition commenced, and then entering a mass of waste disposed for each operational year. Simulating the gas generation using the multi-phase equation also requires the breakdown of the waste using the various waste streams (described below) to be defined for each year of deposition.

Defining the Waste

The breakdown and composition of the waste within the landfill site will affect the rate of generation and total yield of LFG produced, which is determined by the mass and degradability of the cellulose and hemi-cellulose in the waste. However, the ultimate degradability of cellulose polymers differs between waste materials. Different biodegradable materials have different quantities of cellulose and hemi-cellulose, and different waste streams have different compositions (as discussed in Chapter 3). Therefore, GasSim2.5 uses the total waste composition of the different waste streams to determine the mass and degradability of cellulose and hemi-cellulose (discussed below).

GasSim2.5 only models the decay of cellulose and hemi-cellulose, which are known to make up approximately 91% of the degradable fraction of non-source-separated MSW (Barlaz *et al*., 1989). It ignores other potentially degradable fractions that do not contribute significantly, e.g. protein and lipids that normally make up only a small proportion of MSW.

The user characterises the waste deposited by defining the proportion/breakdown of the waste in different default waste streams or by defining their own waste streams, each year for the duration of filling.

Defining the Emissions Ratio

The ratio of methane to carbon dioxide in LFG is used to determine the quantity of methane and carbon dioxide produced by methanogenic decay, which is a site-specific parameter and therefore is user defined.

Data Manipulation

GasSim2.5 uses the data above to calculate the:

- Percentage of each component in the waste;

- Dry weight of each fraction;

- Dry weight of the waste;

- Cellulose and hemi-cellulose content of the waste;

- Degradable carbon content of the waste;

- Fraction of rapidly, moderately and slowly degradable carbon in the waste;

- Conversion of carbon to LFG; and

- LFG (methane, carbon dioxide and hydrogen) production from the waste (hourly, monthly, yearly and cumulatively).

This calculation is undertaken by combining the waste streams into a yearly waste source. Each waste stream is divided into components, i.e. the proportion of paper, garden waste and non-degradable waste. The composition and the waste moisture content of each fraction are then used to calculate the weight of each component and the total amount of waste deposited each year.

The yearly cellulose and hemi-cellulose content of the waste is then determined, using the makeup of the waste fractions along with the proportion of the waste that can degrade. The waste is also partitioned into three fractions that are degraded at different rates (Table 6.1), depending on the degree of lignification of cellulose in the material.

Table 6.1: Degradation Rate Assigned to Each Waste Fraction

Degradability	Fraction
Rapid	Incinerator Ash Sewage Sludge 10 mm fines Other putrescibles Garden Waste
Moderate	Composted Organic Material Other misc. Combustibles Disposable Nappies
Moderate/Slow	Wood (75% / 25%) Other Card (25% / 75%) Card Packaging (25% / 75%) Liquid Cartons (25% / 75%) Other Paper (25% / 75%) Magazines (25% / 75%)
Slow	Newspapers Textiles

The dry weight of carbon available for degradation for each fraction is determined for each year. The model then assumes the each fraction degrades by first order decay at a specific rate. This allows putrescible waste to be degraded at a faster rate than wood or paper.

Biodegradation

GasSim2.5 simulates biodegradation during the aerobic (acetogenic) and anaerobic (methanogenic) stages. This is carried out individually for each year of waste deposition with the results of all the deposition years aggregated before reporting.

To allow the generation of hydrogen to be simulated aerobic (acetogenic) degradation has been included. This is carried out by the rapid acetogenic decay of 1% of the waste deposited in the year. The remaining 99% of the waste is degraded methanogenically, as discussed below. In the second and subsequent years this waste is only degraded methanogenically. The default value of 1% of the waste degrading acetogenically was validated using the HELGA framework (Gregory et al., 1999), with this producing a maximum concentration of H_2 in LFG of around 10%, which fits with the work of Farquhar and Rovers (1973).

Under anaerobic (methanogenic) degradation, GasSim2.5 assumes that the degradable cellulose and hemi-cellulose are converted to carbon available for degradation.

LFG Production

The production of LFG is determined from the mass of available carbon (1 mole of carbon produces 1 mole of carbon dioxide or methane). The proportion of carbon dioxide to methane for methanogenic degradation is determined using the ratio of 1%, as described in Chapter 5. The quantity of carbon dioxide and hydrogen generated acetogenically is determined by the equation below (Equation 6.1).

$$C_6H_{12}O_6 \xrightarrow{Acetogenesis} 2CH_3COOH + 4H_2 + 2CO_2$$

$$\text{or}$$

$$6Carbon \quad = \quad 2AceticAcid + 4Hydrogen + 2CarbonDioxide$$

$$(6.1)$$
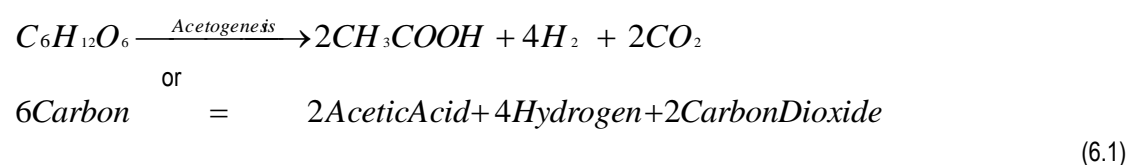
Calculating Landfill Gas Generation

The degradation and biodegradation of organic material is carried out by a multi-phase, first order decay equation (Equation 6.2) that deals with the three degradable fractions separately and aggregates the amount of carbon converted to LFG.

$$C_t = C_0 - \left(C_{o,1} e^{(-k_1 t)} + C_{o,2} e^{(-k_2 t)} + C_{o,3} e^{(-k_3 t)} \right)$$

And $\quad C_x = C_t - C_{t-1}$

$$(6.2)$$

where:

C_t	mass of degradable carbon degraded up to time t (tonnes)
C_0	mass of degradable carbon at time t = 0 (tonnes)
$C_{o,i}$	mass of degradable carbon at time t = 0 in each fraction (1, 2, 3, i.e. rapidly, moderately and slowly degradable fractions, respectively) (tonnes)
C_x	mass of carbon degraded in year t (tonnes)
t	time between waste emplacement and LFG generation (years)
k_i	degradation rate constant for each fraction of degradable carbon (per year)

The rates of decay and degradation half-lives are dependent on the waste moisture content, as a wet waste will degrade at a faster rate than a dry waste. The default decay constants used are discussed in Chapter 5.

Calculating the Trace Gas and VOC Source Term

The concentration of trace gas species can either be entered by the user or using the defaults (discussed in Chapter 3). GasSim2.5 simulates the concentrations of gases as mg/m³. However on-site gas concentrations are normally measured in ppm, these two units can be converted using the following equation (6.3):

$$C_P = \frac{C_{\% v/v}}{100\%} \cdot \frac{(1000 \cdot MW_P)}{(Vm)}$$

$$(6.3)$$

where:

C_p	concentration of species P (mg/m³)
$C_{\% v/v}$	concentration of species P (%v/v)
MW_P	molecular weight of species P (g)
Vm	molar volume (at STP) (2.241×10^{-2} m³/mol)

Using a Declining Source Term

Examination of total VOC emissions from landfills has indicated that the concentration of trace gases emitted from landfills reduce the over time. Therefore, GasSim2.5 simulates the source of traces gases by assuming that these decline over time, following the decay equation (6.4).

$$C_{tg} = C_g . e^{(-k_{tg}t)}$$

(6.4)

where:

C_{tg}	trace gas concentration t (tonnes)
C_g	trace gas concentration at time t = 0 (tonnes)
k_{tg}	decay constant, trace gas half life
t	time between waste emplacement and LFG generation (years)

This declining source was defined by examining the emissions of VOCs in landfill gas from a number of landfills from studies by Knox (1990), Scott *et al*. (1988a, b), Allen *et al*. (1997), Young and Parker (1983), Emberton and Scott (1987), and Jones *et al*. (1988). The data has been analysed using a FITCURVE directive using Genstat 5 Release 4.1 (Third Edition) statistical package (Genstat 5 Committee, 1993) to fit a standard non-linear regression model (Figure 6.4). This directive estimates the model's only non-linear parameter, r, which defines the rate of exponential decrease of VOCs with time. The other linear parameters (a and b) are estimated by linear regression at each stage of an iterative search for the best estimate of r.

This method provides the estimated parameter and error (standard error) values listed in Table 6.2. This fit is statistically significant (P<0.001).

Table 6.2: Fitted Parameter Values for the VOC Declining Source Term

Parameter	Estimate	SE
a (mg/m^3)	0	0
b (mg/m^3)	3067	452
R	0.8449	0.054
k* (year^{-1})	0.1685	0.0639

r^2 = 0.21, r = 0.46, n = 48, df = 47, P < 0.001
* k = - ln(r), Δk = Δr/r

Total trace components as a function of average landfill age

Genstat fitted curve
$y = 3067 (\pm 452) \, e^{-(0.1685 \pm 0.0639) t}$
$R^2 = 0.23$
$t_{1/2} = 4.11 \pm 1.56$ years

Legend:
- observed data
- Genstat fitted curve
- 95% CI
- -95% CI

Axis labels: total VOCs (mg/m3) (y-axis), times (years) (x-axis)
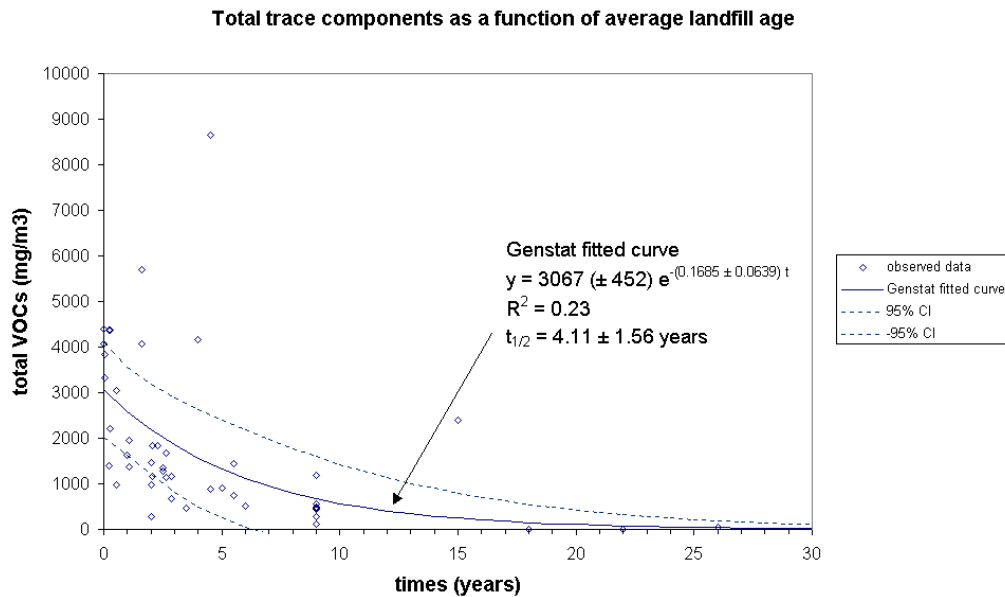
Figure 6.4: Total VOCs Declining Source Term

Simulating a Constant Source Term

Simulations can be undertaken using a conservative constant source term by limiting the rate of trace gas decay, i.e. by defining the decay half life as a large number of years (e.g. 100,000 years).

Emission Model

The emissions from a landfill are normally, but not always, controlled by engineering measures, i.e. the installation of engineered barriers (cap and liner) and gas collection system (Figure 6.5). The gas collected can then be flared or utilised by spark ignition engines to produce electricity. GasSim2.5 uses the information provided on these engineering measures to determine the quantity of uncontrolled LFG releases through the surface, the cap, and/or lateral emissions, through the liner. The model assumes that any LFG generated and not collected is in equilibrium and will be emitted through the landfill cap or liner at steady state conditions. Additionally, GasSim2.5 estimates the surface and lateral emission of trace gases, using either default or user defined values, and the atmospheric emissions from flares and engines, using destruction efficiencies and/or flare/engine exhaust data.
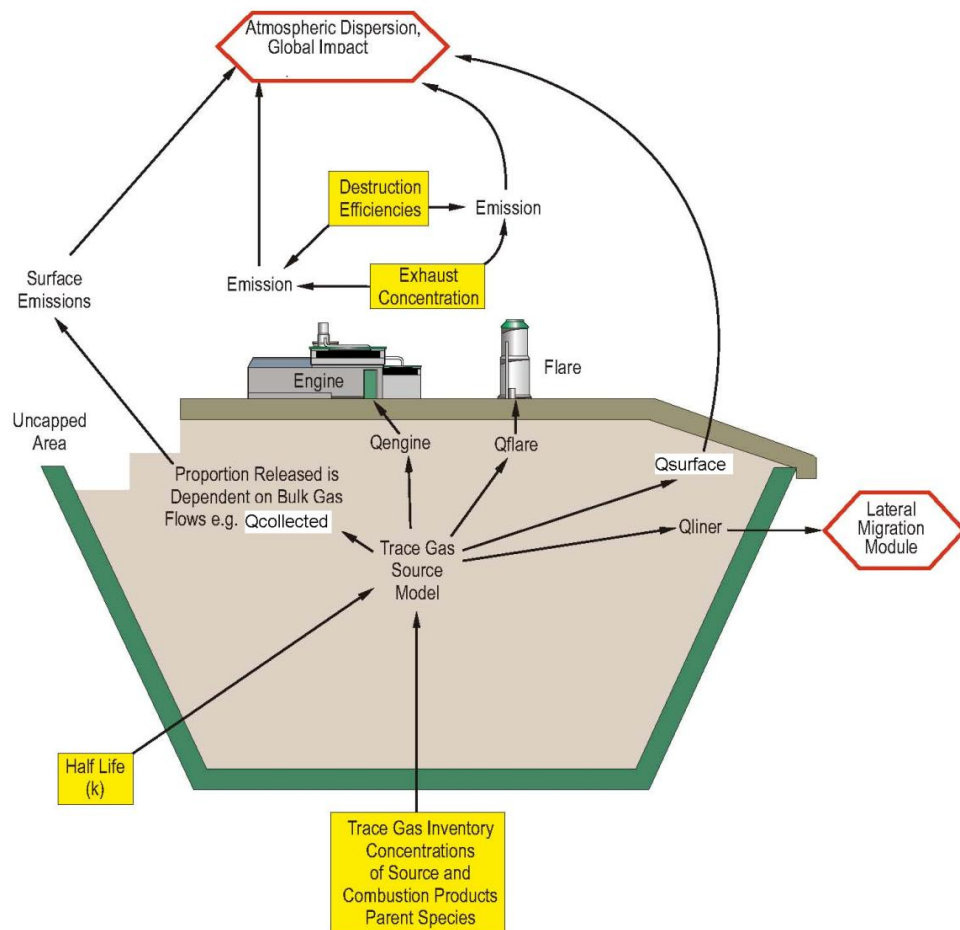
Figure 6.5: Bulk Gas Emissions Model

GasSim2.5 simulates the LFG abstraction by determining the available engine and flare capacity per year and using the collection efficiency of the system and the engine/flare down time to determine the maximum quantity of gas that can be abstracted. If this is greater that the gas generation rate all of the gas, except for the quantity that cannot be collected due to collection efficiency not being 100%, or the engine/flare not operating due to downtime, will be utilised or flared. When the maximum quantity of gas that can be abstracted is less that the amount of gas generated, residual gas will be lost uncontrollably.

The emission model manipulates the data provided by the source model along with the information provided in the Gas Management dialogue box to determine the following for up to a 200 year assessment period:

- Volume of LFG that can be utilised by engines;
- Volume of LFG that can be flared; and
- Volume of LFG lost in uncontrolled emissions:
  - o   Through the cap; and
  - o   Through the liner.
- Methane oxidation in the cap.

Capped and Uncapped Areas

The LFG generated by the source model is split into the proportions generated by the variously capped and uncapped cells of the landfill. This is simulated by the user defining the dates for which each cell is temporarily and permanently capped, with or without sacrificial or permanent gas management systems, therefore allowing the calculation of the proportion of capped and uncapped areas for each year being simulated (Equation 6.5).

This is a slight over simplification of the actual situation and assumes that all the LFG emitted from the uncapped areas is through the surface and open sides of the uncapped areas, i.e. the vertical sides of the modelled caps behave as their surfaces are defined, and that gas generated in the capped areas is not emitted through the uncapped sides of the adjacent operational area.

$$Q_{gen} = Q_{genCapped} + Q_{genUncapped}$$

(6.5)

where:

Q_{gen} LFG generated by the source model (m^3/hr)

$Q_{genCapped}$ LFG generated in the capped proportion of the landfill (m^3/hr)

$Q_{genUncapped}$ LFG generated in the uncapped proportion of the landfill(m^3/hr)

Gas Collection

The gas collection system will extract gas from those cells that the user has defined as emitting combustion gases within the 'cell details' dialogue box. Collection efficiency within cells will vary depending on the system in place, defined within the 'cap and liner data' dialogue box. GasSim2.5 allows the option for a sacrificial gas collection system, often put in place during operation of the landfill and whilst only a temporary cap has been placed on the waste. A permanent gas collection system, installed after restoration of the site, allows for more efficient collection of gas. The user has defined dates for installation of one or both of the gas collection systems for each cell.

GasSim2.5 assumes gas is collected and then either flared or utilised for energy recovery using spark ignition or duel fuel engines for electricity generation at a set efficiency and within a maximum and minimum rate. A fourth option for other gas management technology exists where for instance, gas turbines, micro-turbines, or Voxciboxes could be simulated.

The gas collection system is set up to simulate normal operational practices using one of the following options:

- Commission the engine and flares in the order that they are displayed on the screen ('User Defined');
- Commission the engines first with gassim2.5 determining the optimum order, with excess LFG being flared ('Engines First');
- Commission the flares first with GasSim2.5 determining the optimum order, with excess LFG being utilised by the engines ('Flares First'); and
- Run the simulation without gas utilisation by selecting 'No Engines or Flares'.

However, it should be remembered that GasSim2.5 calculates the available gas removal capacity using engines and flares that are operational, i.e. those that have been commissioned and have not been decommissioned.

The gas collection potential is depended on the LFG generated by the source model and gas collection efficiency and can be determined by Equation 6.6

$$Q_{collection\ potential} = Q_{gen}\ x\ (CF/100)$$

(6.6)

where:

Q_{gem} LFG production (m^3/hr)

CF   LFG collection efficiency (%)

The maximum capacity of the gas plant is then calculated using the above information (the gas collection potential) along with capacity of each engine and/or flare and number of flares and/or engines, allowing for downtime. It is assumed that where multiple flares and/or engines have been specified that new engines/flares will be brought on line when sufficient gas is available and removed when insufficient gas is available. The minimum collected gas is determined by the lowest abstraction rate for a flare or engine. The concept of downtime determines the yearly operational collection rate for each engine or flare by accounting for the proportion of time that they are not operational due to routine maintenance and breakdown. This involves a simple calculation of reducing the yearly capacity for each engine/flare by the downtime percentage, e.g. a 500 m^3/hr engine with 10% downtime will remove on average 450 m^3/hr.

It is assumed when flaring, if gas is produced at a rate between the maximum capacity and reduced capacity allowing for downtime, the operation of the flare will be trimmed to follow the trance of the gas production curve. This is a fairly good assumption as in reality it is trimmed to the point at which air is drawn into the system. If gas collection potential is above the maximum flare capacity after accounting for downtime then the excess LFG will be released uncontrollably, and if gas collection potential is below the minimum flare capacity at which the flare will not operate any gas generated will be released. It should also be noted that in practice no system is 100% efficient, and therefore a quantity of gas will always be emitted.

The uncollected LFG that is emitted by uncontrolled emissions from site can then be determined by Equation 6. 7.

$$Q_{uncontrolled} = Q_{gen} - (Q_{flared} + Q_{utilisation})$$

(6.7)

where:

$Q_{uncontrolled}$ Uncontrolled emissions through surface and/or lateral emissions (m^3/hr)

Q_{gen} LFG generated in the landfill (m^3/hr)

C_{flare} LFG being flared (m^3/hr)

$C_{utilisation}$ LFG being utilised by Engine (m^3/hr)

Surface and Lateral Emission Routes

The presence of uncollected gas in the capped area (Q_{res}) will result in uncontrolled emissions from the cap and/or the liner. The quantity of emission through both the cap and liner are determined by the permeability and thickness of the most impervious layer within each construction. GasSim2.5 assumes that gas movement is via plug flow and that both the cap and liner are homogenous and isotropic, even through in practice poor cap/liner construction and maintenance can result in cracks and micro-fractures. However, although these may be locally important their net effect on the emissions will be averaged out across the site. These emissions are calculated on a cell-by-cell basis. The uncontrolled emissions are calculated in GasSim2.5 from the:

- Cap design;
- Cap hydraulic conductivity;
- Cap thickness;
- Waste thickness;
- Waste hydraulic conductivity;
- Liner thickness;
- Liner hydraulic conductivity;
- Cell dimensions; and
- Relative vertical height of adjacent cells.

In some cases the most impervious layer could be the waste itself, which is also assumed to be homogenous and isotropic. If this is the case then the waste thickness is assumed to be half the average total waste thickness.

GasSim2.5 defines the proportions of surface emissions and lateral emissions from the landfill on a cell-by-cell basis. Commonly surface emissions will occur from the upper surface of the cap or directly from the waste if the cell is operational. However, in addition surface emissions will occur along the capped or uncapped vertical face of the cells adjacent to an operational cell where void space remains.

In cases where adjacent cells have differing geometries and waste input volumes and where one cell is filled to a greater height than an adjacent one, surface emissions can also occur from the vertical sides of the adjacent cell.

Lateral emissions are calculated by GasSim2.5 considering that the gases can only migrate from a cell to outside of the landfill through the cell outer perimeters adjacent to the landfill site boundary. It is assumed that there is no lateral emission or movement between cell internal faces.

The emissions of LFG can be calculated using Darcy's law, for a homogeneous medium. The emissions from the cap and the liner are calculated at the same time, as the excess gas (Q_{res}) will be emitted at different proportions through each medium (Equation 6.8). The equation has been modified from the original HELGA framework by the inclusion of the surface area.

$$Q_c = \frac{Q_{res}}{\left(\frac{d_c}{K_c.A_c} \cdot \frac{K_l.A_l}{d_l}\right)+1}$$

$$Q_l = \frac{Q_{res}}{\left(\frac{d_l}{K_l.A_l} \cdot \frac{K_c.A_c}{d_c}\right)+1}$$

(6.8)

where:

Q_c	flux from cap (l = liner) (m^3/hr)
Q_{res}	residual LFG production (m^3/hr)
K_c	effective permeability of cap (l = liner) (m/s)
d_c	thickness of cap in direction of flow (l = liner) (m)
A_c	surface area of cap in the direction of flow (l = liner) (m^2)

The surface area of the liner is determined from the cell perimeter and the depth of the unsaturated zone within the cell. It is assumed that LFG is not dissolved in the landfill leachate.

The depth of the unsaturated zone is determined by considering the cell leachate level and the water table level surrounding the landfill site, whichever the level that is closer to the ground surface is used in the calculation of the depth of the unsaturated zone. It is assumed that the water table levels at all sides of the landfill are all the same.

The gas produced from the uncapped area ($Q_{resUncapped}$) will all be emitted through the surface as it is assumed the open surface of the waste will be far more permeable that the landfill edge, which may or may not be engineered.

Biological Methane Oxidation

Any landfill gas that is not collected by the gas collection system has the potential to migrate through the cap and laterally through the liner of a landfill, no matter what the design of the lining system. The lateral migration pathway does not simulate methane oxidation since the off-site conditions would be difficult to quantify and thus the model generates a conservative estimate of lateral methane migration. The potential for methane oxidation in the cap is however much better understood, and this is a good secondary methane management system for the residual landfill gas for a site under abstraction, and also for a site generating sufficiently little gas that a gas abstraction system is not able to be used successfully due to the low rate of generation or low calorific value of the gas.

The process is a four stage bacteriological conversion of methane into carbon dioxide (Equation 6.9):

$$CH_4 \rightarrow CH_3OH \rightarrow HCHO \rightarrow HCOOH \rightarrow CO_2$$

| methane | methanol | methanal | methanoic acid | carbon dioxide |

(6.9)
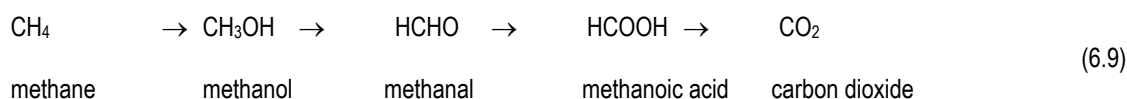
Methanotrophic bacteria use these reactions to gain energy and carbon for their growth (Hanson and Hanson, 1996). Methane oxidation has been linked to the two main types of methanotrophic bacteria (Borjesson at al., 1998) but not in any easily interpreted mechanistic fashion. There are data on field-based observations, which appear to show a seasonal relationship over many orders of magnitude. Laboratory scale observations of conversion of methane to carbon dioxide, which are more likely to be at favourable conditions, i.e. close to the theoretical maximum which biological activity can attain in the soil medium. There are also data on the estimates of the rate of methane oxidation in soil covers using ^{13}C analysis, which gives a measure of the fraction of methane that is actually converted. An empirical approach has to be derived from existing data. Therefore, the best way to represent methane oxidation in the GasSim2.5 model from a scientific perspective is to use known methane oxidation rates in different cover materials and in-situ conversion efficiencies in order to develop an empirical equation for the removal of methane from landfill gas emitted through the surface.

Alternatively, the GasSim2.5 model provides for a default value based on the Intergovernmental Panel on Climate Change (IPCC) (1996) guidelines for methane oxidation. The choice of which option is used for an assessment should be agreed with the regulator prior to commencement. Both approaches are described below.

The Empirical/Scientific Method

This method is based on laboratory estimates of methane oxidation and in-situ estimates of percentage methane oxidised. It is considered that the combination of the two sets of data makes this approach conservative.

Estimates of the fraction of LFG which could be oxidised by methanotrophic bacteria and which actually is oxidised range from 10 – 46% (Borjesson et al., 2000). The GasSim2.5 model assumes a mean value of 25% and a normal distribution between 10 – 46% based on the data presented in that reference.

In addition, it is believed that there must be a limiting rate of methane oxidation for a given soil thickness and type. Methane oxidation occurs predominantly in the upper 50 cm of soil cover where oxygen ingress is facilitated, and appears to be strongest in the zone 20 – 30 cm below the surface. The default figures that are used in GasSim2.5 will be suitable for a soil cover >30 cm thick overlying a single liner, clay or composite cap. Below 30 cm thickness of soil on these engineered designs, or below 1 m thickness of soil if no engineered cap is present, the GasSim2.5 model will switch off all methane oxidation, on the basis that the surface soil cover is insufficiently thick to permit a significant amount of methane oxidation to take place.

It is also known that measured rates of soil methane oxidation capacity are remarkably consistent in their observed range. However, the frequency per year at which the highest rates may apply is not known, and so the shape of the PDF for the oxidising potential is unknown. These high values are probably summer conditions, and so the

10 – 40% factor discussed above is applied to a normal distribution to give an estimate of the overall flux rate at which all the methane may be converted to carbon dioxide. The range of values in both parameters is used to help account for seasonal variation in methane oxidation, which is highest in the summer months.

At all landfill sites, some landfill gas will escape through cracks and fissures and joints in the landfill engineering/gas field infrastructure. The GasSim2.5 default for this quantity of gas lost is 10% of the total landfill gas that could be lost through the surface in any given year. This value can also be measured using the Environment Agency's methane emissions measurement protocol (Environment Agency, 2010d).

If potential landfill methane emissions (methane beneath the cap) are below the oxidising capacity of the cap under field conditions, then no methane (other than that lost through fissures etc.) is released to the atmosphere. If potential landfill methane emissions exceed the oxidising capacity of the cap under field conditions, then only the methane lost through fissures and the excess methane flux through the cap is released, the remainder being converted to carbon dioxide. Table 6.3 lists the typical ranges and means recorded in the literature, and converts them to standard units.

The quantity (i.e. flux) of methane oxidised to carbon dioxide (Q_{ox}) and the calculated methane flux ($Q_{methane\ flux}$) in a given year, for >30cm soil cover above an engineered cap is defined below (Equations 6.10 to 6.12).

If:

$$\Delta_{field\ efficiency} \cdot (Q_{oxidising\ capacity} \cdot 24 \cdot 365) > (1 - \Delta_{fissure}) \cdot (Q_{base\ of\ cap})$$

(6.10)

then:

$$Q_{ox} = (1 - \Delta_{fissure}) \cdot (Q_{base\ of\ cap})$$

$$Q_{methane\ flux} = (\Delta_{fissure} \cdot Q_{base\ of\ cap})$$

(6.11)

otherwise

$$Q_{ox} = \Delta_{field\ efficiency} \cdot (Q_{oxidising\ capacity} \cdot 24 \cdot 365)$$

$$Q_{methane\ flux} = (\Delta_{fissure} \cdot Q_{base\ of\ cap}) + (1 - \Delta_{fissure}) \cdot (Q_{base\ of\ cap} - \Delta_{field\ efficiency} (Q_{oxidising\ capacity} \cdot 24 \cdot 365))$$

(6.12)

where:

Q_{ox}	total quantity of methane oxidised to carbon dioxide (m³/y)
$Q_{base\ of\ cap}$	total quantity of methane at base of cap for surface emission (m³/y)
$Q_{oxidising\ capacity}$	soil oxidising capacity ($m^3 m^{-2} hr^{-1}$)
$\Delta_{fissure}$	empirical correction factor for fraction of methane lost directly through fissures
$\Delta_{field\ efficiency}$	empirical correction factor for effectiveness of oxidation under field conditions

Table 6.3: Methane Oxidation Capacity of Cover Materials

Conversion of Methane Oxidation Measurements to Standard Terminology							
				Oxidation of Methane in Landfill Cover Materials			
				Raw Data from Reference		Standardised Data	
Reference		Cap Type and Scenario		g/m²/hr	litres/m²/hr	mg/m²/s	m³/m²/hr
Hoecks	1983	Field study	max	0.23		6.39E-02	3.22E-04
			min	2.04		5.67E-01	2.86E-03
Mennerich	1986	Lab study	max	7.3		2.03E+00	1.02E-02
Whalen et al	1990	Lab study, topsoil	max	45		1.25E+01	6.30E-02
Figueroa	1993	Sand cap (lab)	max		5.6	1.11E+00	5.60E-03
			min		0.7	1.39E-01	7.00E-04
Jones and Nedwell	1993	Field study 0 – 32 cm	max July	7.21		2.00E+00	1.01E-02
			min	1.34E-05		3.72E-06	1.88E-08
Kightley et al	1995	coarse sand	max	6.95		1.93E+00	9.73E-03
Boeckx and van Cleemput	1996	soil	max	2.36		6.56E-01	3.30E-03
			min	0.84		2.33E-01	1.18E-03
Borjesson And Svensson	1997	Sand cap 0 – 80 cm	max	6.3		1.75E+00	8.82E-03
			min	1.9		5.28E-01	2.66E-03
		Sandy loam	max	8.7		2.42E+00	1.22E-02
			min	0.14		3.89E-02	1.96E-04
		Sewage sludge	max	16.8		4.67E+00	2.35E-02
			min	1.6		4.44E-01	2.24E-03
Scharff et al	2001	0 – 30 cm	max		5.9	1.17E+00	5.90E-03
			min		0.3	5.95E-02	3.00E-04
			mean		3.0	5.95E-01	3.00E-03
		0 – 100 cm	max		3.8	7.54E-01	3.80E-03
			min		1.0	1.98E-01	1.00E-03
			mean		2.6	5.16E-01	2.60E-03

The IPCC Method

The recommended default value provided by the IPCC Expert Group on Waste is that 10% of methane passing through a landfill cap is oxidised. It should be noted that the Kyoto agreements are based on IPCC (1996a) regardless of more recent IPCC (2006) or other work.

It is clear therefore that the empirical scientific model will allow more residual methane oxidation than the policy model provided the engineering and gas collection systems are properly designed. That proviso is the reason for the

conservative value recommended by the IPCC Expert Group (1996b), and why agreement on which method is used should be sought with the regulator before performing an assessment.

Trace Gas Emissions

In addition to the emission of bulk gases, GasSim2.5 also simulates the emissions of trace gases from surface and lateral emissions. The influence of the waste source term on the emission of these trace gases is unknown. Therefore the quantity emitted is determined by the concentration of the species per m^3 of LFG and the LFG emission rate (Figure 6.6).
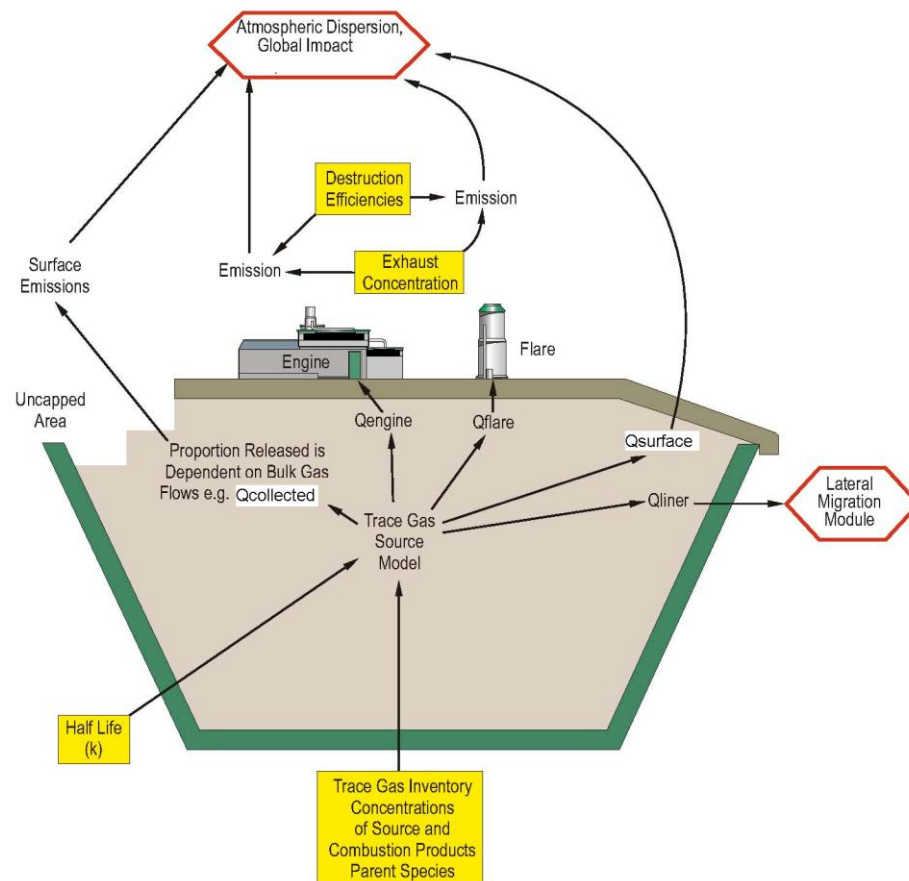
Figure 6.6: Trace Gas Source Model and Emissions Model

The emissions from the surface can be determined by the Equation 6.13:

$$R_{ps} = G \cdot G_p$$

(6.13)

where:

R_{ps}	release of species by surface emissions (mg/hr)	
G	total landfill gas emitted via surface (Q_c) or lateral emissions (Q_l) (m^3/hr)	
G_P	concentration of species P within raw landfill gas (mg/m^3)	

This equation has been used for the surface and lateral emissions of all species, except for those created during combustion (HCl, HF, NO_x, SO_x, HNO_3 and total phosphates), which will have zero emissions if flares and engines are not present.

Engines and Flare Emissions

Where gas is controlled by combustion (flaring and utilisation), this equation is modified to account for species that are assumed to be destroyed (as determined by the destruction efficiency) during the combustion process. The destruction efficiency can be a user defined or default value. Identical equations are used in GasSim2.5 to calculate the emissions for both flares and engines; therefore they have been discussed together here. However, the destruction efficiencies and other inputs are defined individually for flares and engines.

For the purposed of these equations, and subsequent dispersion modelling, GasSim2.5 assumes that all flares are enclosed with unimpeded vertical cowls. Gas engine exhausts also have vertical unimpeded cowls. This maximises plume rise, can be modelled and reflects current best practice.

The emissions are thus calculated by (Equation 6.14):

$$R_{pc} = (Q_{engine} \, or \, Q_{flare}) \cdot G_p \cdot \left(1 - \frac{DE\%}{100\%}\right)$$

(6.14)

where:

R_{pc}	release of species by combustion (mg/hr)
Q_{engine}	landfill gas to engine (m^3/hr)
Q_{flare}	landfill gas to flare (m^3/hr)
DE%	destruction efficiency of the gas flare or engine
G_P	concentration of species P within raw landfill gas (mg/m^3)

This equation is used by GasSim2.5 to determine the atmospheric emissions from engines and flares of all species, except for those listed below that have modified equations.

- Major Gases:
    - Carbon dioxide (Equation 6.15);
    - Hydrogen chloride (Equations 6.16 and 6.17);
    - Nitrogen oxides (Equation 6.16);
    - Sulphur dioxide (Equations 6.16 and 6.17); and
    - Carbon monoxide (Equation 6.16).
- Organic Carbon Groups:
    - Dioxins and furans (Equation 6.16); and
    - PAHs (Equation 6.16).

- Named Organic Compounds:
  - Total non-methane VOCs (NMVOCs or VOCs) (Equations 6.15 and 6.16).
- Other Individual Acid Forming Gases:
  - Hydrogen fluoride (Equations 6.16 and 6.17);
  - Nitric acid (Equation 6.18); and
  - Total phosphates (Equation 6.16).

Determination of Carbon Dioxide Engine and Flare Emissions

GasSim2.5 assumes that emitted carbon dioxide arises from (1) the uncontrolled surface emissions of LFG (with methane oxidation) (discussed above), (2) the combustion of VOCs, and (3) the combustion of methane. The determination of emissions from the combustion process is dependent on the quantity and quality of gas flared or utilised and the destruction efficiency. Therefore, corrections are included to balance the mass of carbon dioxide produced per mole of methane combusted (44/16) or VOC (44/12, based on an average unit of VOC having a generic formula C_nH_{2n}). The VOC composition has been set to be conservative and to simplify the equation, as other substituted groups would reduce the average molar carbon content. The quantity of carbon dioxide emitted is therefore (Equation 6.15):

$$R_{CO_2c} = (Q_{engine} \text{ or } Q_{flare}) \cdot \left\langle \left([G_{CH_4}] \cdot \frac{44}{16} \right) \cdot \left(\frac{DE\%_{CH_4}}{100\%} \right) + \left([G_{VOC}] \cdot \frac{44}{14} \right) \left(\frac{DE\%_{VOC}}{100\%} \right) \right\rangle \quad (6.15)$$

where:

R_{CO2c}	release of carbon dioxide by combustion (mg/hr)
Q_{engine}	landfill gas to engine (m³/hr)
Q_{flare}	landfill gas to flare (m³/hr)
G_{CH4}	concentration of methane within raw landfill gas (mg/m³)
G_{VOC}	concentration of total VOCs (as organic C) within raw landfill gas (mg/m³)
DE%	destruction efficiency of the gas flare or engine

Determination of the Releases of the Major Combustion Products (Other than Carbon Dioxide and Carbon Monoxide) Using Post-Combustion Data

Hydrogen chloride, hydrogen fluoride, dioxins & furans, nitrogen oxides, sulphur dioxide, nitric acid, total phosphates, carbon monoxide, PAHs and non-methane VOCs are produced by the combustion process. Therefore the emissions of these species from engines and flares have been determined using a correction for the proportion of these species formed during the combustion process. This has been undertaken by scaling up the observed emissions from engine exhausts and/or flare stacks according to an assumed air to fuel (landfill gas) ratio of 5:1, with releases increasing in direct proportion to the gas combusted. Thus producing the following equation (6.16):

$$R_{pc} = \cdot (AF+1) \cdot \left(\left[F_p\right] \cdot Q_{flare} + \left[E_p\right] \cdot Q_{engine} \right)$$

(6.16)

where:

R_{pc}	release of species by combustion (mg/hr)
Q_{engine}	landfill gas to engine (m³/hr)
Q_{flare}	landfill gas to flare (m³/hr)
F_P	concentration of species P within flare stack (mg/m³)
E_P	concentration of species P within engine exhaust (mg/m³)
AF	air to fuel ratio

It is common to report emissions from flares and engines in a normalised format (at 273K, 101325 Pa, dry gas, 3% O_2 (flares) or 5% O_2 (gas engines). These data are not suitable for input to AERMOD for the dispersion routines. AERMOD requires engine and flare emissions data under stack conditions: hot, wet, and with excess O_2, with the appropriate air fuel ratio. GasSim2.5 has an emissions converter, which over-writes the default emissions with site-specific ones for the parameters of most interest.

The emissions converter takes the combustion emissions data most likely not to meet air quality standards (NO, NO_2, NOx, CO, SO_2, total VOCs and NMVOCs) and converts these from the normalised conditions reported for regulatory compliance purposes to actual emissions values. This uses the conversion factors for temperature, oxygen content and moisture content as set out in the Environment Agency's guidance (Environment Agency, 2002; 2004a-b, , 2010a-e). A distribution is generated from the PDF's or single values used to populate the converter, and a single value is pasted into the trace.dat file at the percentile of interest (usually the 95th), overwriting the data and enabling the Tier 1 and Tier 2 impact assessments to be carried out at stack conditions.

Alternative Methods for Determining the Emissions of HCl, HF and SO₂ from Combustion

If is often the case that flare and engine emissions of hydrogen chloride, hydrogen fluoride and sulphur dioxide, which are daughter species, are determined using parent species, i.e. total chlorine, fluorine, and an estimated reduced sulphur content in landfill gas. The parent species are simulated as trace gas, as described above, and the emissions are determined using Equation 6.17, where a correction factor is applied for the molecular ratio, based on the molecular mass. These equations are base on those presented in AP-42 (US EPA, 1998).

$$R_D = \left(Q_{engine} \, or \, Q_{flare} \right) \cdot \left[G_P\right] \cdot MM \cdot \frac{DE\%}{100\%}$$

(6.17)

where:

R_D	release of daughter species by combustion e.g. hydrogen chloride (mg/hr)
Q_{engine}	landfill gas to engine (m³/hr)

Q_{flare} landfill gas to flare (m³/hr)

G_P total concentration of parent species within raw landfill gas e.g. Chlorine (mg/m³)

MM   ratio of molecular mass e.g. of HCl to Cl = 1.03

DE%   destruction efficiency of the emitted from the gas flare or engine i.e. HCl (this value cannot be set to 0% and should not be set to 100%)

Because there are limited published data on the total sulphur content of raw landfill gas the total concentration of reduced sulphur is calculated using sulphur dioxide.

Environmental Transport

The environmental transport model has been divided into two discrete topics:

- atmospheric dispersion (Tier 1 and Tier 2); and
- Lateral migration (advection and dispersion under steady state conditions).

GasSim2.5 uses the outputs from the emissions model to provide the appropriate emission rates for the year of interest.

The Environment Agency (England and Wales) recommends using a three-tier approach to the screening of emissions from landfill sites. The summary below is based on current Environment Agency legislation, and as such will be subject to change based on any future changes in legislation.

Tier 1 Atmospheric Dispersion

The Tier 1 stage is designed as a screening process to eliminate those processes that predict 'insignificant' impacts on the environment. The Tier 1 screening module within GasSim2.5 provides an assessment of the maximum short-term and long-term gas concentrations at the landfill/cell boundary and the closest receptor. GasSim2.5 uses integrated 'look up tables', detailed within (Environment Agency, 2004b) to assess whether the emissions from the individual sources; the landfill engines, flares and the surface, are 'insignificant' or 'not insignificant' at a receptor based on the 95%ile emission rate from the source, its height, and the distance to the receptor. The emissions from each source are summed so GasSim2.5 will report the results for all engines together and all flares together.

If the engines and flares are co-located and neither group dwarfs the other in terms of magnitude of impact, their contributions should be summed before assessing significance. GasSim2.5 does not do this for you automatically.

The tables used in Tier 1 screening are not directional and so meteorological factors are not taken into account.

Tier 1 screening can be considered in three parts:

1. Calculation of the contribution from each process (surface emissions, gas utilisation and gas flaring) to the concentration of gas at a receptor (defined as the Process Contribution);
2. Determining whether the process contribution is beneath a certain threshold, and therefore insignificant; and

3.   Determining whether the process contribution is above a different threshold, so that more detailed modelling is required.

Therefore Tier 1 screening assesses whether an emission is 'insignificant' or 'not insignificant' and if the emission is 'not insignificant' it determines whether detailed modelling (Tier 2) is required.

Gaseous emissions to air are considered insignificant, and are therefore considered not to require further detailed modelling, if:

- The maximum long-term Process Contribution is below 1% of the long-term Environmental Assessment Level (EAL) or Environmental Quality Standard (EQS); and

- The maximum short-term process contribution is below 10% of the short-term EAL or EQS.

This is reported in GasSim2.5 by the emissions being either 'insignificant' or 'not insignificant'.

Compounds that are deemed to be 'not insignificant' are then screened in order to determine whether further detailed modeling (and hence Tier 2 assessment is required) using the following rules:

Further detailed modeling is required if:

- The long-term Process Contribution + background concentration > 70% of the long-term EAL or EQS; and

- The short-term Process Contribution +0.2 x background concentration >20% of the short-term EAL or EQS.

Note that the background concentration to be used in short-term assessment is typically twice the annual mean (long-term) background.

When considering the GasSim screening results, an emission is deemed to require further detailed modeling if GasSim reports the following:

- Is the emission rate insignificant? '**No**' and is detailed modeling required? '**Yes**'.

If the benchmark is an EU air quality limit value (most notably long-term NO_2, short-term NO_2 and short-term CO), it also requires further assessment when the table reports:

- Is the emission rate insignificant? '**Yes (at receptor)**' and is detailed modeling required? '**Yes**'.

In this case the emission does not require further assessment because it is the high background concentrations that have triggered the "requirement" for detailed modeling rather than the emission. In other words, if the process contribution is insignificant, the background is considered irrelevant within the risk assessment process.

If a long-term and/or short-term emission is deemed to require further detailed modeling through the screening process outlined above, this typically means that a Tier 2 assessment comprising a GasSim2.5 assessment is

required. GasSim 2.5 Tier 1 Screening process is intended for human health risk assessment only and is not designed as a screening tool for the habitats impact assessment.

Tier 2 Atmospheric Dispersion

A Tier 2 assessment within GasSim2.5 incorporates basic meteorological data, through the use of region-specific, or if appropriate site-specific windroses, in the Atmospheric Dispersion module within GasSim2.5 to assess the maximum ground level concentration of the pollutant.

When carrying out the Tier 2 assessment process, there are various averaging periods that can be assessed; these fall into long-term and short-term periods. While the long-term averaging period for all pollutants is a year, there are varying short-term averaging periods. For example, the short-term averaging period for NO_2 is 1 hour while for PM_{10} it is 24 hours and for CO it is 8 hours. Each long-term and short-term averaging period for each pollutant has its own EAL/EQS that are used in the Tiered screening assessments. These averaging periods and EALs/EQSs are set out in Horizontal Guidance Note H1 - Annex (f) (Environment Agency, April 2010g).

The Atmospheric Dispersion module allows the Process Contribution (PC), which is the concentration of the emitted pollutant, to be calculated at each receptor and site boundary. To this PC the relevant background concentrations can be added to give the Predicted Environmental Concentration (PEC) of each pollutant. If the long-term PEC is greater than the relevant air quality standard, then either further assessment (such as a BAT assessment), air quality monitoring or further detailed modeling is required at the Tier 3 level.

It is considered that a Tier 2 assessment should be appropriate for the majority of landfill sites in the UK.

GasSim2.5 calculates the atmospheric dispersion on-site and off-site from the surface of the landfill (or individual cells), engine and flare emissions using the AERMOD model algorithms. The atmospheric dispersion module within GasSim2.5 calculates ground level concentrations of pollutants.

A small number of equations can be used to estimate the concentration of a pollutant at a receptor from a single source, however at a typical landfill site where multiple sources and multiple receptors exist; a series of equations is needed in the form of an air dispersion model. The atmospheric dispersion module within GasSim2.5 is based on the series of equations. The AERMOD code was developed by the American Metrological Society (AMS)/Environmental Protection Agency (EPA) Regulatory Model Improvement Committee (AERMIC). There is a wealth of material available from the USEPA website on the AERMOD model, and so the following sections are intended to set the scene only.

The dispersion model utilised within GasSim2.5 is based on the Gaussian air dispersion model algorithms and the modern Planetary Boundary Layer (PBL) similarity theory.

Gaussian Plume Theory

The plume distribution in the atmosphere is determined using the degree of mixing within the atmosphere, the height of which varies with changes in the temperature gradient. This allows the introduction of reflections, heights at which the plume is reflected and effectively turned around, preventing the plume from continually expanding vertically. Where allowances are not made for dry or wet deposition, or for plume rise, the mean concentration of a species (Cx(x,z)) in a sector of width α (radians), at a downwind distance x (m), and height z (m) from a point source is given equation 6.18:

$$Cx\big(x,z\big) \; = \frac{Q_0}{\alpha x \sqrt{2\pi}\sigma_z u_s}\left[\exp-\frac{\big(h_e + z\big)^2}{2\sigma_z^{\,2}} + \exp-\frac{\big(2A + h_e + z\big)^2}{2\sigma_z^{\,2}} + \exp-\frac{\big(2A - h_e - z\big)^2}{2\sigma_z^{\,2}}\right]$$

(6.18)

where:

Q_0	release rate from the source (from the emissions model) (mg s^{-1} if Cx is required in mg m^{-3})
σ_z	standard deviation of the vertical Gaussian distribution (m) (the vertical dispersion coefficient) (determined below)
u_s	wind speed at the effective release height (m s^{-1})
h_e	effective release height (m) (engine or flare stack)
A	depth of the mixing layer (m)

Planetary Boundary Layer (PBL) (similarity theory)

Within GasSim2.5, the atmosphere is treated as consisting of two specific regions, the planetary boundary layer (PBL) and the free atmosphere. The PBL typically represents the lowest 1-2 km of the atmosphere, and the free atmosphere represents the area above the PBL. Note the PBL is generally synoptic with the 'mixing layer'. The thickness of the PBL commonly varies dependant on the time of day. During the day the PBL will normally be larger due to the effect of solar radiation heating the surface of the earth. In the absence of solar radiation, the surface cools and hence the PBL will generally be smaller during night time.

The dispersion of pollutants within the atmosphere is dependent on (amongst other things) the degree of turbulence/mixing within the PBL. There are three main categories of the PBL which reflect the magnitude of turbulence/mixing within the PBL:

- Convective (unstable) Boundary Layer (CBL);
- Stable Boundary Layer (SBL); and
- Neutral Boundary Layer (NBL).

Within GasSim2.5 these categories are used to define the degree of turbulence/mixing within the PBL instead of the Pasquill stability categories.

It was noticed that a number of key features were similar in the PBL at different places and times, including vertical wind speed profiles and vertical temperature profiles. Through application of a mathematical theory, 'the similarity theory', a number of key variables associates with the PBL were identified. These key variables include:

- Surface sensible heat flux (H);
- Surface friction velocity (u);
- Convective velocity scale (w);
- Monin-Obukhov length (L); and
- Convective/mechanical mixing height (Z_{ic}) and (Z_{im}).

GasSim2.5 contains algorithms that calculate dispersion in both the convective and stable boundary layers.

In practical terms, the default meteorological data within GasSim 2 have been previously processed, therefore includes the required PBL parameters. If user defined meteorological data is used within GasSim2.5, this data must first be processed using AERMET, which will calculate the PBL parameters ready for processing within AERMOD. AERMET is not provided with GasSim2.5. Data held within GasSim2.5 have been pre-processed. Site-specific data must be pre-processed before use.

Convective Boundary Layer (CBL)

The CBL commonly occurs during the day, and has a thickness of 1 - 2 km. The turbulence/mixing within the CBL are generated in the main by the thermal heating effect of solar radiation. This typically produces large eddie currents that readily disperse pollutants within the atmosphere.

The plume under CBL conditions is represented within GasSim2.5 by a Gaussian distribution in the horizontal and bi-Gaussian (skewed) distribution in the vertical axis. The dispersion of pollutants is modelled in the CBL using a probability density function (PDF) approach where the modelled concentrations are the sum of concentrations from three sources:

- Direct plume;
- Indirect plume; and
- Penetrated plume.

The Direct Plume

The direct plume is modelled to move directly to receptors.

The Indirect Plume

GasSim2.5 locates the indirect plume above the CBL top to account for the slow downward dispersion of buoyant plumes that remain close to, but below the mixing height. This is modelled through excess plume rise.

The Penetrated Plume

All or part of the plume may penetrate the upper limit of the boundary layer. Part of the plume may re-enter the boundary layer and will therefore contribute to ground level concentrations.

Stable Boundary Layer

The plume is represented within AERMOD by a Gaussian distribution in the horizontal and vertical axis that reflects that there are no large eddy currents to create the need for a Bi-Gaussian distribution as in the case under CBL conditions.

Stack Tip Downwash

GassSim2.5 accounts for the effects of stack tip downwash. Stack tip downwash occurs where a source exhaust or stack alters the surrounding air flow around it. The air flow around an exhaust stack creates an area of increased pressure up stream of the exhaust/stack, and an area of lower pressure in the form of a slight vacuum on the downwind side of the exhaust/stack. The effect of stack tip downwash only occurs:

when:

$$v/u < 1.5 \tag{6.19}$$

v = vertical exhaust/stack velocity (m/s)
u = exhaust/stack-top wind speed (m/s)

GasSim2.5 uses the following equation to modify the release height to account for stack tip downwash:

$$h' = h + 2d(v/u - 1.5) \text{ when } v/u < 1.5 \tag{6.20}$$

h'=adjusted release height (m)
h=release height (m)
d=stack diameter (m)
v=vertical stack gas velocity (m/s)
u=(stack-top wind speed)

Plume Rise and Buoyancy

GasSim2.5 calculates plume rise and buoyancy effects of individual sources. The rise of a plume above the release height of the source can be a significant contributing factor to the reduction of ground level concentrations (and hence concentrations at potentially sensitive receptors). Typically plume rise can be 2 - 3 times the release height of the emission. Plume rises from an emissions point due to two main factors, buoyancy and momentum. Buoyancy is related to the density of the emission compared to the density of the surround atmosphere, and

momentum is related to the mass of emissions and the exit velocity. GasSim2.5 combines the effects of momentum and buoyancy using vectoral addition.

The effective height of a source (H) is the plume centreline above the base of the source, when the plume has levelled off. The effective height (H) of an emissions point can be defined by the following equation:

$$H = h + \Delta h \qquad\qquad (6.21)$$

> H = Effective height
> h = stack height
> Δh = plume rise

Note where rain guards or flap valves have been fitted to a flare/engine exhaust stack, the plume rise due to momentum is severely reduced, which effects the effective height of the plume, which may significantly affect the predicted ground level concentrations.

Building Downwash

Buildings can affect airflow and create turbulent downwash. Emissions from a source may be affected by this downwash effect, depending on the location and height of the stack. Therefore building downwash may result in higher surface concentrations. Modelling the effect of building downwash cannot be undertaken within GasSim2.5.

The BPIP-PRIME algorithm relates to building downwash, therefore is also not utilised within GasSim2.5.

Modelling Terrain

It is widely acknowledged that terrain only has a significant effect on dispersion when the height of the terrain on which the receptor is located is significantly different relative to the stack source height. The commonly expressed rule of thumb is that slopes below approximately 10% have only limited effects on dispersion. On this basis most of the UK is considered to be topographically flat and as such a terrain function has not been incorporated into GasSim2.5.

Tier 3 Atmospheric Dispersion

Tier 3 is the most detailed level of assessment. Using a new generation air dispersion model such as ADMS or AERMOD, the PC and PEC of a pollutant at any number of potential receptors is calculated using detailed site layout plans and typically 5 years of hourly meteorological data. A Tier 3 model will incorporate appropriate meteorological data that has been processed using site-specific data, and will typically incorporate terrain data for the area in the vicinity of the site. GasSim2.5 allows the user to export data to allow a Tier 3 model to be used.

Odour Emissions and Modelling of Odour Units

Odour can be a particularly subjective matter. There is little published information on the way odour detectability of a complex cocktail of compounds (as in landfill gas) relates to the individual concentrations of the substances in the gas mixture.

Odour Sources

The specific waste management activities on a landfill generate different sources of odour. These are both advective sources such as escaping landfill gas, emissions from flares, gas engines and aerated leachate treatment plants, and diffusive sources such as waste surfaces, capped waste and leachate holding tanks. Uncontrolled landfill gas contributes most to the odour impact of a site and while point sources such as leachate tanks and lagoons have some local impact, these can be readily managed. For this reason, GasSim2.5 only considers odours from landfill gas.

Because odour is not straightforward to quantify and may be subjective in interpretation and perception, GasSim2.5 handles odour in two ways. Both sets of results should be interpreted by an odour specialist. A cocktail of odorous substances may have a synergistic or even an antagonistic effect on the perception of odorous compounds. For this reason it is suggested that the dispersion of an individual odorous compound is considered if it is the prime cause of odour (e.g. hydrogen sulphide from the co-disposal of sulphate-rich wastes and household wastes), and odour units are used in other cases.

Odorous Compounds and GasSim2.5

The first method considers the emission and atmospheric dispersion of the individual odorous components themselves. The GasSim2.5 inventory of odorous substances is set out in Chapter 5. Additionally odour units can be modelled using this technique by assuming that the odour units behave in a similar manner to odorous trace gases.

GasSim2.5 stores these compounds in the trace gas component database, emits them via landfill surfaces, flares and engine emissions (with suitable destruction efficiencies) and disperses their emissions using AERMOD. Odour units are assessed at the 98%ile. It should be noted that currently in the UK there are no statutory standards or objectives for assessing odour nuisance. On this basis, over all odour benchmark levels are typically based upon guideline documents of *Additional Guidance for H4 Odour Management – How to comply with your environmental permit* (Environment Agency March 2011).

Lateral Migration

Background to Modelling Subsurface LFG Migration

GasSim2.5 simulates the transverse migration of landfill gas through the subsurface as there is a potential for gas movement whenever the gas pressure in a landfill exceeds the pressure in the soil or rock surrounding it. This is likely to be the case in any landfill that is actively generating gas. The magnitude of gas leakage will then depend

on the permeability of any subsurface pathway and the pressure gradient between the landfill and the potential receptor.

There is limited data upon which to base models of landfill gas transport. Williams *et al*. (1999) present data from Foxhall Landfill, and they use a simple mathematical model to match the data. Bogner *et al*. (1997) present data from a site in the USA.

Precise modelling of gas migration through the geosphere from a landfill requires an extremely complicated model. A full 'process' model would need to include 3D geometry of heterogeneous rock/soil, multi-phase flow (gas/water) and multi-components within these phases. Even a single phase model of gas flow would need to consider 3D geometry, transient pressure changes and interaction between different components (oxygen, nitrogen, CO_2, CH_4, VOCs, etc.). These models are reasonably well developed (Bear, 1972) and have been applied to landfill gas migration by, amongst others, Moody *et al*. (1991), Bogner *et al*. (1997), and Tate and Rodwell (1995).

Despite their sophistication, this style of modelling does not lend itself to implementation within a probabilistic performance assessment framework. These models require numerical solutions and a number of site-specific input parameters that need to be determined experimentally. Most importantly, there is little available data to constrain or validate the models.

The approach to modelling subsurface gas migration in GasSim2.5 has therefore been designed to be much simpler and is described in the following sections.

Physics of Gas Migration

Landfill gas migrates because of spatial variations in pressure, density, temperature, concentration, etc. The conceptual model implemented in GasSim2.5 envisages gas migration through the subsurface occurring effectively in a horizontal plane. This assumption is believed to be valid because:

(i)   The depth of the landfill is likely to be small compared with the length of a typical transport pathway (10s of metres compared with 100s of metres);

(ii)   The geology is likely to comprise predominantly horizontal sedimentary bedding;

(iii)   Gas will preferentially move through the largest pores or fissures which are likely to correspond to sub-horizontal bedding plane fissures; and

(iv)   Data from Foxhall landfill (Ward *et al*.) appears to confirm that gas has migrated in a mainly horizontal direction.

These assumptions mean that, for gas flow in the subsurface, our simplified conceptual model can neglect buoyancy-driven flow (vertical flow due to density variations) and temperature-driven flow (convection).

In GasSim2.5 we can constrain the plume to a confined migration pathway, or we can specify an unconfined pathway.

GasSim2.5 considers the movement of gas molecules due to pressure gradients (advection) and concentration gradients (diffusion). In reality, these processes are coupled to each other and to the composition of the gas. For example, the coefficient of molecular diffusion for a particular gas species depends on the composition of the gas through which it is diffusing. The composition is in turn determined by the rate of movement of the different components, driven by pressure and concentration variations.

Despite this complexity, we have assumed that landfill gas migration can be simplified by separating the calculations of flow rate and concentration. Broadly, this can be done by determining the proportion of gas emitted through the liner and the liner surface area to calculate a rate of gas flow. The LFG is assumed to retain the same composition as the gas generated. This rate can then be used to calculate the evolution of concentration with time by solving the advection-diffusion equation. This is the approach used by Williams *et al*.

The approach to calculating lateral migration is therefore as follows:
- Calculate the advective gas flow rate from the boundary of the cell/landfill to the receptor, using the quantity of gas emitted through the liner; and
- Calculate the concentration of the components of the LFG at the receptor, by solving the advection-diffusion equation using the flow rate computed in step 1.

Approach to Calculating Gas Migration through the Sub-Surface

The gas pressure at the boundary of the cell/landfill is determined from the flow of gas from the cell/landfill (the emission rate) (Equation 6.22) using Darcy's Law. The emission rate is calculated from the emission of LFG through the cell/landfill liner and the liner surface area (Equation 6.23).

$$v = \frac{E_r}{3600 \cdot (G_n - G_m)}$$

(6.22)

where:

v	the mean true velocity of flow (m s^{-1})
G_n	geosphere porosity
G_m	geosphere moisture content
E_r	gas emission rate (m^3/m^2/hr), calculated using:

$$E_r = \frac{Q_{lat}}{A_l}$$

(6.23)

where:

Q_{lat}	gas emitted through liner (m^3/hr)

A_l unsaturated surface area of the liner (m^2)

If an artificial liner is modelled, it is assumed to contain no defects, and advective flow does not occur. If a natural clay liner is modelled, the constraining emission rate is calculated on the basis of the engineered specification.

The true flow regime is likely to be three-dimensional. This is because the permeability is likely to be non-homogeneous, resulting in differences in pressure surrounding the landfill, and also because of the real 3D geometry of the landfill. For the purposes of GasSim2.5, this can be simplified to a 1D linear or radial flow field. We consider the linear 1D flow regime to be most appropriate for GasSim2.5 for three reasons:

(i)   Gas is likely to flow along preferential, high permeability linear pathways;

(ii)   The flow rate along a 1d linear pathway will be higher than that for a radial flow regime given the same permeability and pressure gradient, and the assumption of a 1d linear pathway is therefore 'conservative' in the sense of providing the highest flow rate; and

(iii)   Williams *et al*. Successfully model data from Foxhall landfill using a 1d linear version of the advection-diffusion equation.

Capillary forces mean that, in the vadose zone, water wets the pore surfaces. Gas (air or landfill gas) is trapped within the larger pores. This is consistent with the common assumption that gas is static in the vadose zone. Consequently, significant gas flow will occur through the largest interconnected pores, such as fissures. This is in direct contrast to water flow in the vadose zone, which occurs primarily through the smallest pores. GasSim2.5 will assume that permeability is constant along the pathway.

The gas concentrations are determined using a 1D advection-diffusion equation (ADE), as provided in Equation 6.24.

We assume that the components of the gas behave independently and do not interact. This means that we can solve the advection-diffusion equation separately for each component, to calculate concentration as a function of time. As in Chapter 3 assuming that flow occurs along a one dimensional linear pathway is 'conservative' in that it will give the highest concentrations for a given source term.

For each pathway, the one dimensional advection-diffusion equation is:

$$\frac{\partial c}{\partial t} = D_L \frac{\partial^2 c}{\partial x^2} - v \frac{\partial c}{\partial x} - \gamma c$$

(6.24)

where:

x   the distance along the pathway in the direction of flow (m)

t   time (s)

c (x,t)   the concentration at a distance x and a time t (kg m^{-3})

v   the mean true velocity of flow (m s^{-1})

γ   the rate of decay of the gas. Note that this only applies to contaminants that undergo first order decay, for example through biodegradation or radioactive decay (s^{-1}) (not used in GasSim2.5 version 1.0)

D_L the longitudinal coefficient of dispersion (that is, parallel to the direction of gas flow) ($m^2 s^{-1}$), this is determined from the dispersivity of gas in air using Equation 6.25.

$$D_L = D_s .0.0001. G_n^{1.33} \left(1 - G_m\right)$$

(6.25)

where:

G_n geosphere porosity

G_m geosphere moisture content

D_s air dispersion coefficient ($cm^2 s^{-1}$)

In using the advection-diffusion equation to model gas concentrations, we assume that:

1)   The diffusion coefficient for each component is constant;

2)   No partitioning occurs to any dissolved or solid phases present (partitioning to aqueous phase would be governed by Henry's Law); and

3)   Movement of dissolved components is not included.

The ADE is solved using the gas flux, the effective porosity Gn, the coefficient of dispersion D, together with boundary conditions describing the source term. The equation allows the inclusion of decay constant. However, this is not used in GasSim2.5 v1.0. GasSim2.5 v1.0 uses the Laplace Transformation to solve this equation. This approach is described in detail in Chapter 6 of the LandSim v2 manual (2001), which describes the theory behind the model.

GasSim2.5 allows the user to consider soil breathing in the simulation of lateral migration in an unconfined migration pathway. The more conservative confined pathway does not allow soil breathing to take place. Soil breathing is considered to be controlled mainly by the variations of atmospheric pressure over the year. When atmospheric pressure increases, air is effectively pushed into the soil through the ground surface. The air that is forced into the soil will be mixed with the migrating gases. In contrast, as the pressure decreases a proportion of the air-gas mixture will escape into the atmosphere. The processes will continue throughout the year to dilute the initial concentration of the migrating gases. Golder examined three years of typical meteorological data and concluded that approximately 16 -18% of the initial concentration of landfill gases would remain below the ground surface after one year's air exchange.

Migration of LFG through Engineered Barriers

Gas is assumed to migrate laterally and upwards through the sides and top of the landfill. Gas is unlikely to move downwards in significant quantities, because it is buoyant and the bottom part of the waste and engineered barriers are likely to be water saturated, which makes the permeability to gas effectively zero.

The flow mechanisms through mineral liners are essentially the same as in the geosphere. However, the geotechnics of liner emplacement are likely to be important in conditioning the permeability to gas, for example, the extent to which the emplaced mineral liner is water saturated. There is little data on gas movement through geomembranes. There are likely to be two flow mechanisms; molecular diffusion through the material of the membrane and flow through defects, but there is not enough data available to derive models of either of these mechanisms.

In earlier versions of GasSim, the movement of gas through the liner was specified by the calculation of the emission rate; we assumed that the model operated at a steady state, thus implying that the emission rate represented this movement though the liner. For current implementations in GasSim2.5 we have limited this to the engineered performance of a membrane liner (where present). When simulating a clay liner, we use the engineering properties specified to control the rate of gas loss through the liner. It is therefore possible to estimate the performance under as built/as specified conditions, and with defects, by modifying the input values of the liner specification.

GasSim2.5 assumes that there is no biological oxidation of methane, dispersion, retardation or other attenuation/reaction processes that reduce the concentration of any gas as it moves through the ground. This will result in a conservative approach.

Assessing Vegetation Stress

GasSim2.5 determines whether carbon dioxide and methane will cause long-term vegetation stress in the root zone. The concentrations for methane and carbon dioxide at a given year and a given receptor point are taken from the lateral migration model. Research has shown that vegetation stress can be caused by carbon dioxide at between 5 and 10% (v/v) and methane at about 45% (v/v). However, methane can be biologically oxidised to carbon dioxide in the soil. Therefore, GasSim2.5 sums the carbon dioxide and methane concentrations. This summed concentration is then compared to a vegetation stress threshold concentration, which GasSim2.5 has taken as a default of 7.5% (the midpoint between 5 and 10 % limits), or another user defined threshold.

Global Impact

The risk to the global atmosphere from LFG emissions is determined by estimating the detrimental effect of two classes of compound (Figure 6.6):

- Greenhouse gases - mainly methane, chlorofluorocarbons (cfcs) and halocarbons (HFC)s; and
- Ozone depleting compounds – mainly cfcs and hfcs.

The detrimental effect of greenhouse gases is determined using the Global Warming Potential (GWP), which compares the effect of each compound to carbon dioxide, for a specified timeframe, i.e. methane has 21 times the effect of carbon dioxide over a 100 year period. GasSim2.5 provides the option for you to select the gases that you wish to use to determine the GWP, as the determination of the GWP for Environmental Reporting (DETR, 2000) does not include CFCs and HCFCs.
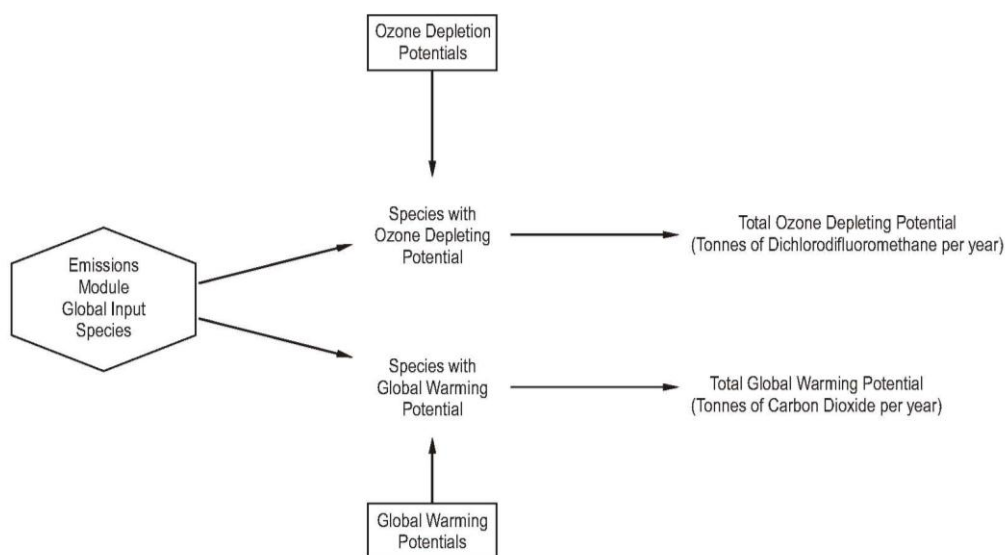
Figure 6.7: Global Impact Module

The effect of ozone depleting compounds is determined in a similar way using the Ozone Depletion Potential (ODP), which compares each species to a fixed standard compound, generally trichlorofluoromethane ($CFCl_3$).

Pollution Inventory (PI) Reporting

Since 1998, the Environment Agency has required the reporting of certain emissions from industrial processes regulated under Integrated Pollution and Control. The reporting of annual emissions from most landfills will become necessary under The Pollution Prevention and Control (England and Wales) Regulations, 2000 in early 2003 for emissions during 2002. Additionally, newly permitted facilities will be required to report PI emissions annually. Reported data may derive from measurement, calculation or estimation techniques and GasSimLite provides the capability to calculate the annual releases and report them in a format suitable to meet PI requirements.

The Environment Agency provides a standard list of substances to be reported based on operation during the previous year to reporting. GasSimLite reports the gases and volatile compounds on the PI list, which are known to occur at reasonably measurable concentrations in landfill gas, as detailed in Environment Agency (2002b). This

list includes forty-five species, which are reported at the 25, 50 and 75%iles in the units required for PI purposes. The 50%iles can then be used to complete the non-notifiable air emission section of the PI reporting form.

The emissions of CFCs, HCFCs, HFCs, PFCs, Halons and VOCs have been reported as sums of the groups of compounds as at the time of publication insufficient data was available on the individual species within these groups.

PI reporting also requires the emissions of PAHs, PCDDS and PCDFS as naphthalene and TEQs, respectively. Due to the lack of emissions data for these species, GasSim2.5 simplifies their emission by using surrogates: Benzo(a)pyrene for PAHs and 2,3,7,8-TCDD, for PCDDS and PCDFS.

CHAPTER 7: VALIDATION

7. VALIDATION

Overview

Verification has been undertaken using the theory in the previous chapter and carrying out code checking, input distribution checks, checks on the calculation of percentiles, and a comparison of the results with equivalent spreadsheets. Verification is not intended to prove the validity of the theoretical framework behind the equations. Therefore to confirm that GasSim2.5 simulates reality and thus can be used with confidence, a series of validation trials have been undertaken. However, research on the theories used in GasSim2.5 is continuing and man's interaction with nature rarely behaves ideally, therefore what matters to the user is the reliability with which GasSim2.5 represents reality.

A substantial amount of validation was undertaken in support of the initial versions of GasSim. For GasSim2.5, the same validation case studies have been retained from GasSim version 2.0 with the exception of air dispersion studies which applied to GasSim v1.0, and a Danish landfill previously used for validating lateral migration. Time and distance dependent outputs have been specifically compared between GasSim2 and GasSim2.5 outputs.

Validation checks of the spatial cellular filling approach implemented in GasSim2 have been performed previously on ten landfills in GasSim2. As the validation was preformed for a commercial client for resource assessment purposes, these validation trials cannot be reproduced in full. The methodology has not changed in GasSim2.5.

No independent validation of the AERMOD model has been performed, as this software has already been accepted by the Environment Agency as suitable for atmospheric dispersion modelling. The implementation of AERMOD within GasSim2.5 is same as the one in GasSim2.0 and it has been independently checked when the GasSim2 was released.

Method

To assess if GasSim2.5 represents reality, the 'predicted' results will be compared to the 'measured', field, results, as no single site provides sufficient data to test all the modules. The case studies (Table 7.1) have been chosen to validate the source and key environmental transport modules. These case studies include the landfill used to validate the HELGA framework (Gregory et al., 1999) and additional sites.

Table 7.1: Summary of Validation Case Studies

Landfill Site (UK sites unless otherwise stated)	Module(s) Evaluated	Description
Auchencarroch Test Cells	Source Term Module – bulk gas generation	Well monitored test cells used to validate the HELGA framework gas generation module.
Brogborough Test Cells	Source Term Module – bulk gas generation	Well monitored test cells.
Unnamed Buckinghamshire Landfill	Source Term and Emissions Modules – bulk gas generation and methane emissions	Data for a well characterised site in Buckinghamshire, which had been used previously to validate the HELGA gas generation and emissions module.
Unnamed Quarry Landfill	Source Term Module – bulk gas generation	Data for characterised landfills in the United Kingdom.
Unnamed Berkshire Landfill	Emissions Module – bulk gas generation	Data for characterised landfills in the south of England.
Ten Unnamed Landfills	Source Term Module, Landfill Characteristics, Cellular filling routines- bulk gas generation and gas utilisation potential	These ten landfill models were prepared for gas utilisation potential assessments and validated against well characterised abstraction data.[1]
Green Valley Landfill (US)	Surface Emissions – VOCs	The monitoring data of VOC surface emissions from a well characterised landfill.
Foxhall Landfill	Lateral Migration Module	This site has been monitored and modelled the lateral migration of off-site carbon dioxide, methane and VOCs. The simulated data was compared to the observed concentrations along the plume.
Skellingsted Landfill (Denmark)	Lateral Migration Module	This site has been monitored and modelled the lateral migration of off-site carbon dioxide and methane. The simulated data was compared to the observed concentrations along the plume.

1. *These case studies are not provided in full as the data for the sites could be considered to be of a commercial nature. Summary data for 2005 are provided in this manual.*

Validation of Source Term Model

Case Study: Auchencarroch Test Cells

Introduction

The Auchencarroch test cells were used to validate the gas generation module of the HELGA framework (Gregory et al., 1999), the source of the GasSim gas generation equations. Therefore GasSim has been validated against this data to ensure consistency. The test cells are shallow (approx 10 m or less depth), filled within 1 year, and were monitored on an hourly basis for gas generation. The cells have received a range of treatments, and the HELGA framework was validated against the sum of all the emplaced waste for the gas produced 2 and 3 years after filling.

Input Values

The input values are summarised in Table 7.2. Where site-specific data was not available, default values, reported in Chapter 5, have been used.

Table 7.2: Summary of Site-Specific Inputs for Auchencarroch Test Cells

Input Parameter	Value	Units	Distribution	Justification
Infiltration	676 ± 67.6	mm/y	Normal	Gregory et al. (1999).
Filling Time	1	years	-	Gregory et al. (1999).
Waste Input	3,500	t	Single	Gregory et al. (1999).
Waste Breakdown	Dom 100	%	Single	Gregory et al. (1999).
Composition	1980 - 2010	-	-	Gregory et al. (1999).
Capping	100	%	Single	Gregory et al. (1999).
Waste Density	0.75	tm^{-3}	Single	Gregory et al. (1999).
Effective Porosity	10	%	Single	Default.
Leachate Head	0.5	m	Single	Gregory et al. (1999).
Hydraulic Conductivity	$1x10^{-7}$	m/s	Single	Default.
Adsorptive Capacity	10	%	Single	Default.
Leachate Recirculation	0.5	m^3h^{-1}	Single	Gregory et al. (1999).
Carbon Dioxide to Methane Ratio	50:50	-	Single	Default.
Landfill Area	625	m^2	Single	Gregory et al. (1999).

Validation Results

The range of LFG production reported by the cells for years 2 and 3 (Table 7.3) has been compared to the predicted results, demonstrating that these lie within the observed range (Figure 7.1a from GasSim2 and Figure 7.1b from GasSim2.5). The simulation has calculated the waste moisture content within the cells as wet, which will lead to rapid degradation. The results show that the experimental ranges overlap the model results, indicating that the model produces realistic results.

From Figures 7.1a and 7.1b, GasSim2.5 outputs of concentrations are similar to the results predicted by GasSim2.

Table 7.3: Measured and Predicted LFG Production, Auchencarroch Test Cells (m3h-1)

Year	Cell 1	Cell 2	Cell 3	Cell 4	GasSim Simulation
2	8.47	5.8	5.68	5.48	6.89
3	5.27	3.67	3.52	5.51	4.82

Figure 7.1a: Auchencarroch Test Cells: Modelled Data Overlain by the Observed Range – GasSim2
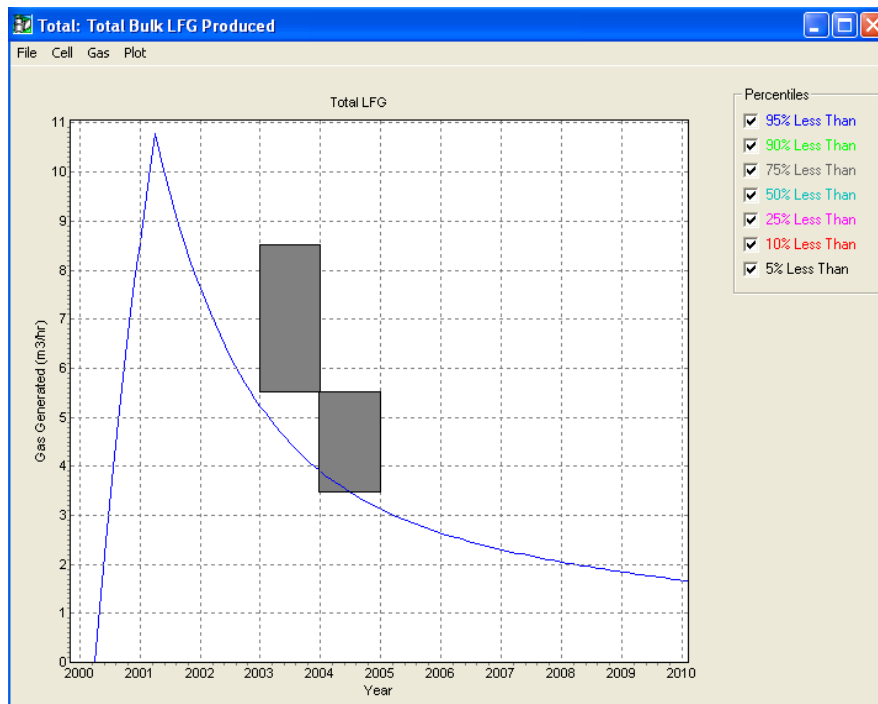
Figure 7.1b: Auchencarroch Test Cells: Modelled Data Overlain by the Observed Range – GasSim2.5

Case Study: Brogborough Test Cells

Introduction

The Brogborough test cells were constructed to demonstrate and compare the effects of selected pre and post placement techniques on methane production. The test cells are 40 m long, 25 m wide and 20 m deep, thus each cell contains approximately 20000 m^3 or 15000 t of waste. The cells were constructed and filled over a two-year period and have a 2 - 3 m thick clay cap. The methane and carbon dioxide production has been regularly monitored.

Input Values

The input values are summarised in Table 7.4. Where site-specific data was not available, default values, reported in Chapter 5, have been used.

Table 7.4: Summary of Site-Specific Inputs for Brogborough Test Cells

Input Parameter	Value	Units	Distribution	Justification
Infiltration	50 ± 5	mm/yr	Normal	Not required as the moisture content will be entered rather than calculated.
Waste Input	15,000	t	Single	Croft et al. (2001).
Waste Breakdown	Dom. 100	%	Single	Croft et al. (2001).
Composition	1980 - 2010	-	-	Domestic waste assumed to have a default composition.
Capping	100	%	Single	Croft et al. (2001).
Waste Density	0.8	tm^{-3}	Single	Croft et al. (2001).
Effective Porosity	1, 20	%	Uniform	Not required as the moisture content will be entered rather than calculated.
Leachate Head	3.3, 3.3, 8.5	m	Triangular	Croft et al. (2001).
Hydraulic Conductivity	$1x10^{-9}$, $1x10^{-5}$	m/s	Log Uniform	Not required, as the moisture content will be entered rather than calculated.
Adsorptive Capacity	1, 5	%	Uniform	Not required, as the moisture content will be entered rather than calculated Brogborough data.
Leachate Recirculation	0	m^3h^{-1}	Single	Croft et al. (2001).
Carbon Dioxide to Methane Ratio	40:60	-	Single	Calculated from data provided.
Landfill Area	1,000	m^2	Single	Croft et al. (2001).

Validation Results

The reported range of LFG production from the cells has been compared to the predicted results (Figure 7.2a from GasSim2 and Figure 7.2b from GasSim2.5). The simulation has calculated the waste moisture content within the cells, and thus determined the rate of LFG generation. The results show that the experimental ranges lie within the model results. The shape of the modelled and predicted results are slightly different due some of the test cells receiving liquid or air injection between 1992 and 1994, part of the experimental trails. These enhanced the gas production in test cells and may also have affected the gas generation in both the injection and surrounding cells. This would result in the enhanced gas production in years 1992 to 1996.

From Figures 7.2a and 7.2b, GasSim2.5 outputs of concentrations are similar to the results predicted by GasSim2. However, a wider range of values between the 5%ile and the 95%ile is predicted by GasSim2 comparing to the range by GasSim2.5. The wider spread of percentile values on version 2.0 is the result of a conservative bug whereby the LFG percentile graphs were calculated by summing the percentiles for CO_2, CH_4 and H_2. The bug has been fixed in Version 2.5 therefore the GasSim2.5 output in Figure 7.2b is a correct and realistic result.
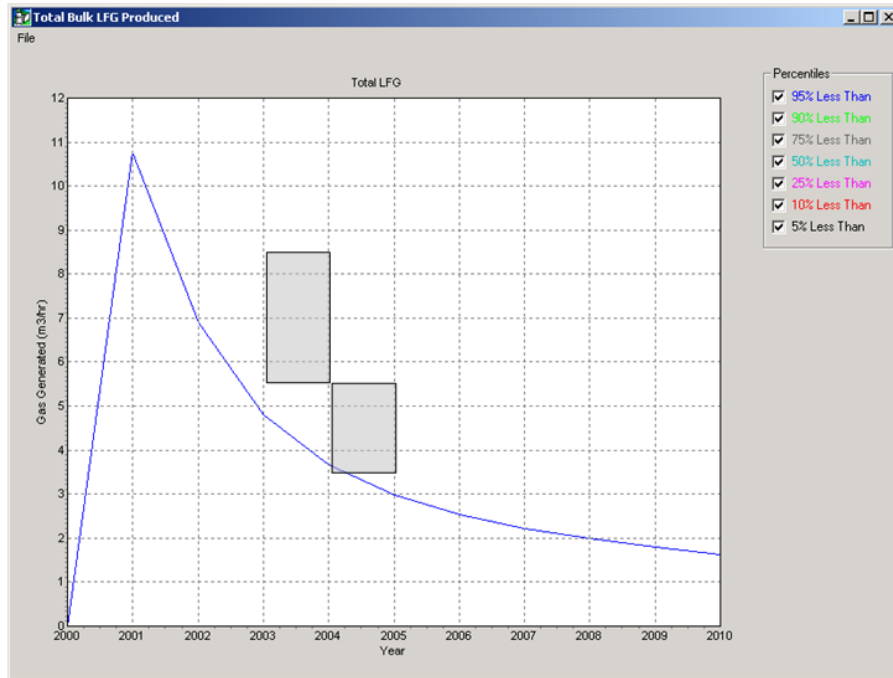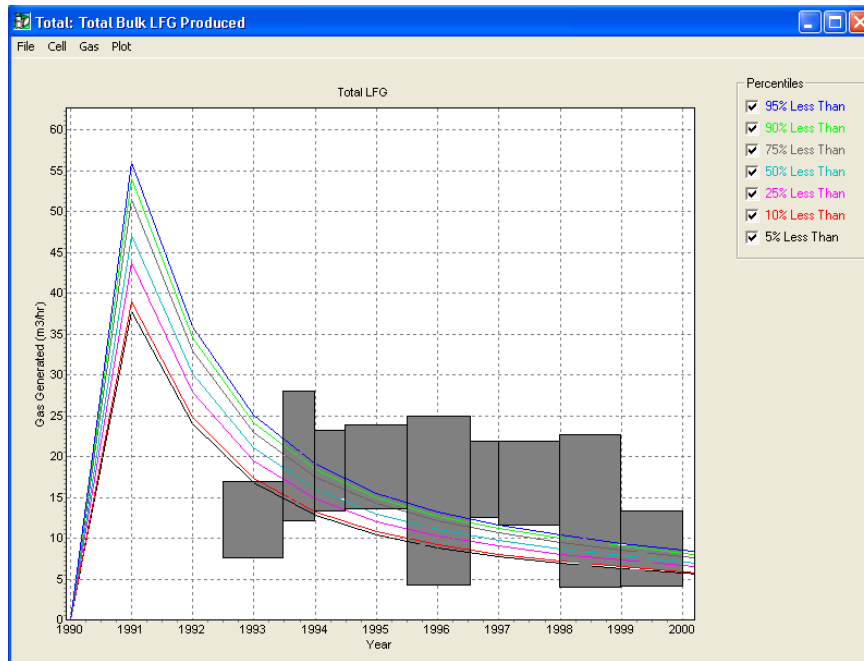

Figure 7.2a: Brogborough Test Cells: Modelled Data Overlain by the Observed Range - GasSim2
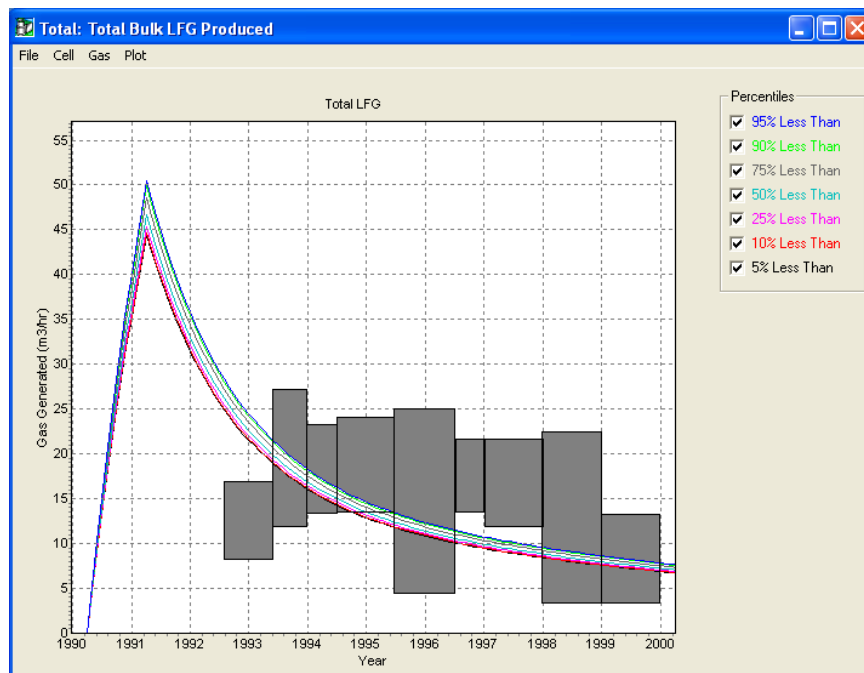
Figure 7.2b: Brogborough Test Cells: Modelled Data Overlain by the Observed Range - GasSim2.5

Case Study: Buckinghamshire Landfill (Unidentified)

Introduction

A Buckinghamshire Landfill (otherwise unidentified) was validated against by the HELGA framework. Therefore GasSim2.5 source and emissions modules have been validated against the data provided.

Input Values

The input values are summarised in Table 7.5. Where site-specific data was not available, default values, reported in Chapter 5, have been used.

Table 7.5: Summary of Site-Specific Inputs for Buckinghamshire Landfill

Input Parameter	Value	Units	Distribution	Justification
Infiltration	50 ± 5	mm/y	Normal	Not required as the moisture content will be entered rather than calculated.
Moisture Content	Wet	-	-	Gregory et al. (1999).
Waste Input	2×10^6	t	Single	Waste filled over 8 years: 78/79 - $200,000 \pm 10,000$ ty^{-1} 80/81 - $200,000 \pm 10,000$ ty^{-1} 82/83 - $260,000 \pm 10,000$ ty^{-1} 84/85 - $333,000 \pm 10,000$ ty^{-1} Gregory et al. (1999) with some uncertainty added.
Waste Breakdown	Dom 100	%	Single	Gregory et al. (1999).
Composition	1980 - 2010	-	-	Gregory et al. (1999).
Surface Capping	1 m clay at 1×10^{-11}, 1×10^{-10}, 1×10^{-9}	m and ms^{-1}	Log Triangular	Gregory et al. (1999).
Liner Construction	1 m clay at 1×10^{-9}	m and ms^{-1}	Log Triangular	Assumed to be the same design as the surface capping.
Gas Collection	700 - 1,000	m^{3}h^{-1}	-	Gregory et al. (1999).
Carbon Dioxide to Methane Ratio	50:50	-	Single	Assumed.
Landfill Area	70,000	m^2	Single	Gregory et al. (1999).

The surface emissions were modelled using the same scenarios as the HELGA framework:

- Scenario 1: 85% LFG collection efficiency and 70% biological oxidation of fugitive methane in the cap; and
- Scenario 2: 95% LFG collection efficiency and 90% biological oxidation of fugitive methane in the cap.

Validation Results

The monitored gas productions have been overlain on the simulated gas production curve and the range of LFG production reported for years 18 to 20 (Figure 7.3a from GasSim2 and Figure 7.3b from GasSim2.5). GasSim2.5 outputs of concentrations are similar to the results predicted by GasSim2.

Figure 7.3a: Buckinghamshire Landfill: Modelled Data Overlain by the Observed Range – GasSim2 Output

Figure 7.3b: Buckinghamshire Landfill: Modelled Data Overlain by the Observed Range – GasSim2.5 Output

The simulation has simulated the waste moisture content within the cells as wet, which will lead to rapid degradation of the waste. The results show that the simulated gas production curve lies within or very close to the monitoring data. This simulation has been undertaken mainly using single values, due to the lack of published data on this site. However, increasing the uncertainty in the inputs would increase the percentile range and therefore it is anticipated that the observed values would lie within this range.

Case Study: Quarry Landfill (Unidentified)

Introduction

The bulk gas generation module, with a flaring scenario implemented, has been validated against data provided from an unidentified landfill site. The landfill site is situated within a former quarry covering a total area of nearly 10 Ha. Waste emplacement began in 1990 and is planned to have totalled 1.5 million tonnes by completion in 2006.

Input Values

The input values are summarised in Table 7.6 – 7.7. Where site-specific data was not available, default values reported in Chapter 5 have been used.

Table 7.6: Summary of Site-Specific Inputs for Quarry Landfill (Unidentified)

Input Parameter	Value	Units	Distribution	Justification
Infiltration	32.5	mm/y	Normal	Operator value provided.
Moisture Content	Calculated	-	-	Moisture content is calculated.
Waste Density	1.0	tm^{-3}	Normal	Operator value provided.
Waste Input	1,478,292	t	Single	Total waste emplaced over 17 years, variation with time shown in Table 7.7.
Waste Breakdown	See Table 7.7	%	Single	Assumed domestic waste is as 1980's – 2010 waste stream and 75% of commercial and industrial waste is as commercial waste, remainder is inert (Operator values provided).
Composition	1980 – 2010	-	-	Assumed GasSim default.
Carbon Dioxide to Methane Ratio	45 ± 10:55 ± 10	-	Triangular	Within the range of operator's records from the site.
Capped	Various	-	Single	Progressively capped from 1997 to 87% capped at 2006 (Operator data).
Cap Design	Single	-	-	Operator information.
Cap Thickness	0.0020 – 0.0025	m	Uniform	Estimated for a HDPE cap.
Cap Hydraulic Conductivity	$1x10^{-14}$ - $1x10^{-12}$	ms^{-1}	Log uniform	Estimated for a HDPE cap.
Liner Design	Composite			Operator information.
Layer 1 Thickness	0.0020 – 0.0025	m	Uniform	Estimated for a HDPE liner.
Layer 1 Hydraulic Conductivity	$1x10^{-14}$ - $1x10^{-12}$	ms^{-1}	Log uniform	Estimated for a HDPE liner.
Layer 2 Thickness	1 – 1.5	m	Uniform	Estimated for a clay liner.
Layer 2 Hydraulic Conductivity	$1x10^{-10}$ – $1x10^{-9}$	ms^{-1}	Log uniform	Estimated for a clay liner.
Leachate Head	1.0, 0.5	m	Normal	Operator information.
Landfill Length N/S	312	m	Single	Derived from operator information.
Landfill Length E/W	309	m	Single	Derived from operator information.

Table 7.7: Summary of Site-Specific Annual Waste Inputs and Waste Breakdown for Quarry Landfill Site

Year	Total Waste (t)	Domestic (%)	Commercial (%)	Inert (%)
1990	30,000	100	0	0
1991	30,000	100	0	0
1992	30,000	100	0	0
1993	30,000	100	0	0
1994	30,000	100	0	0
1995	30,000	100	0	0
1996	30,000	100	0	0
1997	140,500	72	9	19
1998	193,372	77	9	14
1999	226,045	74	11	15
2000	255,550	75	11	14
2001	148,700	54	24	22
2002	104,700	53	27	20
2003	69,425	58	27	15
2004	55,000	55	34	11
2005	45,000	67	25	8
2006	30,000	100	0	0

Validation Results

Bulk gas emissions simulated using GasSim (Figure 7.4b from GasSim2.5) indicate that the total landfill gas production for the site peaks over the period 2002 - 2007, with peak landfill gas production between 525 and 1,040 m^3h^{-1} (5% and 95%iles, respectively). Using monitoring data provided by the site operator, the quantity of landfill gas collected by the gas transmission pipework (corrected by removal of air ingress) was quantified at 570 m^3h^{-1} in February 2000 and at 770 $^3h^{-1}$ in December 2000. These data lie between the 50% and 95%iles of the simulated landfill gas profile (Figure 7.4b from GasSim2.5).

From Figures 7.4a and 7.4b, GasSim2.5 outputs of concentrations are similar to the results predicted by GasSim2. However, a wider range of values between the 5%ile and the 95%ile is predicted by GasSim2 comparing to the range by GasSim2.5. The wider spread of percentile values on version 2.0 is the result of a bug whereby the LFG percentile graphs are calculated by adding up the percentiles for CO_2, CH_4 and H_2. The bug has been fixed in Version 2.5 as there is a fixed amount of carbon and only two possible degradation rates so you only get two visible percentile curves (one for the 95%ile and 90%ile, and the other for all percentiles below 75%ile).
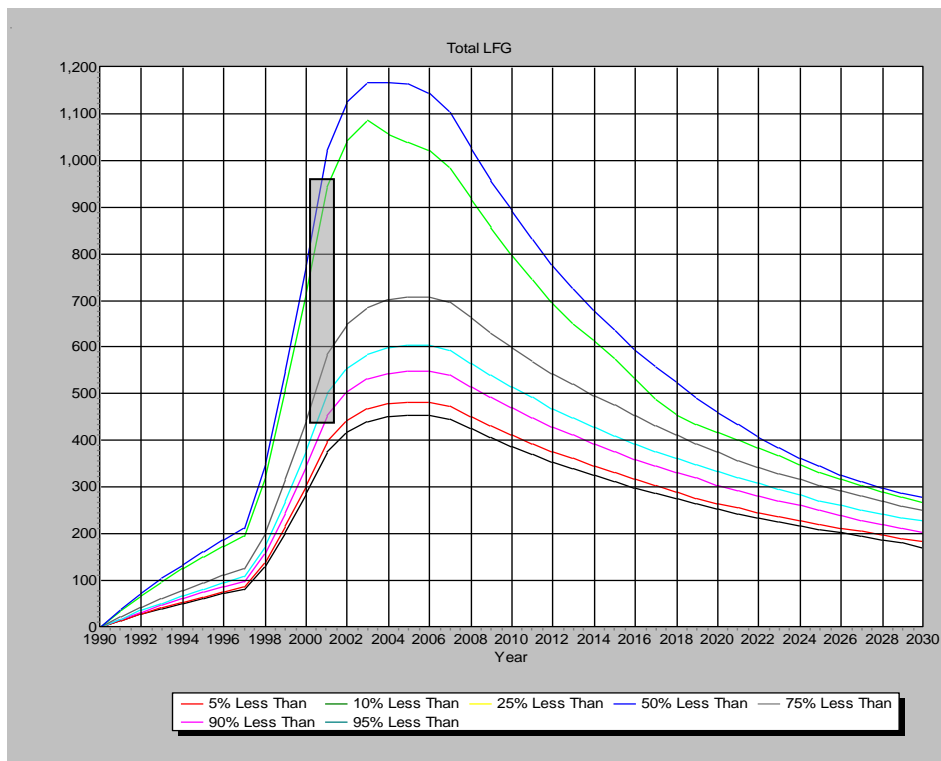
Figure 7.4a: Gas Production Curves for Quarry Landfill – GasSim2 Output
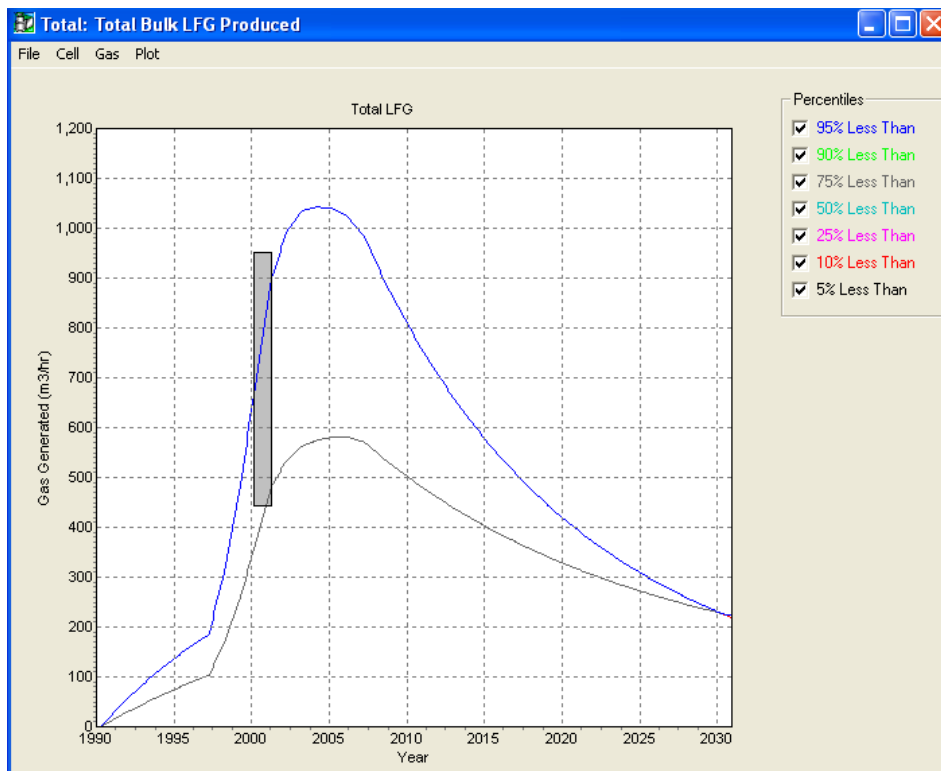
Figure 7.4b: Gas Production Curves for Quarry Landfill – GasSim2.5 Output

Case Study: Berkshire Landfill (Unidentified)

Introduction

A Berkshire Landfill (otherwise unidentified) has been monitored for surface emissions, using flux boxes, for validation with the surface emissions module of the model.

Input Values

The input values are summarised in Table 7.8 – 7.9. Where site-specific data was not available, default values, reported in Chapter 5, have been used.

Table 7.8: Summary of Site-Specific Inputs for Berkshire Landfill

Input Parameter	Value	Units	Distribution	Justification
Infiltration	63, 6.3	mm/y	Normal	Site-specific data, supplied by the operator.
Moisture Content	Calculate	-	-	Site-specific data, supplied by the operator.
Waste Density	1.0	tm^{-3}	Single	Site-specific data, supplied by the operator.
Waste Input	-	T	Single	Site-specific data, supplied by the operator: (Table 7.8a).
Waste Breakdown	Varies	%	Single	Varies from 100% commercial, with quantities of domestic to inert and civic amenity wastes. Site-specific data, supplied by the operator.
Composition	1980 - 2010	-	-	Default.
Carbon Dioxide to Methane Ratio	42.86: 57.14	-	Single	Site-specific data, supplied by the operator.
Capped	100% in 2002	-	Single	Site-specific data, supplied by the operator.
Cap Design	0.65 m clay at 1×10^{-9}, 1×10^{-10}, 1×10^{-11}	m and ms^{-1}	Single and Log triangular	Default values.
Liner Design	1.5 m clay at 1×10^{-9}, 1×10^{-10}, 1×10^{-11}	m and ms^{-1}	Single and Log triangular	Site-specific data, supplied by the operator.
Landfill Length N/S	490	m	Single	Default values.
Landfill Length E/W	490	m	Single	Assumed that the landfill is a cube, with a total area as defined in Bogner et al., 1997.
Flare Capacities	3 x 50 - 500 and 1 x 50 - 1500	m^3hr^{-1}	Single	Site-specific data, supplied by the operator.
Engine Capacity	450	m^3hr^{-1}	Single	Site-specific data, supplied by the operator.

Table 7.9: Summary of Site-Specific Annual Waste Inputs and Waste Breakdown for Quarry Landfill Site

Year	Total Waste (t)
1978	87,860
1979	107,000
1980	10,500
1981	71,000
1982	63,000
1983	72,000
1984	75,000
1985	78,000
1986	80,000
1987	88,000
1988	114,000
1989	125,000
1990	141,000
1991	109,000
1992	38,000
1993	58,000
1994	26,000
1995	30,000
1996	30,000
1997	30,000
1998	30,000
1999	30,000
2000	20,000
2001	10,000

The surface emissions were modelled assuming 90% collection efficiency and 0% biological oxidation of fugitive methane in the cap.

Validation Results

The model predicts that the average net surface emissions (after allowing for LFG collection and biological methane oxidation) were between 5×10^{-2} and 8×10^{-2} mgm^{2}s^{-1}. These values were slightly higher than the methane emissions reported in the field from the different capping types, which ranged from 2×10^{-4} mgm^{2}s^{-1} to 4×10^{2} mgm^{2}s^{-1}, but very close to the measured net average emission of 9×10^{-2} mgm^{2}s^{-1}.

Case Study: Green Valley Landfill

Introduction

The trace surface emissions module has been validated against Green Valley Landfill Site (USA), which has been monitored for the emissions of a number of trace gas species (Bogner et al., 1997). GasSim has been validated against the emission rates for benzene, tetrachloroethene, trichloroethene and vinyl chloride in a similar way to the HELGA framework.

Input Values

The input values are summarised in Table 7.10. Where site-specific data was not available, default values, reported in Chapter 5, have been used.

Table 7.10: Summary of Site-Specific Inputs for Green Valley Landfill

Input Parameter	Value	Units	Distribution	Justification
Infiltration	10 ± 1	mm/y	Normal	Assumption. However, this parameter is not used as the moisture content is defined as dry.
Moisture Content	Dry	-	-	Gregory et al., (1999).
Waste Density	0.8 - 1.2	tm^{-3}	Single	Default.
Waste Input	322,262	T	Single	Assumed 146,454.5 ty^{-1} for 22 years, Bogner et al., (1997).
Waste Breakdown	Dom 100	%	Single	Gregory et al., (1999).
Waste Hydraulic Conductivity	$1x10^{-5}$ – $1x10^{-7}$	ms^{-1}	Log uniform	Default value - increased to $1x10^{-7}$ to $1x10^{5}$, to reflect the permeability of the waste at the landfill sides.
Composition	1980 - 2010	-	-	Assumed that USA and UK waste streams are similar.
Carbon Dioxide to Methane Ratio	50:50	-	Single	Default.
Capped	100%	-	Single	Bogner et al., (1997).
Cap Design	1 m clay at$1x10^{-9}$	m and ms^{-1}	Single	Bogner et al., (1997).
Liner Design	None	-	-	Assumed that no liner was present.
Landfill Length N/S	894.4	m	Single	Assumed that the landfill is a cube, with a total area as defined in Bogner et al., (1997).
Landfill Length E/W	894.4	m	Single	Assumed that the landfill is a cube, with a total area as defined in Bogner et al., (1997).
Flare Capacity	2 x 3,541	$m^{3}hr^{-1}$	Single	Bogner et al., (1997).
Engine Capacity	2 x 2,354	$m^{3}hr^{-1}$	Single	Bogner et al., (1997).
Trace Gas Concentrations	-	mgm^{-3}	-	Default values.

Validation Results

The model simulation undertaken using the default trace gas concentrations indicated that the observed range of benzene, tetrachloroethene and vinyl chloride matched the default range that GasSim simulates (Table 7.11). GasSim overestimates the emissions of VOCs with the 95%ile emissions occurring at a similar order of magnitude as the maximum observed emission. This is due to the fact that GasSim does not simulate the reduction of VOCs

in the soil cap by microbiological and other processes, as discussed by Bogner et al., (1997) and that the observed data is limited and may not have detected high emissions sources, e.g. fissures.

Table 7.11: Green Valley Simulated and Observed Trace Gas Emissions

Species	GasSim Outcome		Bogner et al., (1997) Reported Range	
	5% (mgm^{-2}s^{-1})	95% (mgm^{-2}s^{-1})	Min (mgm^{-2}s^{-1})	Max (mgm^{-2}s^{-1})
Benzene	1.7x10^{-7}	6.9x10^{-5}	-	5.37x10^{-5}
Tetrachloroethene	3.5x10^{-8}	4.3x10^{-4}	3.99x10^{-7}	1.23x10^{-5}
Trichloroethene	6.9x10^{-8}	9.8x10^{-5}	4.50x10^{-10}	3.10x10^{-6}
Vinyl Chloride	1.7x10^{-7}	6.6x10^{-5}	9.61x10^{-6}	3.18x10^{-5}

Case Study: Ten Unnamed Landfills

Validation of ten unnamed landfills was previously performed in the summer of 2005 using GasSim2. The validation of those ten sites has not been repeated using GasSim2.5. The general characteristics of the landfills using GasSim2 are given in Table 7.12 below, to show that the sites were quite varied in terms of their current masses of waste in place, waste compositions, and the sizes of gas plant used to manage emissions. The gas plant abstraction data was very accurately known, and this was used as the benchmark against which the sites were calibrated. The recommended process for calibrating a GasSim model against real site data is to tailor the waste degradation rates to achieve a modelled abstraction rate similar to the known value. This was done without varying other default parameters such as gas collection efficiency, to see how realistic the other defaults in the gas management module were. Calibration was achieved for all ten sites while keeping the waste degradation rates within the normal range of default parameters supplied with the model (dry site – average site – wet site). Well managed bioreactor landfills may exhibit degradation rates faster than those supplied for a wet site, and these landfills require site-specific waste degradation factors.

Table 7.12: Summary of Sites A – K: Waste types, Waste in Place, Cells Modelled, Moisture Content Modelled, and Gas Production and Abstraction Compared to Site Data

Site	Waste Types Accepted (>10% of waste stream)	Waste in place in 2005 (Mt)	No of cells modelled in GasSim2	Moisture content modelled (dry/average/wet/range of these) (state which)	50%ile Gas production forecast in 2005 (m³/h)	50%ile Gas abstraction forecast in 2005 (m³/h)	Site data for Gas abstracted to engine/flare in 2005 (m³/h)
A	Domestic, Commercial, Industrial, Inert	13.50	26	Slow: 0.0343 Dry Moderate 0.0566 to Fast 0.0864 Average	8289	7470	7400
B	Domestic, Commercial, Industrial, Inert	15.52	16	GasSim Default Wet	6195	5610	5700
C	Domestic, Commercial, Inert	17.27	18	16 cells modelled as wet 2 future cells modelled as average	12979	7700-9600	10000
D	Domestic, Commercial, Industrial, Inert	2.74	7	GasSim Default Average. Forecasts include entrained air to align model with abstraction data	2002: 2128 2004: 2177	2002:1754 2004:1446	2002: 1800 2004: 1393
E	Domestic, Commercial, Industrial, Inert	10.33	5	GasSim Default Wet	6700	4230	4672
F	Domestic, Commercial, Industrial, Inert	5.58	24	Slow: 0.025 Dry Moderate 0.055 to Fast 0.085 Average	2320	1860	2029
G	Domestic, Commercial, Industrial, Inert	1.95	16	Slow: 0.0575 Average Moderate 0.0950 to Fast 0.1450 Wet	1420	1190	1200
H	Domestic, Industrial, Inert	3.89	14	GasSim Default Average	2320	2120	2177
J	Domestic, Commercial, Inert	3.52	5	GasSim Default Wet	1656	1300	1280-1400
K	Domestic, Commercial, Industrial	41.02	11	GasSim Default Wet	17955	11887-12516	11843

GasSim Default Dry/Saturated Degradation Rate		GasSim Default Average Degradation Rate		GasSim Default Wet Degradation Rate	
Slow:	0.013	Slow:	0.046	Slow:	0.076
Moderate	0.046	Moderate	0.076	Moderate	0.116
Fast	0.076	Fast	0.116	Fast	0.694

Case Study: Foxhall Landfill

Introduction

The Lateral Migration module has been validated against Foxhall Landfill Site, which is well characterised and has bulk gas and VOC monitoring data for the lateral emission plume (Williams et al., 1999). This landfill was also used to validate the HELGA framework.

Input Values

The input values are summarised in Table 7.13. Where site-specific data was not available, default values, reported in Chapter 5, have been used.

Table 7.13: Summary of Site-Specific Inputs for Foxhall Landfill Site

Input Parameter	Value	Units	Distribution	Justification
Infiltration	50 ± 5	mm/y	Normal	Assumed, as most cap are designed to allow around 50 mm/yr infiltration.
Moisture Content	Calculated	-	-	Calculated using default values.
Waste Density	0.8 - 1.2	tm^{-3}	Single	Default Values.
Leachate Head	1.5	m	Single	Williams et al., 1999.
Waste Input	-	t	Single	Waste filled over 6 years: 1982 - 1987 133,333 ty^{-1} (Williams et al., 1999).
Waste Breakdown	60% Dom., 30% Inert, 20% Com.	%	Single	It has been assumed that proportions of waste entered represent the breakdown of domestic, commercial and industrial waste deposited.
Composition	1980 – 2010	-	-	Assumed.
Carbon Dioxide to Methane Ratio	40:60	-	Single	Assumed proportion outside the liner and inside are the same (Williams et al., 1999).
Capped	100%	-	Single	100% capped at the end of the operational period. (Williams et al., 1999).
Cap Design	$1x10^{-9}$, $1x10^{-8}$, 1.0	m/s	Log triangular	HDPE cap, assumed to be 0.005 m thick with a hydraulic conductivity of range to account for the passive pipe works and venting wells (Williams et al., 1999).
Liner Design	$1x10^{-6}$, $5x10^{-3}$, $9x10^{-2}$		Log triangular	Assumed for sand permeability.
Landfill Length N/S	180	m	Single	Measured from (Williams et al., 1999).
Landfill Length E/W	350	m	Single	Measured from (Williams et al., 1999).
Ground Porosity	25, 25, 50	%	Triangular	The most likely has been obtained for Williams et al., (1999) and a typical value within the range provided by a hydrogeological text book (Freeze and Cherry, 1979).
Moisture Content	1.0, 5.0	%	Uniform	Assumed to be well drained.

Validation Results

Bulk gas lateral migration simulated using GasSim2.5 (Figures 7.5a and 7.6a from GasSim2 and Figures 7.5b and 7.6b from GasSim2.5) indicate that the emission curves broadly follow those observed at Foxhall, with the observed data lying within the predicted range.

For the results from GasSim2, 5% or 10%ile values slightly over predict the distance over which the 60% and 40% methane and carbon dioxide concentrations extend, respectively. This results in the gas concentrations declining slightly faster after 40 m than was observed in the field and thus potentially slightly under predicting the extent of the plume (which extended 80 m before methane reduced below 1% and over 100 m for carbon dioxide to reduce to below 1%). It should also be noted that the GasSim2 50% and 95%iles over predict the extent of the gas migration. These differences may be accounted for by the assumptions that have made when creating the model, e.g. the waste breakdown and composition etc., may have increased the quantity of gas generation and thus lateral emission. Also GasSim2 does not allow the methane to oxidise to form carbon dioxide, assumes no losses, and also assumes that the gas migrates in all directions from the landfill, which may not be the case.

For the results from GasSim2.5, 5% or 10%ile values slightly under predict the distance over which the 60% methane concentrations were observed range 0 – 15m. However, 90%ile values of methane are very close to the observed on site. The measured methane concentrations between 60% and 65% were measured over a range of 0 - 15 m from the site boundary. A methane concentration of 35% - 50% was observed at locations 30 m from the boundary and the methane concentration decreases to 25% - 40% at a distance of 40 m. The methane concentrations were measured between 15% and 24% at locations of 50 m from the site boundary.

Figure 7.5a: Predicted Range of Laterally Migrated Methane from Foxhall Landfill – GasSim2 Output
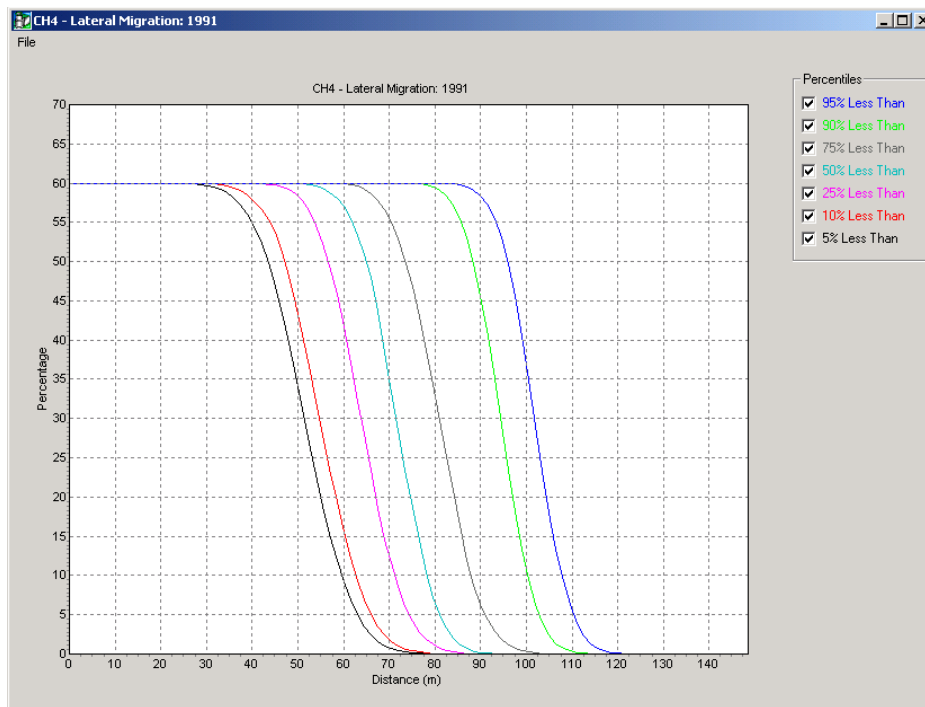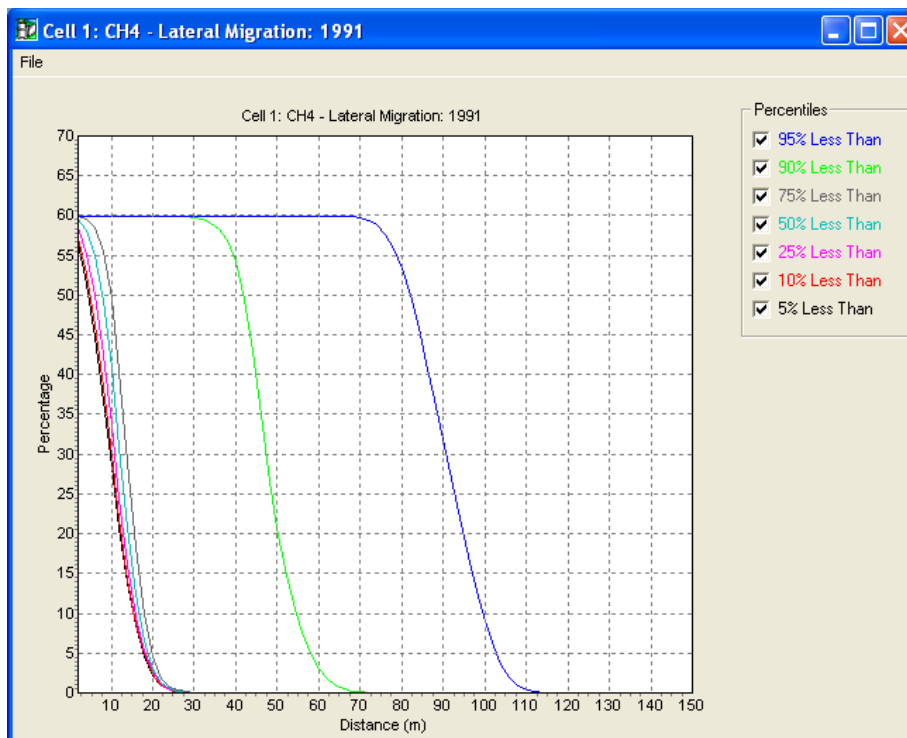

Figure 7.5b: Predicted Range of Laterally Migrated Methane from Foxhall Landfill – GasSim2.5 Output
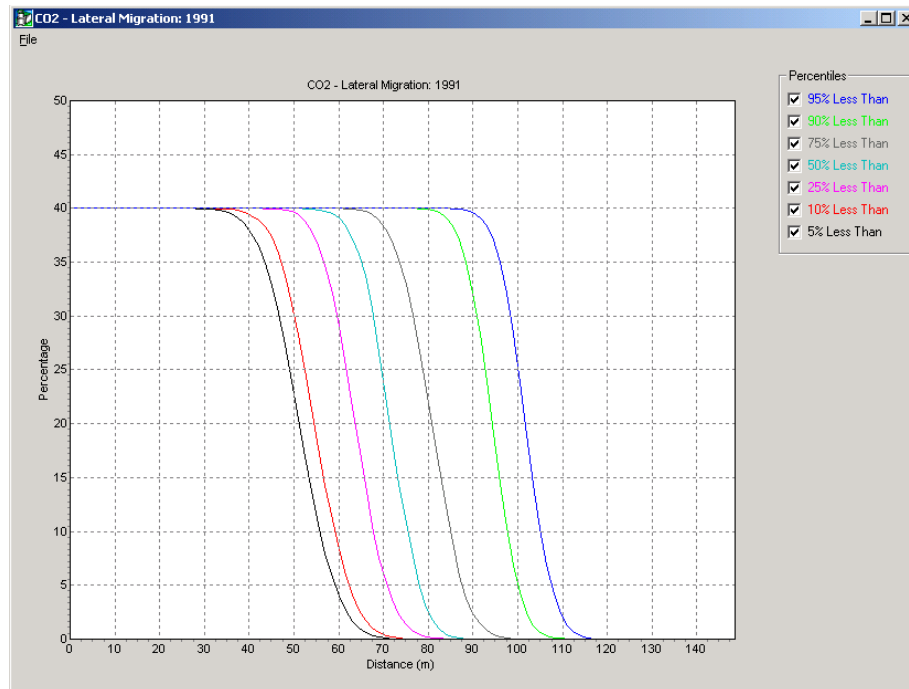
Figure 7.6a: Predicted Range of Laterally Migrated Carbon Dioxide from Foxhall Landfill – GasSim2 Output
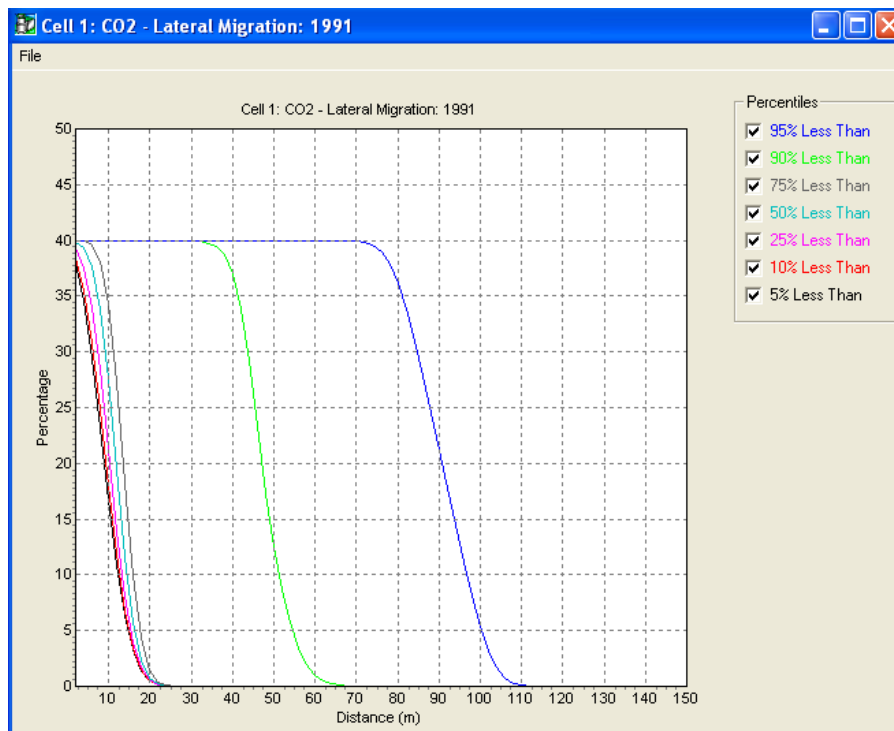

Figure 7.6b: Predicted Range of Laterally Migrated Carbon Dioxide from Foxhall Landfill – GasSim2.5 Output

CHAPTER 8: GLOSSARY

Acetogenic degradation	The aerobic degradation of waste resulting in the generation of carbon dioxide, hydrogen and fatty acids.
Adsorptive capacity	Capacity for the waste to adsorb water before generating free leachate.
Air diffusion coefficient	Rate at which a gas will move through air solely due to molecular movement.
Air:fuel ratio	Ratio of air to LFG (fuel) used by an engine or flare.
Atmospheric density	Ratio of the proportion of atmosphere mass to the volume it occupies.
Atmospheric deposition - wet	Deposition of species contained within the atmosphere as a result of rainfall/washout.
Atmospheric deposition - dry	Deposition of species contained within the atmosphere during dry conditions.
Atmospheric dispersion	Mechanism for distribution of species within the air around the landfill. The atmospheric dispersion module incorporates the USEPA's latest version of AERMOD, developed by the American Meteorological Society (**A**MS) and the US**E**PA **R**egulatory **M**odel **I**mprovement **C**ommittee, AERMIC. AERMOD is thus the **AER**MIC **Mod**el.
Atmospheric temperature	Average temperature of the atmosphere.
Available carbon	Quantity of carbon that is available to undergo decay to form LFG.
Biological methane oxidation	Conversion of methane to carbon dioxide in the soil as a result of micro-organisms.
Breakdown (of waste)	Definition of the waste mix by waste stream, e.g. 50% domestic, 40% commercial and 10% inert.
Bulk gas	Gases that make up the majority of the LFG volume, i.e. methane, carbon dioxide and hydrogen.
Cap	Engineered barrier used to cover a landfill.
Capped area	Area of a landfill that has been covered by an engineered barrier. Within GasSim it is also assumed that the gas control system is only active in the capped area.
Cellulose decay constants	Half-life values for the degradation of carbon and thus generation of LFG.
CFCs	Chlorofluorocarbons.
Co-disposal	The combined deposition of hazardous and non-hazardous waste.
Combustion	Burning of LFG.
Composition (of waste)	Fractionation or make up of the waste streams, i.e. the amount of paper, fines, putrescibles, etc.
Conceptual model	A simplified representation of how a real system is believed to behave based on qualitative analysis of field data. A quantitative conceptual model includes preliminary calculations for key processes.
Conductivity	See Hydraulic conductivity.
Daughter species	Species formed during combustion from a parent species in LFG, e.g. hydrogen fluoride (HF) is formed during the combustion process from fluorine (F).
Decay – rapid, moderate, slow	Decomposition of available carbon to generate LFG. GasSim simulates waste fractions degrading at three different rates – rapid, moderate and slow.
Decomposition	Decay of available carbon to generate LFG.
Default values	Generic information provided with GasSim that may be used where site-specific data is unavailable.
Degradable carbon	The quantity of carbon that is degraded to generate LFG.
Degradation rate	A constant that defines the rate at which waste decomposes and thus LFG is generated.
Destruction efficiencies	The ratio of a species removed from the 'raw' LFG by the process of combustion (by either flaring or engines).
Deterministic model	A model where all elements and parameters of the model are assigned unique values.
Discrete feature	An anisotropic area of the cap, e.g. fissures, passive venting wells, etc.
Downtime	The proportion of time that engines and flares are not operating as a result of routine servicing and maintenance.
Effective porosity	Volume of void space in a solid that is available for fluid (liquid or gas) movement.
Effective rainfall	Total rainfall less evaporation, evapotranspiration, run-off and storage.
Emissions	Release of gas from a landfill surface, side, or from an engine/flare exhaust.

Engine	A spark ignition machine which generates electricity from the combustion of LFG.
Engine capacity	The volume of gas that an engine uses at the defined methane to carbon dioxide ratio.
Engine output	The bulk and trace gas emissions from the engines.
Engineered barrier system	A containment structure designed and constructed to inhibit the migration of landfill leachate and/or gas from operating or closed landfills.
Environmental transport	The movement of LFG through the geosphere and the atmosphere.
Engineering controls	Operational measures for the management of emissions of LFG.
EPER	European Pollutant Emission Register. The EU equivalent of the Pollution Inventory for IPPC.
Exhaust height	The distance above ground level of an engine exhaust.
Expected value	Most likely value of a forecast.
Flare	Equipment used to combust LFG.
Flare capacity	Operational range of the flare in terms of a minimum and maximum quantity and quality of LFG that may be combusted.
Flare output	Bulk and trace gas emissions from the flares.
Flaring	Combustion of methane and other LFG components by burning in an enclosed flare.
Flux	Emissions from an area measured as mass per unit time.
Gas collection	Removal of gas from a landfill by vertical and horizontal gas wells and sent to a flare or engine.
Gas collection efficiency	Percentage of gas generated within a landfill that is removed by the gas collection system.
Gas conductivity	This is a measure of the ability of a geological unit or engineered barrier to transmit a unit volume of gas through a unit cross-sectional area under a unit gradient in a unit time. The parameter is a function of both the properties of the fluid and the properties of the geological unit through which the fluid is transmitted.
Gas plant module	Part of the model which includes the specification of the LFG collection and utilisation options for conversion to energy using spark ignition engines, or flaring.
Gas production curve	Graph of LFG volume (generated or emitted) against time.
Gas viscosity	The resistance of a gas to flow.
GasSimLite	A simplified version of GasSim, designed to allow Pollution Inventory (PI) reporting to be carried out. This model is available free on the internet, but has limited functionality.
Generated gas	The amount of bulk or trace gas simulated, used as the source term for the rest of the model.
Global impact	The effect on the earth's environment from ozone depletion and global warming.
Global warming potential (GWP)	Contribution to climate effects by contaminant emissions.
Half-life	Time for the concentration of a species to decay to 50% of its original mass. Half-lives are used in GasSim to define decay of trace gases and cellulose degradation rates.
HCFCs	Hydrochlorofluorocarbons.
Head	A measure of fluid potential (either groundwater or leachate) where flow occurs from regions in which potential is high to those in which it is low. Head is commonly expressed in metres of fresh water and is the sum of both an elevation and a pressure term.
HELGA framework	The initial Environment Agency project that produced the majority of the equations that have been coded in GasSim (Reference: Gregory RG, Revans AJ, Hill MD, Meadows MP, Paul L and Ferguson CC. (1999). A Framework to Assess the Risks to Human Health and the Environment from Landfill Gas, Environment Agency Technical Report P271 (CWM 168/98), ISBN 1 85 705254 4).
Histogram	Chart showing frequency distribution of parameter values on an interval scale.

Infiltration (net)	The volume of water per unit area which passes into the waste mass. In GasSim this parameter includes both effective rainfall and any other source of water that may affect the water balance of the landfill under consideration, for example lateral inflows, leachate re-circulation and co-disposal of liquids.
IPCC	Intergovernmental Panel on Climate Change.
IPPC	Integrated Pollution Prevention and Control.
Iteration	A single run of the model, using one randomly selected value (within the constraints of the probability distribution function) for each input parameter and generating a single realisation.
Landfill characteristics	The landfill geometry and cap/liner characteristics.
Landfill gas (LFG)	Volatile species produced by the decomposition of waste.
Landfill geometry	The landfill length (north-south) and width (east-west). These are used to calculate the surface area and depth, along with the waste density.
Lateral emissions	Uncontrolled release of LFG below ground from the sides of a landfill.
Lateral migration	The movement of LFG from the sides of a landfill transversely through the unsaturated zone of the geosphere.
Leachate	Contaminated water generated within a landfill as a consequence of the reaction between decomposing waste materials and infiltration.
Leachate head	Height (head) of leachate above the base of the landfill.
LFG management systems	Processes used to limit uncontrolled emissions of LFG.
Liner	Engineered medium installed in the base and sides of a landfill, primarily to prevent the release of leachate.
Log normal (probability) distribution	A probability distribution defined by the logarithm of the mean and the standard deviation expected for a given parameter.
Log triangular (probability) distribution	A probability distribution defined by the logarithm of the minimum, most likely and maximum values expected for a given parameter.
Log uniform (probability) distribution	A probability distribution defined by the logarithm of the minimum and maximum values expected for a given parameter.
Maximum flare capacity	Greatest amount of gas that a flare can use at a defined methane to carbon dioxide ratio.
Mean	An arithmetically-derived value calculated by dividing the sum of all of the values by the total number of values. More commonly referred to as the average and may be differentiated from both the mode (most frequent value in a distribution) and the median (central value in a distribution).
Membrane	A synthetic material manufactured and installed in the base of a landfill cell to reduce the rate of leachate and gas egress (and groundwater ingress). Can also be used as a capping system. In GasSim, membrane refers only to a synthetic (HDPE type) containment layer.
Methanogenic degradation	Decomposition of waste under anaerobic conditions principally to produce carbon dioxide and methane.
Minimum flare capacity	Smallest amount of gas that a flare can use at a defined methane to carbon dioxide ratio.
Moisture content	Ratio between the mass of water present in a sample and the dry mass of the solids.
Molar volume of a gas	Volume a gas occupies per mole of molecules. This value is the same for all gases at equal temperature and pressure. Molar volume (at STP) is 2.241×10^{-2} m^3mol^{-1}.
Molecular ratio	The ratio of a Parent to its Daughter Species, based upon molecular weights, i.e. F to HF is 1.05.
Monte Carlo simulation	A system that uses random numbers to repeatedly sample from within a probability distribution to measure the effects of uncertainty.
Non co-disposal	The disposal of non-hazardous waste, without the disposal of hazardous waste.
Normal (probability) distribution	A probability distribution defined by the mean and the standard deviation of the mean expected for a given parameter.
Odour threshold value	Point at which the odour is no longer considered to be detectable.
Operational area	Area of a landfill that is uncapped and/or receives waste.
Operational period	Total number of years for which a landfill site is being filled.
Orifice diameter	Size of an engine exhaust or flare stack.

Ozone depletion potential (ODP)	The ODP is the ratio of the impact on ozone of a chemical compared to the impact of a similar mass of CFC-11. Thus, the ODP of CFC-11 is defined to be 1.0. Other CFCs and HCFCs have ODPs that range from 0.01 to 1.0. The halons have ODPs ranging up to 10. Carbon tetrachloride has an ODP of 1.2, and methyl chloroform's ODP is 0.11.
PAHs	Poly-aromatic hydrocarbons.
Parameter	A variable used in calculations performed by GasSim.
Parent species	Species destroyed during combustion to generate a daughter species in LFG, i.e. fluoride (F) is destroyed during the combustion process to from hydrogen fluorine (HF).
PI reporting	Information on the Pollution Inventory release of gases as required by the Environment Agency.
Porosity	Ratio of the volume of voids in a porous geological medium to the volume occupied by matter.
Potential temperature gradient	Potential temperature gradient: The change in temperature of the atmosphere with height which would exist for dry air if brought adiabatically from its initial state to the standard pressure (selected arbitrarily) of 1000 mb.
PPC	Pollution Prevention and Control. Applies to facilities regulated under the Pollution Prevention and Control (England and Wales) Regulations 2000 (as amended).
Pressure	Force applied to a unit area of surface.
Project details	The dialogue box that contains information on the model run along with the initial set up parameters, e.g. operational period, project name and number of iterations.
Realisation	Forecast generated by a single iteration of the model.
Residual results	Amount of gas remaining after collected (flared or utilised) gas has been removed.
Roughness length	A measure of the mechanical turbulence introduced into the atmosphere by the roughness of the underlying surface, which is roughly 10% of the average height of the surface protrusions.
Simulation	Predictive model of the conditions at a site, which incorporates uncertainty in the input parameter values.
Simulation period	The time period for which the modelling will be undertaken.
Single Value	The case where a single value is used instead of a PDF within a probabilistic assessment.
Soil cap	Soil that is either placed directly on the waste or on the engineered cap.
Source depletion	The decline of a source as a result of releases or deposition.
Source term	The module used to determine the degradation of waste and thus the generation of bulk and trace gas.
Species	Term describing elements, ions or molecules.
Stack height	The distance above ground level of the flare stack.
Standard deviation	A measure of the spread of a series of values from the arithmetic mean of that series.
Surface emissions	Uncontrolled release of gas from capped and uncapped areas of a landfill.
Terrain type	A description of the characteristics of the ground surface over which the plume is dispersing.
Thermal buoyancy	The floating of the plume as a result of heat convection.
Time slices	Time series defining points in time, after the commencement of landfilling at which forecasts are made.
Trace gas	Minor species contained within LFG, e.g. benzene.
Trace gas inventory	The list of trace gases to be simulated.
Triangular (probability) distribution	A probability distribution defined by the minimum, most likely and maximum values expected for a given parameter.
Uncapped area	An open area of the landfill not covered by an engineered cap, but which may be covered by daily cover. This area is normally the operational area of the landfill in which filling is taking place.
Uniform (probability) distribution	A probability distribution defined by the minimum and maximum values expected for a given parameter.
Unsaturated zone	Portion of a porous permeable geological unit that lies above the water table but below the ground surface.
Utilisation (energy recovery)	Generation of electricity from LFG using spark ignition engines.

Vegetation stress	The inhibition of vegetation growth as a result of methane or carbon dioxide displacing oxygen from the soil around roots.
Vegetation stress limit	The threshold at which methane and carbon dioxide will cause vegetation dieback.
VOCs	Volatile Organic Compounds.
Volume of leachate recirculated	The quantity in m^3 of leachate that is recycled through the waste, normally by removing the leachate from the base of the landfill and reinjecting it near the top.
Waste breakdown	See Breakdown.
Waste component	Type of material contained within a waste stream, e.g. newspaper, cardboard, etc.
Waste composition file	File containing information on the composition of various waste streams.
Waste density	Mass of the waste per unit volume.
Waste deposition	Placement/filling of waste within the landfill during the operational period.
Waste fraction	A group of materials within waste components that decay at a similar rate, i.e. rapidly, moderately or slowly.
Waste hydraulic conductivity	The hydraulic conductivity of waste. This will be dependant upon the depth of waste and other waste characteristics.
Waste input	Tonnage of waste deposited each year.
Waste moisture content	Ratio between the mass of water present in the waste and the dry mass of the waste solids.
Waste streams	The breakdown of the waste mixture, i.e. domestic, commercial, inert, etc.
Water balance	An assessment of the volume of (water) recharge, storage and discharge within a system.
Water content	Ratio between the mass of water present and the dry mass of the solids.
Year/month commissioned	The time that an engine or flare is made available.
Year/month decommissioned	The time that an engine or flare ceases to be available.

GASSIM

CHAPTER 9: REFERENCES

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