A Framework to Assess the Risks to Human Health and the Environment from Landfill Gas

WS Atkins Environment

R&D Technical Report P271

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Statement of use
This R&D technical report documents the development of a framework for a landfill gas risk assessment tool to help the Environment Agency and others assess the human health and environmental risks of landfill gas emissions from landfill sites. The HELGA model is currently based in Microsoft Excel 97™ and requires further development before being released internally and externally complete with User Manual. R&D Technical Summary PS257 is also available and is related to this report.

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SUMMARY

This is the final report for R&D Project P1-283; *A Framework to Assess the Risks to Human Health and the Environment from Landfill Gas.* The project has delivered a model framework entitled HELGA (Health and Environmental risks form Landfill GAs), to help the Environment Agency assess the risks to human health and the environment from landfill gas (LFG). HELGA is a demonstration framework to test the feasibility of a fully developed model. When developed to commercial standards, the code is expected to be complementary to LANDSIM, the Environment Agency's risk assessment model for leachate migration into groundwater.

The HELGA model contain ten related modules:

1. Source term gas generation;
2. Emissions;
3. Atmospheric dispersion;
4. Lateral migration;
5. Migration into houses;
6. Human exposure;
7. Odour;
8. Vegetation stress;
9. Global atmospheric risk; and
10. a summary Output module.

The foundation of the model is a source term module, which is a flexible landfill gas (LFG) generation model that the user can tailor to an individual landfill site. The user can define the waste composition in terms of various waste streams, including *inter alia*, municipal, commercial, industrial and inert waste types, the era in which the waste was emplaced (to reflect compositional changes in different decades) and the moisture content of the waste.

These waste characteristics then feed into a first-order decay model that estimates LFG generation for up to 150 years. Programming limitations exist when combining the Microsoft Excel™ spreadsheet and Crystal Ball™ probabilistic risk assessment software, which limits the model working in a fully probabilistic mode. Therefore the source term module has been designed to be pseudo probabilistic. This means that ranges for gas generation forecasts, perhaps the most uncertain data to be generated by the model, have been sampled using the Crystal Ball™ Monte-Carlo sampling package, and the 95^{th}, 50^{th} and 5^{th} percentile results for gas generation per tonne of waste have been set as constants in a look-up table. The user can choose which set of forecasts (95^{th}, 50^{th} or 5^{th} percentiles) to use with the other user defined parameters, to give a maximum, average or minimum result for the outputs from the model.

The Emissions module takes the output (for 95^{th}, 50^{th} or 5^{th} percentiles) of the source-term module for a specified year and uses it to calculate LFG flux to the environment after allowing for gas collection, flaring, energy recovery and biological methane oxidation. This module uses information on the site gas collection system, flare and engine, cap and liner (if any) to calculate for a given year what proportion of the gas generated is emitted via each route. LFG generated and not collected is assumed to be in equilibrium with that emitted from the landfill cap or liner at a steady state.

The Atmospheric Dispersion module is in two parts:

- Atmospheric dispersion off site; and
- Atmospheric dispersion on site (only for worker exposure).

The off site dispersion module uses a Gaussian plume model that has some probabilistic aspects incorporated, and includes; chemical deposition, wind direction, flare plume buoyancy and atmospheric layer stability. On-site dispersion is calculated using a simple box model, and this gives a good approximation of exposure on site.

The lateral migration module comprises a diffusion model that uses a concentration gradient to drive LFG migration. The model accounts for the physical characteristics of the soil and gases or VOCs, and distance to the receptor. The model does not account for advective flow or methane oxidation in the ground due to a dearth of available information. The risk from a migration event is accounted for by examining the occurrence of various scenarios that may lead to advective flow through fractures in permeable ground.

Migration into houses is simulated to allow for gas entry via the ground and the atmosphere. There are two different types of building considered; those with suspended floors or cellars, and those with a slab floor design.

The exposure assessment module focuses on calculating intakes of pollutants by members of the public through three main routes; ingestion, inhalation, and dermal exposure. The data used for these modules comes mainly from work carried out by NRPB, with some information from other US or EU sources.

The odour module compares the chemical odour threshold with the concentration in air at the receptor. Similarly, the vegetation stress module compares the concentration of methane and carbon dioxide in the ground at the receptor with the concentration where vegetation stress is first observed.

The global atmospheric risk module uses the total emissions (including VOCs) from the site in a specified year to calculate the corresponding ozone depletion potential (ODP) and global warming potential (GWP). These figures can be compared with other model runs on the same site with different cap designs and gas management options to evaluate the best combination of gas management options for the environment.

The Output Module collates the results from the various modules in the spreadsheet workbook, and presents them in an easy to understand tabular form.

Validation of the model has been carried out on five landfills, to evaluate key outputs in the model. In all cases, the forecasts are in good agreement with observed measurements. Four Scenarios have also been developed to demonstrate how decisions on landfill gas cap design, flaring and gas utilisation can be made to optimise LFG emissions to the benefit of the local and global environment and human health. These scenarios demonstrate that good cap design together with gas collection and flaring and/or gas utilisation reduce global environmental risks, and generally reduce local human health risks. The only emissions to increase as a result of gas utilisation are the engine emission products, and these are not forecast to be generated in sufficient quantity to appear to be a health risk.

CONTENTS

1. INTRODUCTION

1.1 Purpose of this report

This is the technical report for Environment Agency R&D Project P1-283:

A Framework to Assess the Risks to Human Health and the Environment from Landfill Gas.

This report describes the methodology used in the development of a framework for risk assessment, and the implementation of this framework as a spreadsheet model, HELGA (**H**ealth and **E**nvironmental Risks from **L**andfill **GA**s). The model allows both landfill site operators and regulators to review and plan landfill gas management techniques to benefit human health and the environment. This final report is designed for widespread dissemination amongst the waste management community. The project commenced in August 1997 and the technical work was completed in August 1998. Since that period, the model has been trialled amongst the project steering group members.

1.2 Background to project

The Waste Management and Regulation Policy Group (WMRPG) of the Environment Agency for England and Wales (the Agency) recruited this project on behalf of the Agency's National Waste Group. The project was designed to assist waste regulators, local authority planners and landfill site operators, amongst others, to assess the risks to human health and the environment associated with landfill gas (LFG) emissions. In addition, the project was intended to help the Agency and other relevant organisations compare the relative risks associated with different waste management options, and provide a framework that will contribute to the assessment and valuation of the inventory of burdens associated with landfilling of wastes.

The work has been undertaken under the guidance of the Landfill Gas Task and Finish Working Group, set up under the National Waste Group of the Agency to review current guidance on LFG and to develop new guidance as required. Members of the working group formed a steering group for the project. The Landfill Gas Group is responsible for reviewing internal guidance and, for example, to consider appropriate revisions to Waste Management Paper 27 (DoE, 1991). This group is therefore the expert centre on LFG issues.

Members of the Landfill Gas Task and Finish Working Group are:

John Keenlyside	Anglian Region
Jan Gronow	Head Office
Richard Smith	Head Office
Trevor Howard	Midlands Region
Ian Cowie	North East Region (Chair)
Dave Walmsley	North West Region
Louise McGoochan	Southern Region

Catriona Bogan	South West Region
Alan Rosevear	Thames Region
Pete Stanley	Environment Agency, Wales
Rowland Douglas	Scottish Environment Protection Agency (SEPA)

This project focused on:

- the risks associated with LFG from waste disposal by landfill;
- explosion and fire hazards from accumulation of landfill methane in buildings or other enclosed spaces;
- harm to both the local and global environment.

The project complements the following Environment Agency R&D Projects:

- an assessment of the risks to human health from landfilling of household wastes R&D Project P1-236;
- a risk assessment methodology for landfills (LANDSIM) R&D Project P1-294.

1.3 Aim of project

The overall aim of this project was to develop a useable framework model to help Agency staff assess the risks to human health and the environment from landfill gas. The framework that was developed consists of spreadsheet modules integrated to provide a working model, which may eventually be developed into a package comparable in style and approach to the Agency's LANDSIM risk assessment methodology for landfills and groundwater protection.

1.4 Summary of project tasks

The project comprised a number of specific tasks, designed to address the objectives of the project brief.

- Task 1, Development of the conceptual model. This is described in Chapter 2.
- Task 2, Development of the source term model. This is described in Chapter 3.
- Task 3, Environmental transport models. These are described in Chapter 4.
- Task 4, Exposure assessment. This is described in Chapter 5.
- Task 5, Impact assessment. This is described in Chapter 6.
- Task 6, Validation, simulation and option evaluation. Validation of the model framework is described in Chapter 7. Simulation and options evaluation is carried out in Chapter 8.

- Task 7, A user manual for the spreadsheet. This task has been reported separately from this report, in the form of a user manual and training day programme for Agency staff on the Task and Finish Group.

These tasks 1-6 are described in the subsequent Chapters of this report.

2. CONCEPTUAL MODEL

This Chapter describes the broad approach adopted for the simulation of LFG emissions. More detailed descriptions of the approach to each module within the model itself are given in subsequent sections of this report. This section covers:

- intended use and limitations of the model;
- choice of wastes to be considered;
- the generation and emission of gases and trace components (the source term);
- choice of pollutants to be considered;
- pathways and targets; and
- probabilistic aspects of the model.

Figure 2.1 shows the sources, pathways, and target receptors considered.

2.1 Intended use and limitations of the model

The HELGA risk assessment framework model is intended to help waste regulators, landfill operators, local authority planners and others assess the risks to human health and the environment associated with landfill gas emissions. It is a stand-alone spreadsheet model designed to demonstrate the functions that could ultimately be built into a commercial piece of software to partner the Agency's LANDSIM landfill leachate risk assessment model. The model can be tailored to site-specific parameters and conditions; particularly those that relate to the types of waste accepted in the site, site design, and gas management options. The model will help users develop, present and defend decisions about gas management for a specific landfill, by demonstrating the health and environmental effects of different landfill gas management scenarios.

In common with all landfill models, this model has significant uncertainties associated with its outputs. The user should be aware of these uncertainties. The model cannot provide precise answers to specific questions. It is a support tool within a decision making process but cannot decide specific licensing and planning issues.

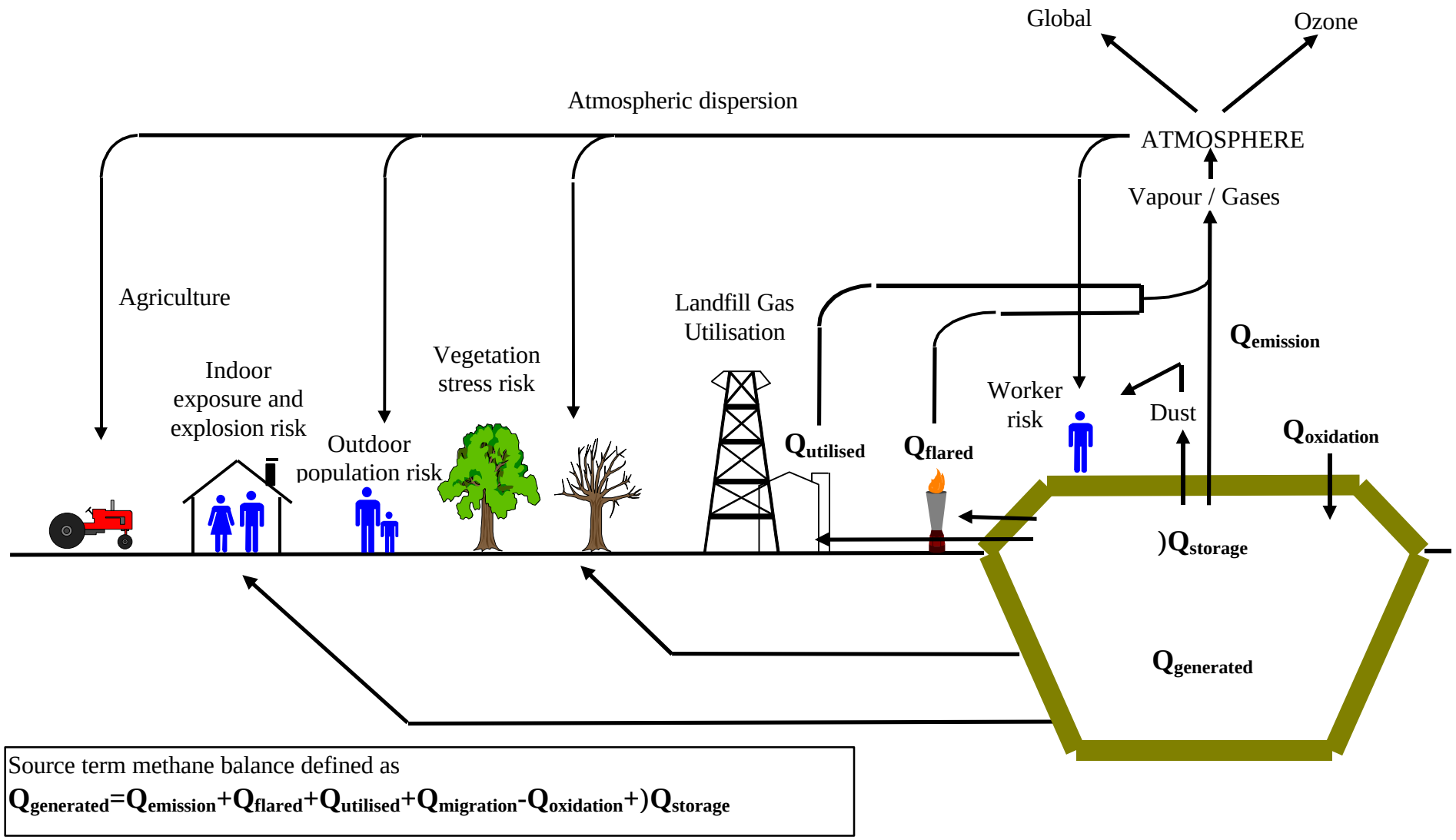

Figure 2.1 The conceptual model

2.2 Wastes considered in the model

Consideration of the fate of pollutants arising from the disposal of household waste is an important part of the risk assessment framework.. More information is available on the composition and variability of household waste than any other landfill feedstock. As a consequence, the capacity to represent a household waste landfill has never been better. However, very few sites have been developed in the past, or are operated today, which only accept household waste. In order to make the model more flexible, other categories of waste have been built into the model framework.. The model in its current version will accept waste from the following waste streams:

- household;
- civic amenity;
- commercial;
- industrial;
- inert solids and/or daily cover;
- inert sludges;
- sewage sludge; and
- liquid wastes.

Wastes differ in their degradation and gas generation characteristics according to their composition. For example, household wastes from the 1950s have a very different composition than those of the 1980s or 1990s. Although the model was conceived against a brief to examine current or new-build landfills, it became clear that the model could be used retrospectively on existing sites. In addition, the model could be used to forecast the effect of future legislation on landfilling at a national policy level. In order that all these options could be accommodated, the model allows a choice of waste filling era, allowing forecasting to be tailored to past and future practice. The eras considered are:

- Pre 1970;
- 1970-2010; and
- post 2010

Again, most data are available for household waste compositions, and some waste streams (e.g. civic amenity wastes) would not have existed in certain eras. Figure 2.2 shows how household waste composition has changed over the past 60 years. These data are included in the source term module.

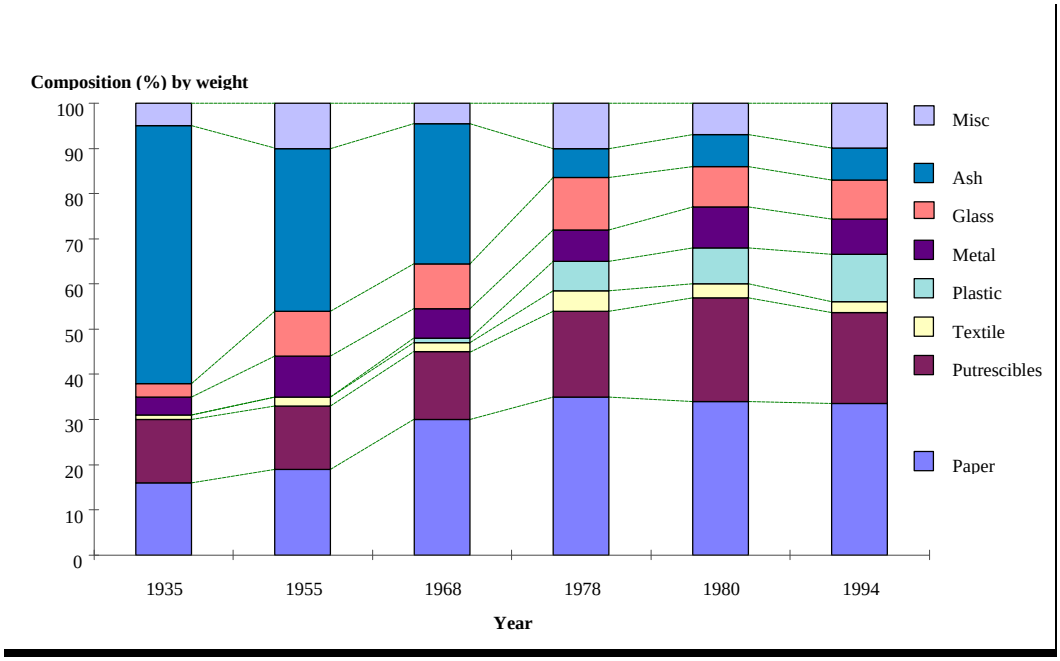

Figure 2.2 Changes in waste composition over the past 60 years. After Agriculture and Food Research Council (1988), Senior (1989), and the National Household Waste Analysis Programme (DoE, 1994).

2.3 Source term modelling

The timeframes in which LFG emissions and leachate formation are important in environmental risk assessment modelling are quite different, and the nature of the source terms are quite different. Simulation of leachate loss from a landfill, using for example the leachate risk assessment model LANDSIM, is relatively straightforward. The assumption can be made that the source term (or the material which gives rise to the leachate), once determined, is non-variant with time (although a time-dependent source term is also available in LANDSIM for particular modelling circumstances). The same is not true for LFG. The amount of gas generation for any particular landfill in any particular year varies significantly with, *inter alia*:

- the age of the site;
- the nature of the waste deposited in the site;
- the quantity of waste deposited; and
- the hydrological, physical, chemical and biochemical regimes within the site.

The rate at which gas is generated within a site can vary significantly from year to year, particularly in the early phases of a sites' gas generation lifespan, and the period over which gas generation is an important consideration is much less than the time frames considered for leachate formation.

As a consequence, the approach adopted in this LFG risk assessment model is somewhat different to that found in LANDSIM. The LFG source term model was developed initially as a stand alone deterministic model. By this we mean a model which does not operate in a probabilistic fashion, but which generates for the user 'best estimates' of LFG production and emission over the period of filling for the different waste compositions supplied to the model.

The modelling steps considered in the deterministic model are as follows:

1. Input waste composition as primary user input data on a yearly basis.
2. Input waste quantities deposited in the landfill as primary user input data on a yearly basis.
3. Input user defined information on the usage of LFG flares, and gas utilisation schemes; and cap and liner designs, on a yearly basis.
4. Calculate bulk gas generation on a yearly basis;
5. Calculate trace gas and volatile organic compounds (VOC) generation on a yearly basis;
6. Pass the bulk gas and trace gas/VOC generation rates to an output file/matrix for plotting.

The user has the option to stop at this stage, in order to:

- reassess the data used in the simulation; or
- run the simulation again, using different gas management options, cap designs, etc.

This **d**eterministic **emi**ssions model (DEMI) was a development stage on the route to the more complex HELGA model, but the flexibility of the source term module in DEMI made it appropriate to calculate some of the parameters required for the probabilistic HELGA model. These parameters were the ranges in waste composition available for degradation and the subsequent degradation rates.

2.4 Selection of pollutants to be modelled

LFG comprises a complex cocktail of many gases and VOCs. There is no single composition that is appropriate to all sites. Rather, ranges of concentrations of any particular component within the gas will be observed between usually well observed and defined limits. The gases produced will also depend to a certain extent upon the nature of the feedstock.

In selecting gases and VOCs to simulate in the model, we have had to split the method of representation in the model into two:

1. Those gases, for which mechanistic pathways have been identified, may comprise a significant proportion of the gas generated, and whose particular temporal behaviour is reasonably well understood.
2. Those gases and VOCs for which mechanistic pathways may or may not have been identified, but whose temporal behaviour is not well understood.

Conveniently, gases that fall into group 1 above are produced in sufficient quantities to be considered as bulk components of LFG. Those which fall into group 2 above are found in LFG at much lower (but much more variable and therefore less predictable) concentrations. Group 1 gases are modelled in a different fashion to group 2 gases and VOCs, because of the concentrations at which they occur in LFG.

2.4.1 Bulk gases

The following bulk gases are represented in the model:

- methane
- carbon dioxide; and
- hydrogen.

Methane and carbon dioxide together represent typically more than 95% of the gas generated by the decomposition of the waste in the landfill. Methane is flammable, and poses a fire and explosion hazard to neighbouring property. Laterally migrating methane can also be responsible for displacing or removing oxygen from the root zone of vegetation, causing vegetation stress.

Carbon dioxide build up in properties can have an asphyxiant or other physiological affect on the human body at relatively low concentrations, when compared to that found in LFG. Laterally migrating carbon dioxide can also be responsible for displacing or removing oxygen from the root zone of vegetation, causing vegetation stress. Both gases have a global climate effect, although only methane, because of its high global warming potential relative to carbon dioxide, is considered in the UK inventories of greenhouse gases.

Hydrogen is represented in the model, as it is produced primarily in the early acetogenic phase of gas production, and although produced in lesser quantities than methane, has a lower explosive limit (LEL) than methane.

Combustion of methane and hydrogen in flares or gas utilisation plant convert a proportion of the methane to carbon dioxide, and hydrogen to water. Thus the result of running different simulations, with or without active gas control, will be a quantitative measure of the risk reduction for particular components of the LFG for certain pathways, and a quantitative measure of the increased risk from other components in the system. The user will have to make a decision, based on the tolerability of risk, as well as on other considerations, as to which management option is the most favourable.

2.4.2 Trace gases and VOCs

There are scant data available on the rate of production of trace gases and VOCs from landfills. The production of these species is conceptually linked to the rate of production of bulk gases. Thus, the rate of decomposition of materials in the waste which evolve the bulk gases is used to similarly evolve trace gases and VOCs at rates proportional to the rate of bulk gas production.

Trace gases and VOCs in the model's database have been selected for their potential contribution to human health and environmental effects. Other trace gases and VOCs may be added on an ad hoc basis once the model has been completed, as data become available. Not all trace gases or VOCs will be emitted from each gas emissions pathway, as some are emitted directly from the landfill surface, as components of the LFG, and others will be products of combustion or incomplete combustion of LFG from flares or utilisation plant. The emission pathways, and the key trace gases/VOCs for each emission pathway, are shown in the sections below.

2.4.3 Surface emissions

The following components were included in the surface emissions model.

- Benzene and vinyl chloride, for their carcinogenic properties.
- Trichloroethene and tetrachloroethene, as representative chlorinated solvents, for their health effects.
- Dioxin and furans for their health effects.
- Carbon monoxide for its toxicity effects.
- Chlorodifluoromethane and dichlorodifluoromethane for their global climate effects.
- Hydrogen sulphide and methanethiol for their odour effects, as well as the toxicity of hydrogen sulphide.
- PM_{10}.

Chemical conversion or degradation of any of these species during surface emission and subsequent atmospheric transport was not considered.

2.4.4 Lateral emissions

The following trace components were included in the lateral emissions model:

- All components, except PM_{10}, considered for surface emissions.

Chemical conversion or degradation of any of these species during lateral migration was not considered.

2.4.5 Flare emissions

The following components were included in the flare emissions pathway:

- All components considered for surface emissions. Conversion to other species in the flare reduced the proportion of many of these components for this pathway. The proportion of some components, e.g. PM_{10}, may increase.
- Additional emissions of nitrogen oxides (NOx), sulphur oxides (SOx), hydrogen chloride, hydrogen fluoride, and carbon monoxide as specific flare emission products.

Chemical conversion or degradation of any of these species during subsequent atmospheric transport was not considered.

2.4.6 Utilisation plant emissions

This pathway considered emissions for a gas engine used for power generation, rather than direct use of the gas, as this is the most common use for landfill gas at the present time. The following components were included in the utilisation plant emissions pathway:

- All components considered for surface emissions. Conversion to other species in the utilisation plant reduced the proportion of many of these components for this pathway. The proportion of some components may increase.
- Additional emissions of nitrogen oxides (NO_x), sulphur oxides (SO_x), hydrogen chloride, hydrogen fluoride, PM_{10}, and carbon monoxide as specific engine exhaust emission products.

Chemical conversion or degradation of any of these species during subsequent atmospheric transport was not considered.

2.4.7 Odour

A special case is the consideration of odour. Two gases are represented in the model for odour emissions from the surface of landfills: hydrogen sulphide and methanethiol. Their odour properties will be significant reduced via the lateral migration pathway due to sorption processes, or via flares or utilisation plant, due to destruction in the combustion process.

2.5 Pathways and targets

The pathways considered in the environmental transport module are:

- atmospheric dispersion off-site;
- atmospheric dispersion on-site; and
- lateral migration through the ground.

Atmospheric dispersion off-site is considered for pollutant emissions from the landfill cap, landfill gas flares and gas utilisation plant. Dispersion on-site is relevant to the estimation of risks to landfill workers. In this instance all surface emissions are considered.

For lateral migration of gases through the ground a distinction has been made between a steady state situation and unusual conditions. For the steady state case annual average emissions from the landfill boundary will be used as input to the migration model. The unusual conditions part of the module simulates the sorts of situations in which emission and migration rates increase well above the annual average for a brief period. The occurrence of such a condition has been treated as a probabilistic event.

The exposure assessment module has two major functions:

- the calculation of concentrations of pollutants in indoor air, as a result of atmospheric dispersion and lateral migration; and
- the calculation of intakes of pollutants by humans.

In the latter case both members of the public and workers are considered but the emphasis is on members of the public. The main exposure pathways included for members of the public are inhalation, ingestion of home-grown vegetables and dermal exposure. For workers inhalation and dermal exposure are considered.

The impact assessment module estimates risks to human health, using output from the exposure assessment module. It also estimates local and global environmental impacts using output from the source term and environmental transport modules. Vegetation stress is the local impact considered, while global impacts are greenhouse gases and ozone depletors.

2.6 Probabilistic aspects

Many of the data that drive the model have a wide margin of uncertainty. This could lead to large uncertainties in the outputs, particularly in the landfill gas generation module. It was a requirement for the project that the probabilistic approach in the gas risk assessment model should be consistent with that in LANDSIM. The intention was to couple the Microsoft Excel™ spreadsheet package to Microsoft Crystal Ball™, which allows probability density functions (pdfs) to be attributed to certain parameters which have a high uncertainty. This approach was not adopted in the final version of HELGA for the following reasons:

- pdfs would have been required for a large number of user specified and model supplied parameters;
- Crystal Ball™ can only work satisfactorily with a smaller number of probabilistic variables than would have been required in the model;

- the coupled Excel™/Crystal Ball™ model would have run at an unacceptably slow rate for model users; and
- not all Environment Agency users would have had access to the Crystal Ball™ software, whereas all had access to Excel™.

With these considerations in mind, a pseudo-probabilistic approach to the model was devised. The HELGA model now represents uncertainty by using look-up tables generated by sampling parameter values from probability distributions for the source term (gas generation and emission) module. The software used to generate these look-up tables was Crystal Ball™, but there is now no reliance on Crystal Ball™ when using HELGA.

Outputs from the Crystal Ball™ simulations were pdfs of landfill gas generation. From these, the mean, 95th percentile and 5th percentile values of landfill gas generation were derived. These were imported into HELGA as look-up tables calibrated per tonne of waste per year, which could then be scaled up to individual site tonnages. Landfill gas generation is then predicted as the mean, 95th percentile and 5th percentile values for subsequent use in the emissions, atmospheric dispersion, exposure assessment and impact assessment modules. The data on VOC and trace gas concentrations in landfill gas are used directly to calculate the proportion of trace gases released via each emission pathway. No chemical reactions are represented in the model which could convert trace gases to other chemical species, although the emissions pathways (lateral migration, cap, flare or gas utilisation) consider different components characteristic of those pathways, and methane oxidation is permitted in the capping layers.

The atmospheric dispersion part of the environmental transport model is probabilistic in the sense that it produces primarily annual average concentrations of pollutants in air, taking into account the probabilities of occurrence of various weather conditions during a year.

The exposure assessment module is deterministic, because the people and buildings considered are notional, and the parameters which characterise them are not subject to the same kind of uncertainty as those in the source term and environmental transport modules (where the values of all the parameters are, in principle, measurable). The impact assessment module is also deterministic, because detailed consideration of uncertainties in parameter values for the various parts of this module is beyond the scope of this project.

Figure 2.3 summarises the probabilistic and deterministic aspects of the model.

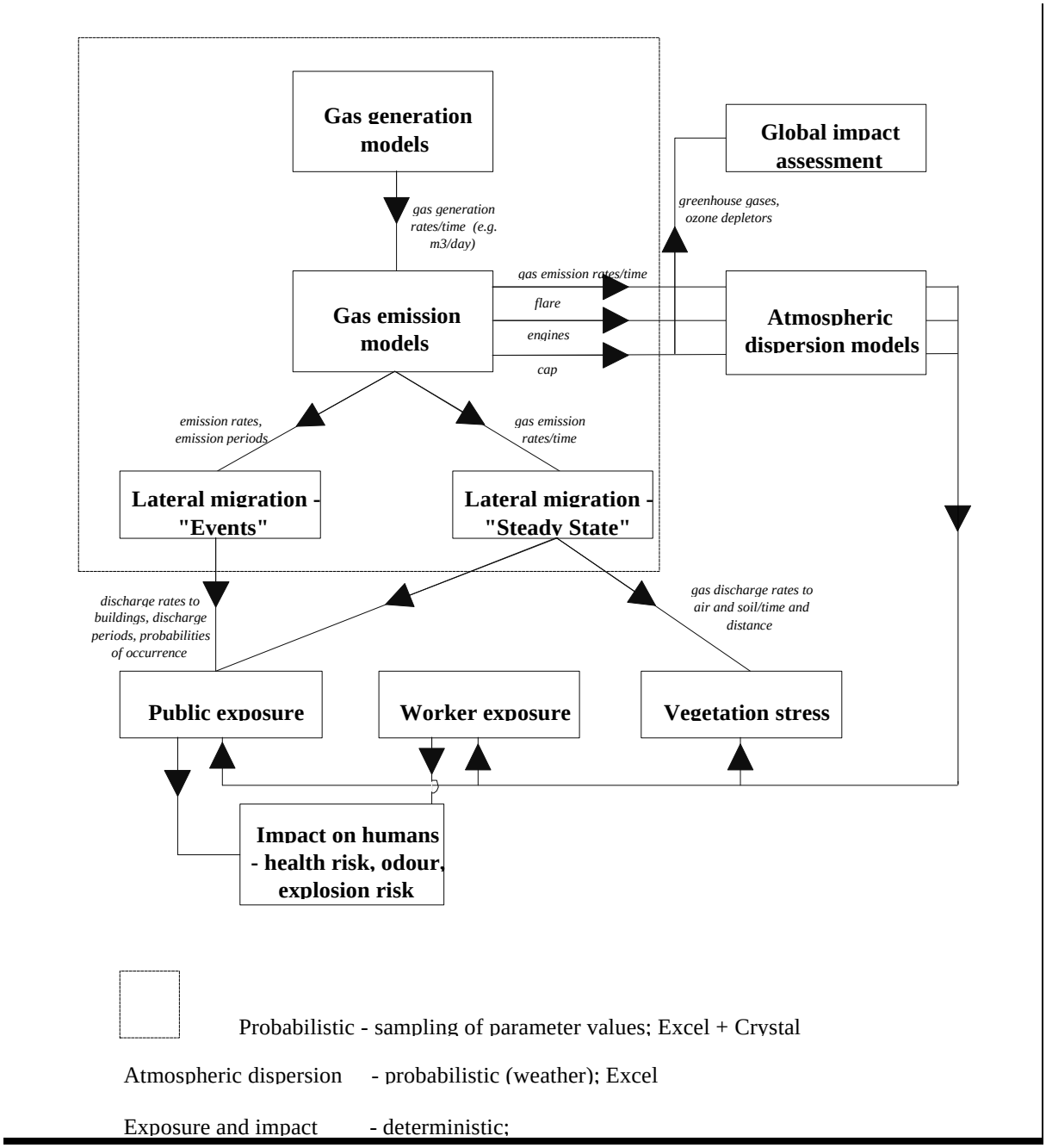

Figure 2.3 Probabilistic approach, interfaces and software

3. SOURCE TERM

The emission rate of LFG from the landfill site is the source term for the risk assessment model (see Figure 2.1). The source term module is the critical component of the overall risk assessment model because the risk from LFG is proportional to its release from the site.

The generation rate and total yield of LFG are landfill site specific. LFG generation depends on the waste mix[1] and composition[2] and the environmental conditions in which the waste degrades. All these factors differ from site to site. Additionally LFG generation and composition at any site change with time. The actual production and flux of gas from a particular site at a particular time can only be ascertained by lengthy and comprehensive direct measurement.

Mathematical modelling provides an approximation of LFG processes and so is useful to estimate LFG generation when comprehensive site measurements are not available. This is usually the case. In particular LFG generation models are necessary to make projections of LFG generation and emissions.

3.1 Landfill gas generation

The are several methods for modelling LFG generation. Most are based on a description of LFG formation based on laboratory experiments or full-scale field measurements. The models range from relatively simple zero-order (time-independent) equations through first-order model that have a decay function to more complex second-order equations that try to model a number of different reactions taking place at different rates.

Oonk et al. (1994) validated a number of LFG models using data from gas recovery schemes. They concluded that the description of LFG formation improves going from a zero-order model, to a first- and second-order model. However a variant on the single-order model, a multi-phase model, provided the best correlation with field results (see Section 3.1.1.2).

All LFG models produce uncertain results. This uncertainty derives from the heterogeneity of both landfilled waste and the conditions under which it degrades, and the limited availability of information and data to put into models. Any new LFG model should aim to reduce these uncertainties whilst allowing for limits in input data. We have developed a new multi-phase LFG generation model. It is based on the model developed originally by Hoeks and Oosthoek (1981) and described by van Zanten and Scheepers (1996). The model is a significant development on previous models because it can:

- define precisely the mix, composition and moisture content of waste in the landfill site; and
- calculate LFG generation based on the degradation rates of the individual materials in the landfilled waste.

[1] The proportion of different types of waste, e.g. household, commercial, industrial, in the landfilled waste.
[2] The specific materials, e.g., newspaper, food waste, cardboard, textiles, in each type of waste in the mix.

These additions make the model highly flexible. It can be tailored to individual landfill sites, taking account of specific waste streams, filling rates and environmental conditions. As with all LFG models, the accuracy of this module is limited by the availability of input data. The more site specific information there is, the more certain the module outputs will be. However, if there is limited input data, the module has default parameters that can be chosen by the user. This allows the module to approximate LFG generation using the user's best knowledge of any landfill site.

3.1.1 Module description

There are two main processes in the module:

1. Defining the waste in the landfill site; and
2. Calculating LFG generation from a specified mass of waste.

3.1.1.1 Defining the waste

The rate of generation and total yield of LFG depends on the mix and composition of waste disposed in the landfill site. The main source of carbon in LFG is from the degradation of cellulose and hemi-cellulose. Different biodegradable materials in the waste have different proportions of cellulose and hemi-cellulose. The ultimate degradability of the cellulose polymers also differs between waste materials. Thus the total yield of LFG and its rate of production depend on the mass and degradability of the cellulose and hemi-cellulose in the waste.

This module is highly flexible because it can accommodate any combination of waste types, mix and composition This allows the user to customize the module according to the waste in place or that projected for individual sites.

In all cases the user will choose the proportion of different waste types in the total mix.

The user can also define the composition of each waste in the mix. If the waste composition is not known then an approximation can be chosen. To help with this, the module at present contains three pre-selected waste types:

Waste 1	Typical composition of waste during the period 1956 -1976;
Waste 2	Typical composition of waste during the period 1976 to the present date;
Waste 3	Future Landfill Directive waste composition[1]; and
Waste 4	User defined (may also cover wastes prior to 1956).

Table 3.1 shows the composition of degradable components in Waste 2. Each waste type also contains inputs for the non-biodegradable, or inert, components of the mix (not shown in Table 3.1). The composition of Waste 2 is typical of contemporary waste. The proportion of

[1] This is a projected waste stream make up, that will take into account the proposed directives on the landfilling of wastes.

different materials in the domestic waste and the cellulose/hemi-cellulose content are from the National Household Waste Analysis Project (DoE, 1994). The percentage degradability is from Barlaz *et al*. (1996).

Although provided in the module, the user can alter all the parameters such as composition, water content, cellulose and hemi-cellulose content and percentage degradation if better or alternative information is available.

Table 3.1 Composition of waste components in a contemporary waste mix

1980's - 1997
FRACTION

Degradable		Domestic	Civic Amenity	Commercial	Industrial	Inert	Liquid Inert	Sewage sludge	Water content (%)	Cellulose (%)	Hemi-cellulose (%)	Decomposition (%)
Paper/Card												
	Newspapers	11.38	10	10					30	48.5	9	35
	Magazines	4.87	11						30	42.3	9.4	46
	Other paper	10.07		50.1					30	87.4	8.4	98
	Liquid cartons	0.51							30	57.3	9.9	64
	Card Packaging	3.84							30	57.3	9.9	64
	Other card	2.83							30	57.3	9.9	64
Textiles												
	Textiles	2.36	3						25	20	20	50
Miscellaneous												
combustible	Disposable nappies	4.35							20	25	25	50
	Other misc. combustibles	3.6							20	25	25	50
Putrescible												
	Garden waste	2.41	22						65	25.7	13	62
	Other putrescible	18.38		15					65	55.4	7.2	76
Fines												
	10mm fines	7.11	15						40	25	25	50
Sewage sludge												
	Sewage sludge							100	70	14	14	75

3.1.1.2 Calculating landfill gas generation

At the heart of all LFG generation models is an equation that describes LFG formation from the degradation of biodegradable organic material.

We have derived a multi-phase, first-order decay equation:

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

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

Equation 3.1

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 (rapidly, moderately and slowly degradable (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 multi-phase model allows for the different rates of degradation of different waste components. In this model, a number of waste fractions are distinguished in which LFG formation is described separately. The usual approach, which we have also adopted, is to separate degradable waste into three fractions:

- waste that degrades slowly;
- waste that degrades at a moderate rate; and
- waste that degrades rapidly.

The model then assumes that each of these fractions degrades with a specific rate of first-order decay. For example, putrescible waste will be converted to LFG faster than wood or paper because of its high moisture content and better hydrolysis properties. Different degradation rates (k) are assigned to the different degradable fractions.

Figure 3.1 shows the input parameters for Equation 3.1. Once the user has chosen or input the waste data, the module runs the LFG generation calculation for each component in the waste mix. The module then sums the LFG generated per year from each component to give a total LFG production for the waste in question.

3.2 Using the source term module

The LFG source term model has been constructed in a modular form, that presents the required inputs and outputs in a logical fashion to facilitate its use. The model is based around nine Excel work sheets (Figure 3.2):

- QA Sheet;
- Input Sheet;
- Wastes 1 - 4;
- Wastes Water Content;
- Defaults and Data; and
- Data Manipulation.

The inputs, links, calculations and output of the worksheets are described in the following sections.

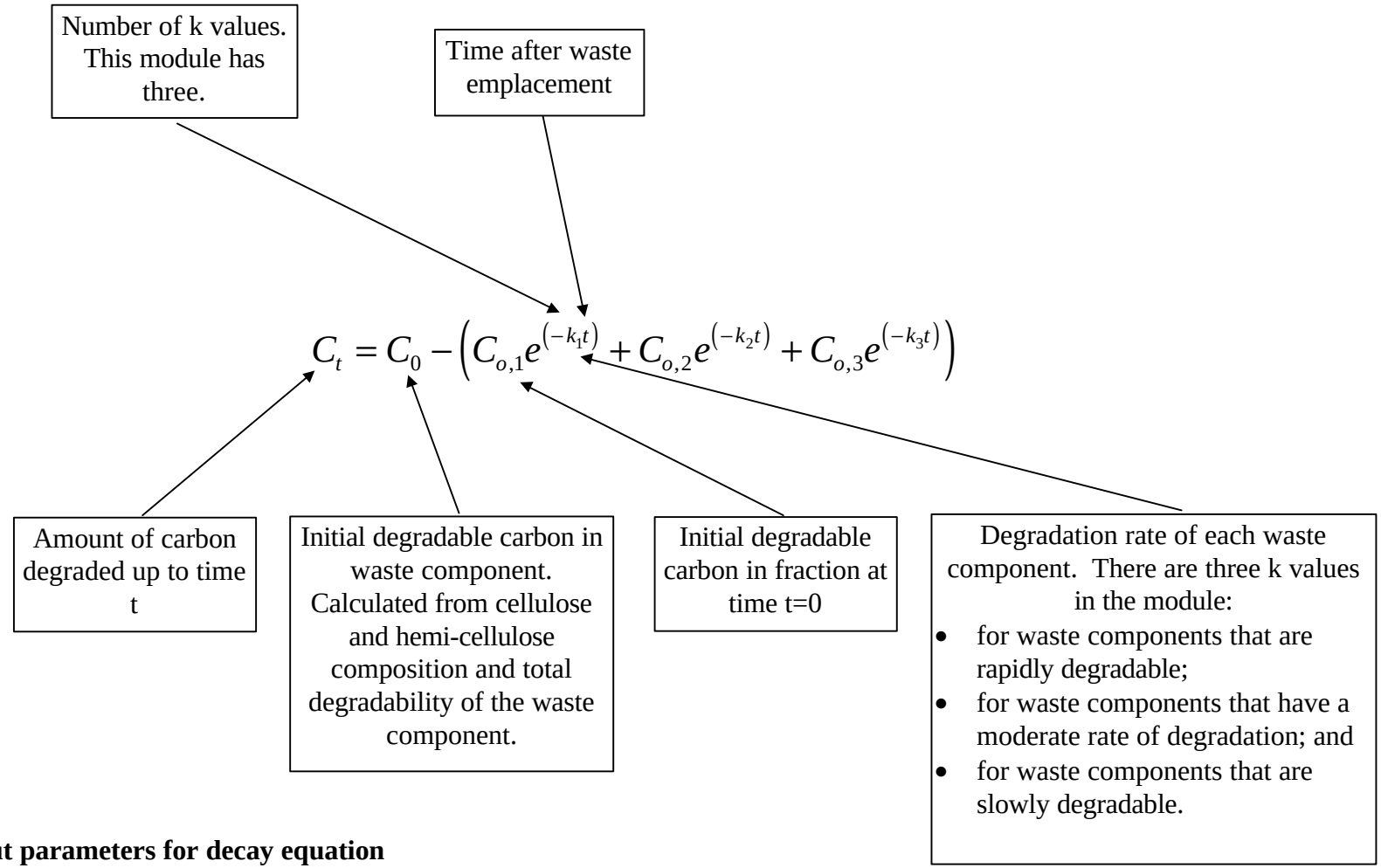

Figure 3.1 Input parameters for decay equation

3.2.1 QA sheet

The QA Sheet has been included to allow relevant project details to be entered and saved as an integral part of each run. It is hoped that these details will be unique, allowing each run to be traceable to the relevant time, project and user. This sheet allows for the input of:

- project name;
- project number;
- site details (location and owner); and
- site fill time details

The QA sheet as it stands is an initial pass and is expected to be modified once the rest of the model has been constructed and validated. It is considered to be an important part of the final model, and will be straight forward to develop once the model is more fully developed.

Details on the commencement of waste filling in the landfill site is linked into the Input Sheet, so that the specific date for each year of filling is presented.

3.2.2 Input sheet

The Input Sheet requires data input for the fill rate of the landfill site; included in this is the facility to apportion the waste entering the site to different production streams (see Section 2.2).

The user can input up to 50 years' data on the volume of waste entering the site (50 years fill time is expected to be the maximum likely for a landfill, as agreed with the project steering committee). The volumes of waste are converted to tonnage using an input density for the waste, the default will be 1 tonne.m^{-3}. The waste mass entering the site can be used, but the calculation to convert from volume to tonnes will be overwritten.

The make up of the waste streams coming to the landfill is known to have changed over time, so the model has the flexibility to input four different waste stream make-ups. The four defined time periods will initially be:

- 1956 - 1976;
- 1976 - present day;
- Landfill Directive mix; and
- user defined (may also include pre 1956 waste).

Most data available are for the period 1976 to present day.

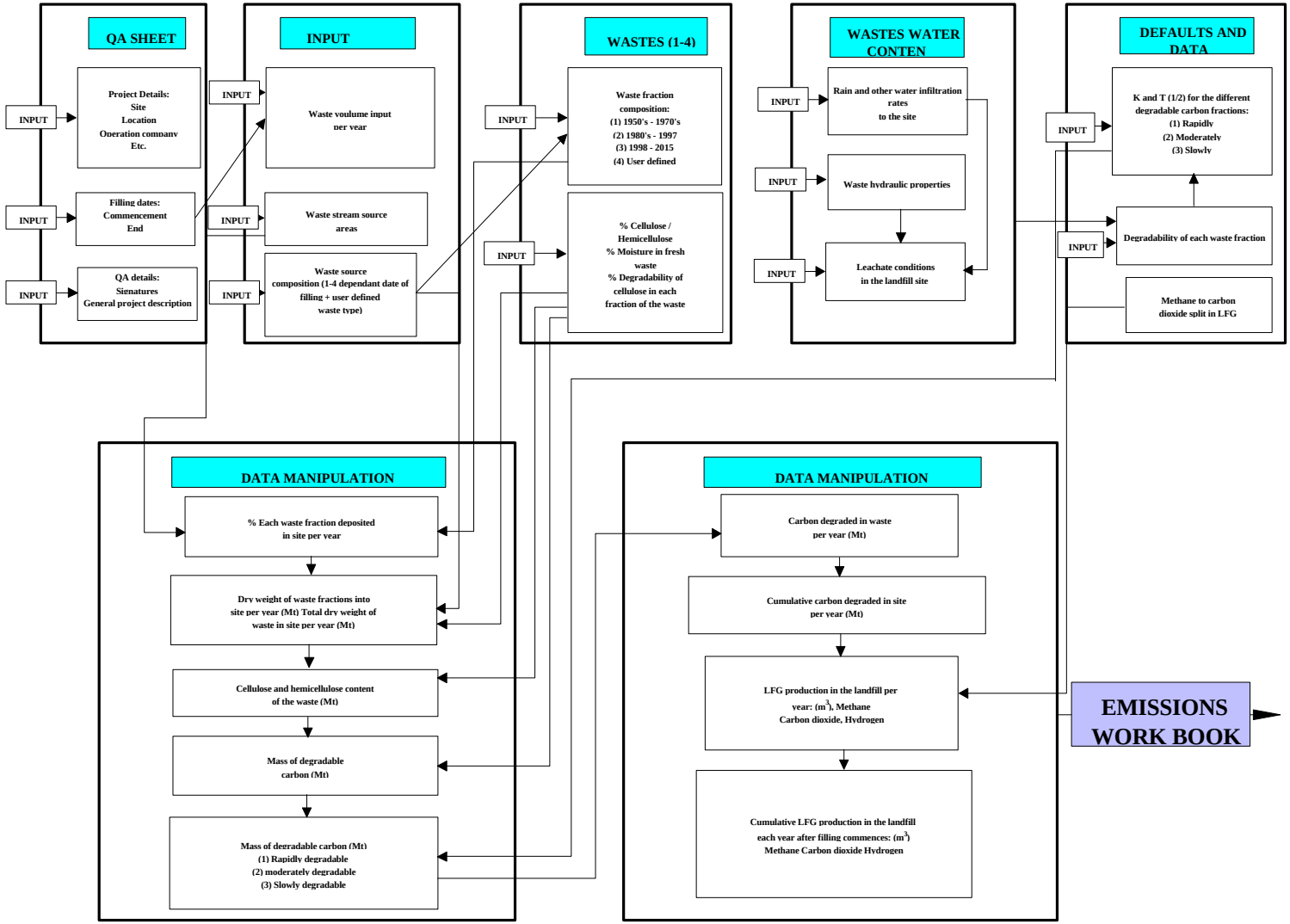

Figure 3.2 Source term model flow diagram

3.2.3 Wastes 1 - 4

The user inputs the waste stream mixes in each of these sheets. The waste streams are disaggregated into a number of components, as designated in the National Household Waste Analysis Programme (DoE, 1994), with two other components (soil and brick) to allow for building wastes. Each of the sheets inputs are taken as the default of the waste stream composition for a specific time period to allow for temporal trends in the waste make-up.

Included on Waste 4 are the data on the cellulose and hemi-cellulose content of each biodegradable waste component and the degradability of the cellulose and hemi-cellulose. These compounds are known to make up about 91%, of the degradable fraction of refuse (Barlaz et al., 1989). Other potentially degradable fractions, e.g. protein and lipids, are not included here as they do not contribute significantly to LFG emissions (although they may be a source of pollutants in leachate).

The degradability of the waste is input at this point in the model, rather than later as seen on a number of models (Oonk 1994). This allows greater flexibility in describing the wastes entering the site, and will allow for greater manipulation of the input data as further research provides more information.

The moisture content of each component is entered on the Waste 4 sheet. This allows the dry weight of the waste to be calculated on the Data Manipulation Sheets.

The cellulose and hemi-cellulose content of the waste components is linked to the Data Manipulation Sheet, and is used to calculate the dry mass of each component in the waste for every fill year.

3.2.4 Waste water content

The hydraulic and physical properties of the landfill are entered on this sheet in order to determine the percentage saturation of the waste mass. These data are then used to select the degradation rate constants of the slowly, moderately and rapidly degradable cellulose fractions in the waste.

3.2.5 Defaults and data

The degradation rate constants for each fraction of the cellulose/hemi-cellulose are related to the level of saturation of the waste. This is known to have a significant effect on the degradation rate. Therefore, we have linked the degradation rate constants for each of the three cellulose fractions to the waste saturation level (Table 3.2).

Table 3.2 Degradation rate constants for the three fractions of the degradable cellulose in the waste, dependent on the saturation level of the waste mass. (These k values are current best estimates, but will be replace by mean, max and min of relevant published figures in the final deterministic model.)

Waste Saturation Level (water-filled porosity)	Degradation rate constant	Degradation halflife, t ½
<20%	k_1= 0.694	$t_{½(1)}$ = 1
	k_2= 0.116	$t_{½(2)}$ = 6
	k_3= 0.076	$t_{½(3)}$ = 9
≥20% and <50%	k_1= 0.116	$t_{½(1)}$ = 6
	k_2= 0.076	$t_{½(2)}$ = 9
	k_3= 0.046	$t_{½(3)}$ = 15
≥50%	k_1= 0.076	$t_{½(1)}$ = 9
	k_2= 0.046	$t_{½(2)}$ = 15
	k_3= 0.013	$t_{½(3)}$ = 53

The ratio of methane to carbon dioxide in the LFG can also be entered on this sheet. It has been noted that the ratio of these two gases in LFG change over time in actively extracted landfill sites. We assume a constant mix of methane to carbon dioxide (entered by user), as the ratio changes are very site specific.

3.2.6 Data manipulation

The Data Manipulation worksheet contains all the calculations that lead to the determination of LFG (methane, carbon dioxide and hydrogen) production from the waste as described in the Input Sheet. The parameters calculated include 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 in the waste;
- fraction of rapidly, moderately and slowly degradable carbon in the waste;
- conversion of carbon; and
- LFG production from the waste (hourly, yearly and cumulatively).

3.2.6.1 Calculation of the percentage of each waste component in the waste

The split of the waste streams entering the site for each year combined with the data on the Waste 1-4 sheets will give the breakdown of each waste stream into its individual components.

Using this information, the percentage wet weight of each component in the waste deposited per year can be determined.

3.2.6.2 Calculation of the dry weight of each fraction in the waste

Using the waste percentage composition of the various components and the moisture content of each waste fraction entered on Waste (4) sheet, the dry weight of the components and the total waste deposited yearly can be calculated.

Details on the moisture content of various waste fractions are only available in general terms, and therefore these can be defined if more reliable data are available for specific waste fractions.

3.2.6.3 Calculation of the cellulose and hemi-cellulose content of the waste

The cellulose and hemi-cellulose content of each waste fraction are provided along with the moisture content in Waste (4) sheet. Therefore the cellulose/hemi-cellulose content of the waste input can be determined for each year. Waste (4) sheet also accepts the degradability of the cellulose and hemi-cellulose fractions in the waste, and thus the degradable cellulose and hemi-cellulose mass can be calculated. This is then sub-divided into three fractions:

- rapidly degradable;
- moderately degradable; and
- slowly degradable.

The waste is partitioned into these three fractions using a qualitative evaluation of the degradability of each waste fraction. The degree of lignification of the cellulose in the waste is known to reduce its availability and thus the rate of its degradation. The fractions have been assigned as described in Section 3.2.6.4.

Table 3.3 Degradation rate assigned to each waste fraction

Degradability	Fraction
Rapid	Putrescibles
	Fines
	Garden wastes
	Sewage sludge
Moderate	¼ Paper
	Nappies
	Miscellaneous combustible
Slow	¾Paper
	Newspaper
	Textiles

3.2.6.4 Biodegradation

The degradable cellulose and hemi-cellulose in the waste are converted to degradable carbon compounds. It is assumed that the anaerobic degradation is generally methanogenic, with the ratio of methane to carbon dioxide specified in the Defaults and Data sheets.

To allow for the inclusion of hydrogen in the model, a percentage of the rapidly degradable fraction of the waste is assumed to be degraded acetogenically, with the formation of acetate, carbon dioxide and hydrogen (no methanogenesis occurs in the newly deposited anaerobic waste, so the hydrogen and carbon dioxide are free to be produced and not converted to methane). This is assumed to occur only in the first year after waste is deposited, then the degradation follows the methanogenic pathway. The percentage of the waste degraded by this pathway may be entered, but we have set the default at 1%, as this gives a maximum concentration of hydrogen in LFG of around 10%. This fits our understanding of landfill processes, including the pioneering work of Farquhar and Rovers (1973). The inclusion of hydrogen will allow us to initially evaluate the risk it presents, with the result that it may eventually be removed, depending on the results of the scoping work.

3.2.6.5 Degradation of the degradable carbon compounds

Degradation of the degradable carbon compounds in the waste is described by a first-order, multiphase equation where each of the three degradable fractions are dealt with separately and the resultant amount of carbon converted to LFG per year is aggregated. The degradation rate constants used in the equation are taken from published data, and derived from the waste saturation levels, as detailed above.

3.2.7 LFG production

Once the carbon available to be converted per year has been calculated, the volume of methane, carbon dioxide and hydrogen can be determined. The ratio of methane to carbon dioxide in the LFG, is entered on the Defaults and Data sheet and 1 mole of carbon produces 1 mole of methane or carbon dioxide. The conversion of carbon to an equivalent of hydrogen is given by Equation 3.2. From this the total LFG production, both hourly and cumulative can be evaluated.

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

$$or\ Cellulose \xrightarrow{Acetogenesis} Acetic\ Acid + Hydrogen + Carbon\ Dioxide$$

$$or\ 6Carbon = 2\ Acetic\ Acid + 4\ Hydrogen + 2\ Carbon\ Dioxide$$

Equation 3.2 Production of hydrogen from the degradation of cellulose

The results produced in this sheet are then copied to the emissions model. Having the two models running in series, reduced the size of a single Excel file and thus the run time for any manipulations.

3.3 Landfill gas emissions

The LFG generation details are copied from the generation model (both have to be open to do this) using a macro that is activated using <Ctrl + d>. This pastes data from the generation model into the LFG Data sheet, where it is then used in emission calculations.

The emissions model is based around six work sheets (Figure 3.3):

- LFG Data;
- Flare Input;
- Utilisation;
- Waste Water Content;
- Emissions Route; and
- Output.

There are currently two graphical outputs. One presents a yearly averaged hourly emission from the site to the different routes over the assessment period (user defined) and the other gives the cumulative emissions. The carbon is degraded for a period of 300 years as this period will result in the degradation of the majority of the carbon, the period of interest generally may only be 100 years, but it gives the flexibility to look over longer time frames. The pathways considered are:

- utilisation (energy recovery);
- flare; and
- uncontrolled emissions (cap and liner).

3.3.1 Landfill gas data

The LFG Data sheet is used in the calculation of the emissions from the site for the whole assessment period (300 years). As detailed above data from the Data Manipulation sheet of the source term model are copied onto this sheet and, then manipulated to give:

- volume of LFG to engine;
- volume of LFG to flare;
- volume of LFG lost in uncontrolled emissions;
    - volume through the cap
    - volume through the liner
- methane oxidation in the cap.

3.3.1.1 Landfill collection

The LFG collection system has been specified to have a maximum and minimum capacity, and can be specified to commence operation after a fixed time period or when the LFG production is high enough to allow it to work (as detailed above).

It is assumed that if any gas is collected and not utilised in any manner (flared or used for energy recovery) then that gas is assumed to be emitted through the cap and liner.

The collection system is assumed to have an envelope of operation, and if the gas production in the site is less than the maximum capacity, then its operation is taken to be trimmed to follow the gas production curve (in reality it is trimmed to the point just before air is pulled into the site).

The input of a collection efficiency allows the gas collection system to be less than 100% effective. Therefore when all the gas is being collected and utilised there will still be some LFG emissions from the site. This has been shown by other workers (Oonk et al., 1994), and such emissions are observed in practice (WS Atkins, 1997).

3.3.1.2 Volume of landfill gas to energy recovery plant

The routing of LFG to an energy recovery plant (utilisation) is either dependent on the time as specified in the Utilisation sheet or linked to the LFG production rate. If the production rate of gas is below the units utilisation volume, as specified in the Utilisation sheet, it is deemed inoperative, and the gas collected is either flared or emitted from the site.

3.3.1.3 Volume of landfill gas to flare

As with the collection system the flare has a maximum and minimum operational rate, and this is usually scoped to deal with all the LFG collected. A flare system can be specified for the site or not. If no flare is specified then it will be omitted from any of the calculations and assumed that the gas collection system is being controlled solely on the engine capacity. If a flare is specified then it will operate if the collection system is in operation and the gas available is greater than its minimum requirement.

3.3.1.4 Uncontrolled emissions from the site

Uncontrolled emissions from the site are split into two emissions routes, cap and liner. Both are based on a steady state system where Q_{RES} (residual gas production) is equal to the emissions from the site (Equation 3.3). This Q_{RES} results in a slight excess pressure in the site (P_w) (Equation 3.4), compared to the atmosphere and can be used to calculate $Q_{STORAGE}$ (gas stored in landfill site). The storage capacity is slightly higher than that determined from solely the pore volume.

$$Q_{res} = Q_{gen} - (Q_{flare} + Q_{utilisation})$$

Where:

Q_{gen}	LFG generated in the landfill
Q_{flare}	LFG routed to flare system
$Q_{utilisation}$	LFG routed to the energy recovery plant

Equation 3.3

For a homogeneous medium Darcy's law gives:

$$Q = \frac{K^*\left(P_w^2 - P_s^2\right)}{2\mu_g P_0 d}$$

Equation 3.4

Where:

Q	gas volume flux (volume at pressure P_0) to surface
K^*	effective permeability of medium (taking into account any water present)
P_w	pressure in waste (not a function of depth in this formulation)
P_s	pressure at surface
P_0	standard pressure
μ_g	gas viscosity
d	thickness of medium in direction of flow

Emissions from the cap or liner are regulated by the permeability and thickness of the most impervious layer. Therefore this data is taken from the Emissions sheet where the thickness and permeability of the emissions regulating layer have been determined. If the waste is the most impervious layer then its thickness is assumed to be half the average waste thickness.

Emissions from the cap and liner can then be calculated using Equation 3.5.

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

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

Equation 3.5

Where:

Q_c Flux from cap (l = liner)
the rest are as previously stated

This pressure can be used in the simulation of an 'event', where the atmospheric conditions change radically, for example a rapid decrease in atmospheric pressure. The difference between the atmospheric pressure and the landfill will be the driving force for such a migration event

3.3.1.5 Methane oxidation

Methane oxidation in the cap of landfills is well known (DoE 1991; DoE 1994a), but the extent to which it occurs is related to the cap type, thickness and the LFG flux. This model has two defaults for methane oxidation in the cap that are related to the residence time of the LFG as it passes out of the site. The residence time is related to the cap thickness and the emissions rate from the cap. The model assumes 50% methane oxidation for thick caps with low emissions or high residence times. The model assumes 10% for thin caps and high emission rates or short residence times. This part of the model needs further development, but we have included it now to show how it is to be integrated into the whole framework.

3.3.2 Flare Input

The Flare Input sheet allows data on the operational capabilities of the LFG collection and flare systems to be entered.

3.3.2.1 Collection system

The LFG collection system is assigned a maximum and minimum extraction capacity, a commissioning time after waste tipping commences and a collection efficiency. The collection system, for the sake of this model, follows the gas production trend from its commissioning until it reaches the maximum capacity of the flare specified. Then gas produced is lost by uncontrolled emission. When the LFG production rate drops below the minimum operational

level of the flare system, the flare is switched off, and LFG is then emitted from the site either through the liner or cap.

3.3.2.2 Flare system

The flare can be switched off or on, and it is assigned a maximum and minimum capacity. It is assumed to be operational when the collection system has been commissioned (dependent on the expected commissioning date entered). The flare is assumed to be running if the collection system is in service and the LFG available is sufficient for flaring, i.e. greater than its minimum operational needs. The flare can be used in conjunction with the utilisation plant, when it can collect any excess gas that is not used for energy recovery.

Details on the flame temperature and residence time in the flare are also input for use in the emissions model. This section of the model has not yet been developed.

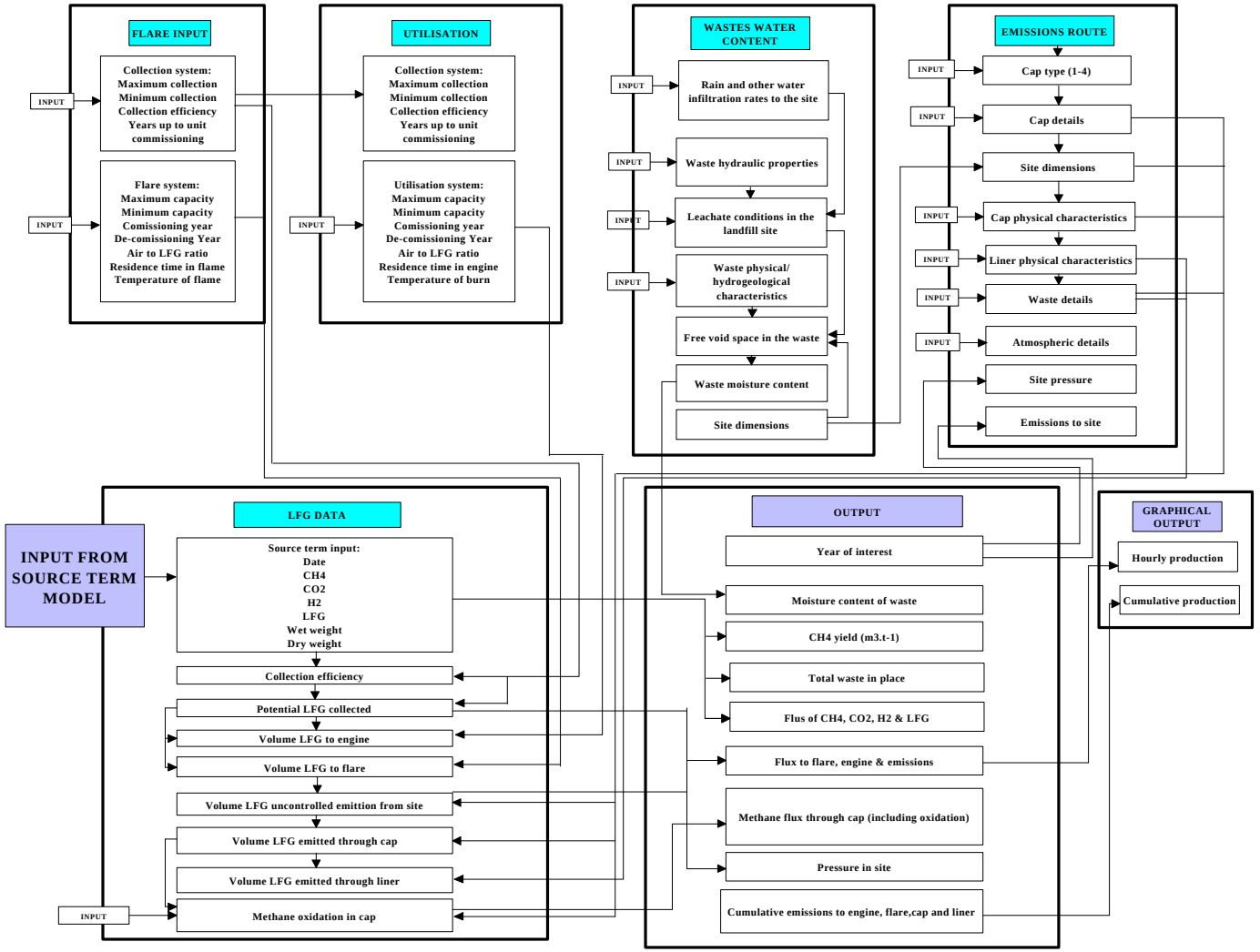

Figure 3.3 Emissions model flow diagram

3.3.3 Utilisation

The Utilisation sheet allows for the use of LFG utilisation systems for energy recovery. Data requirements include:

- number of engines units;
- average run conditions (m^3(LFG at x% CH_4).hr^{-1});
- commissioning time for the engines after waste is first emplaced; and
- life expectancy of the units.

The model allows for multiple engines to be commissioned on site and they can be brought on line if and when sufficient gas is available. The engines are run at a constant gas requirement, with a constant output. Therefore, if the predicted gas collection is initially only sufficient for one engine then only that volume of gas will be diverted to the engine. If LFG production increases, then another unit may be added if there is sufficient LFG to run two units, and so on, until the units are decommissioned or there is insufficient gas to run a single unit. Figure 3.4 shows for a fictitious scenario how the different emission routes can interact over the assessment period.

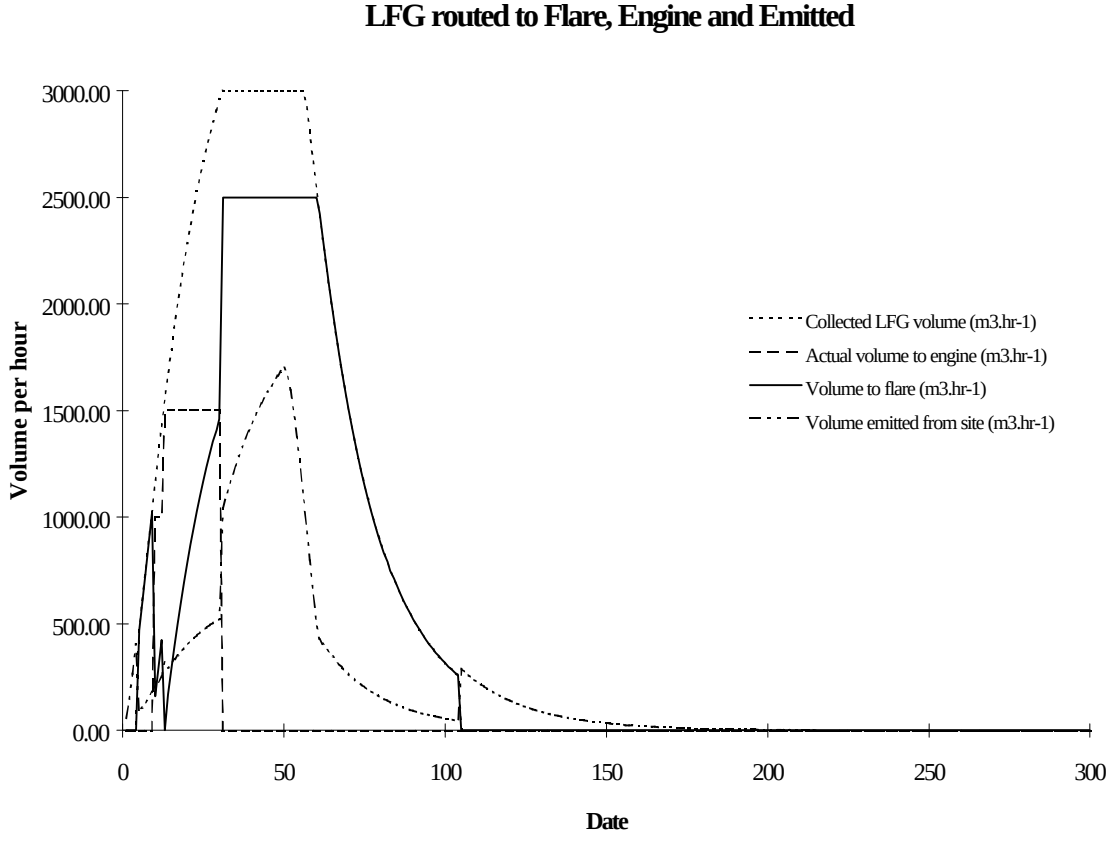

Figure 3.4 Collection system, flare, utilisation plant, and emissions displayed for a particular scenario.

3.3.4 Water content of the waste

The Waste Water Content sheet allows entry of waste physical and hydrological data as well as site design details. This is used to calculate the free void space of the waste mass and thus the effective pore volume (this is the volume available for gas to reside). The effective pore volume of the waste in conjunction with the over pressure in the site (covered below) is then used in the calculation of Q storage for the landfill.

No migration of LFG is simulated in the saturated zone of the waste.

The water content of the waste will affect the permeability of the waste and give us an effective permeability. If this is greater than that of the cap or the liner then it will control the rate of LFG migration from the site (see the section Emission Route below).

3.3.5 Emission route

Details on the site design are entered here, they include:

- cap design;
- cap permeabilities;
- cap thickness;
- waste thickness;
- waste permeabilities;
- liner thickness;
- liner permeability; and
- site dimensions.

From these data, the layer that controls the emission rate through of the cap or liner can be determined, this is the layer with the lowest permeability. As mentioned previously, this may be the waste material. The emissions from the site assume a steady state situation with all the residual gas (that not collected) in the site being emitted. The emissions via the cap and the liner are proportional to the effective permeability of these layers and their thickness.

3.3.6 Model output

The Output sheet allows the selection of a year in the landfill life after filling has commenced and it presents data for that year. Data presented are for:

LFG production

- methane production ($m^3.hr^{-1}$);
- carbon dioxide production ($m^3.hr^{-1}$);
- hydrogen production ($m^3.hr^{-1}$);
- LFG production ($m^3.hr^{-1}$); and
- cumulative production of the gases mentioned above (m^3).

Emission routes

- LFG routed to energy recovery ($m^3.hr^{-1}$);
- LFG routed to the flare system ($m^3.hr^{-1}$);
- LFG lost from the site in uncontrolled emissions ($m^3.hr^{-1}$);
  - through the cap:
  - through the liner:
- LFG uncontrolled emission rates from the cap and liner ($m^3.hr^{-1}.m^{-2}$); and
- cumulative volumes of LFG to the emission routes mentioned above (m^3).

The Output Sheet also calculates the theoretical methane potential of the waste in $m^3.t^{-1}$ dry weight of waste. This is calculated over the 300 years of the assessment period, and it is a useful calculation check.

The spreadsheet also has two graphical outputs: one that shows emissions to each route in $m^3.hr^{-1}$; the other gives a cumulative figure in m^3.

4. ENVIRONMENTAL TRANSPORT

The environmental transport module deals with the following topics:

- atmospheric dispersion off-site;
- atmospheric dispersion on-site;
- lateral migration through the ground under steady state conditions;
- lateral migration through the ground in unusual conditions ("events").

The atmospheric dispersion parts of the module operates deterministically but takes into account the probabilities of occurrence of various weather conditions. Sections 4.1 and 4.2 show how this is done, describe the dispersion models used and give sources of parameter values. In the current version of the code, lateral migration of gas through the ground under steady state conditions is modelled deterministically. The assumptions, approach and equations used are given in Section 4.3. For lateral migration under unusual conditions the approach is to estimate the probability of occurrence of such an extraordinary migration event but not to attempt to estimate the consequences (see Section 4.4).

4.1 Atmospheric dispersion off-site

4.1.1 Types of models and sources

The models used to calculate pollutant concentrations in air off-site, and corresponding deposition levels on the ground, are all of the Gaussian plume type. This type of model is used in a variety of contexts in the UK, particularly when a number of sites are to be considered, rapid calculations are required and limited site-specific data are available. Gaussian plume models first began to be used more than 20 years ago and have been the subject of many validation and uncertainty analysis studies.

In the dispersion calculations three types of source are considered: flares, engines and caps. In each case releases of pollutants to atmosphere are assumed for the purpose of dispersion calculations to be continuous over a year. Flares and engines are treated as elevated point sources, and for flares, plume rise resulting from thermal buoyancy is included. Caps are treated as ground-level area sources, without any plume rise.

4.1.2 User input

User inputs to the models are:

i) the year to be considered (which the code uses to select the appropriate emission rates of the pollutant from the results produced by the source term module);

ii) the location at which pollutant concentrations in air and deposition level on the ground are to be calculated (specified as distances from the source, and directions as points of the compass);

iii) the windrose for the site (see below);

iv) the annual frequencies of occurrence of the various Pasquill stability[1] categories (see below);

v) the deposition characteristics of the pollutant (see below).

The code contains four reference windroses from which the user can choose: a uniform windrose (the default); and three windroses based on data for sites on the west coast of England, the east coast of England and central southern England. In addition there is an option for the user to input a windrose specific to the site being considered. Four sets of frequencies of occurrence of the Pasquill stability categories are provided, one for each windrose, and the user has the option to input site specific data. For deposition characteristics the user chooses whether the pollutant being considered is to be assumed to be a non-reactive gas or a reactive gas/particulate. There is also an option for the user to input pollutant-specific values for the dry deposition velocity and washout coefficient. Table 4.1 shows the values of deposition parameters included in the code.

In the case of the location of the point of interest, the user specifies any distance (in metres) in the range 0m to 25km. To look at on-site dispersion (see Section 4.2) the distance should be less than 10m but not zero. Directions must be specified as N, NNE, NE, NEE, E etc.

Table 4.1 Values of deposition parameters

Type of material	Deposition velocity, ms^{-1}	Washout coefficient, s^{-1}
Unreactive gases	0	0
Reactive gases, small particulates	10^{-2}	10^{-4}

4.1.3 Equations and parameter values

The equations used for dispersion from point sources are those given in the first two reports of a UK working group on atmospheric dispersion and which are summarised in a more accessible form in a recent report for the European Commission (UK Working Group on Atmospheric Dispersion 1979 and 1981; NRPB et al 1995). Equations and approximations for area sources are taken from work for UK Nirex Ltd.

4.1.3.1 Dispersion from a point source, without deposition or plume rise

Without allowance for dry or wet deposition, or for plume rise, the mean concentration of a pollutant in a sector of width α radians at a downwind distance x (m) and height z (m) from a point source is given by:

[1] A set of parameters that characterise dispersion.

$$X(x,z) = \frac{Q_0}{ax\sqrt{2p}\,s_z u_s}\left[\exp-\frac{(h_e+z)^2}{2s_z^2}+\exp-\frac{(2A+h_e+z)^2}{2s_z^2}+\exp-\frac{(2A-h_e-z)^2}{2s_z^2}\right]$$

Equation 4.1

where:

Q_0	release rate from the source (mg s^{-1} if X is required in mg m^{-3})
σ_z	standard deviation of the vertical Gaussian distribution (m) (the vertical dispersion coefficient)
u_s	wind speed at the effective release height (m s^{-1})
h_e	effective release height (m)
A	depth of the mixing layer (m).

In the current version of the code 30° sectors are assumed so α is $\pi/6$.

σ_Z , u_s and A vary from one stability category to another. σ_z and u_s also depend on the roughness of the ground. Values of σ_z are given by:

$$s_z = \frac{ax^b}{1+cx^d}F(z_0,x)$$

Equation 4.2

where:

a, b, c, and d	are constants which vary from one stability category to another (see NRPB *et al*. 1995 for values),
$F(z_o,x)$	is the roughness correction factor, and
z_0	is the roughness length.

For simplicity only one value of roughness length is used, appropriate to arable agricultural land, allotments and gardens. This is 0.1m, in which case the roughness correction factor is unity.

NRPB *et al.* 1995 gives typical values of the wind speed at 10m (u_{10}) and the mixing layer depth for Pasquill categories A-F. The windspeed at any other height z, for a ground roughness of 0.1m, is given by:

$$u(z) = u_{10}\,(z/10)^{0.2}$$

Equation 4.3

but for release heights below 10m the wind speed is taken to be u_{10}.

4.1.3.2 Dry deposition

Deposition of reactive gases and small particulates in dry conditions is modelled using a deposition velocity, v_g. The dry deposition rate D_D (mg m^{-2} s^{-1}), or its time integral, is then given by:

$$D_D = v_g C$$

Equation 4.4

where:

C is the concentration (mg m^{-3}) of the pollutant in air at ground level or its time integral.

The effects of dry deposition on the concentration of a pollutant in air can be estimated by modifying the source strength, Q_0. This is known as the "source depletion" model. The value of the modification factor is very close to unity for most Pasquill categories at most of the distances from the source which are of interest here (NRPB *et al* 1995). However, for ease of coding, the source depletion model is used at all distances, using the values in NRPB *et al* 1995.

4.1.3.3 Wet deposition

For long duration releases it is conventional to assume, for simplicity, that wet deposition only occurs in category D. It is also assumed here that the mean rainfall rate is 1mm h^{-1} and that the mean durations of dry and wet weather in the UK are 60 hours and 6 hours, respectively.

The wet deposition rate per unit area is given by:

$$D_w = \frac{\Lambda Q'_w(t)}{x a u_s}$$

Equation 4.5

where:

Λ is the washout coefficient (s^{-1})

$Q'_w(t)$ is the amount of material remaining in the plume at time t (s) if it is raining at that time.

To obtain the concentration in air we need Q'(t), the amount of material remaining in the plume at time t is it has rained for part of that time. The equations for $Q'_w(t)$ and Q'(t) are:

$$Q'(t) = \frac{Q_0}{m_1 - m_2}\left[(m_1 + \Lambda f_w)e^{m_2 t} - (m_2 + \Lambda f_w)e^{m_1 t}\right]$$

Equation 4.6

$$Q'_w(t) = \frac{Q_0}{m_1 - m_2}\left[(m_1 + \Lambda)e^{m_2 t} - (m_2 + \Lambda)e^{m_1 t}\right]$$

Equation 4.7

where:

f_w is the fraction of the time for which rain falls (i.e. 0.1 for the UK), and m_1 and m_2 are given by:

$$2m_1 = -(\Lambda + P_D + P_W) - \sqrt{(\Lambda + P_D + P_W)^2 - 4\Lambda P_D}$$

$$2m_2 = -(\Lambda + P_D + P_W) + \sqrt{(\Lambda + P_D + P_W)^2 - 4\Lambda P_D}$$

where:

P_D is the probability of dry weather;

Pw is the probability of wet weather; P_D and P_W are equal to the reciprocal of the mean durations of dry and wet weather (see above).

4.1.3.4 Plume rise

To include the effects of plume rise it is sufficient to adopt a virtual release point directly above the actual release point, and to modify the value of σ_z. The effective release height in this instance is:

$$h_e = h + \Delta h$$

where:

Δh is derived from

$$\Delta h = 2.6\left[\frac{F_b}{u_a s'}\right]^{1/3}$$

Equation 4.8

The value of σ_z. with plume rise is related to σ_{zD} without plume rise by

$$\sigma_z.^2 = \sigma_{zD}^2 + z_p^2/12$$

Equation 4.9

where:

z_p is the plume rise and is derived from:

$$z_p = \left[\frac{3F_m x}{b u_a^{\,2}} + \frac{3F_b x^2}{2 b^2 u_a^{\,3}}\right]^{1/3}$$

Equation 4.10 (for neutral and unstable conditions (categories D-F))

$$z_p = \left[\frac{3\left(s'^{1/2} F_m \sin s'^{1/2} t + F_b\left(1-\cos s'^{1/2} t\right)\right)}{b^2 u_a s'}\right]^{1/3}$$

Equation 4.11 (for stable conditions (categories A-C))

where:

F_b	is the initial buoyancy flux
u_a	is the wind speed averaged over the height through which the plume has risen
s’	is the stability parameter
β	is an entrainment parameter (≈0.6)
F_m	is the momentum flux of the source

Further details of these parameters are given in NRPB et al 1995 (p25).

4.1.3.5 Averages over stability categories and wind directions D

In general the pollutant concentration in air (or the deposition rate) in direction i is given by:

$$X_i\,(r,z) \;=\; \Sigma\, f_{ij}\, X_{ij}\,(r,z)$$

Equation 4.12

where:

f_{ij} is the frequency with which the wind blows into the sector in direction i in stability category j, and r is the distance from the source. If only the windrose and the frequencies of stability categories are available then:

$$f_{ij} \;=\; f_i \;\; f_j$$

where:

f_i is the frequency with which the wind blows into sector i and f_j is the frequency of occurrence of stability category j.

Then;

$$X_i\,(r,z) \;=\; f_i\, \Sigma\, f_j\, X_{ij}\,(r,z)$$

Equation 4.13

4.1.3.6 Dispersion from a ground level area source

For a ground level area source the average concentration of a pollutant in air (and also the deposition rates) can be calculated by dividing the release area into strips of length L(x) perpendicular to the wind direction and integrating over the strips. In this formulation the point of interest is at the origin. When the wind is blowing into the same sector as the point of interest the concentration at ground level is:

$$X(0,0) = \frac{Q_0}{A_s}\int_{x_{\min}}^{x_{\max}} \frac{L(x)}{\sqrt{2p}\, a\, s_{\ z} u_{10} x}.dx$$

Equation 4.14

where:

Q_0 release rate from the source (mg s^{-1})

A area of the source (m^2)

x_{max} , x_{min} distances of the point of interest from the nearest and furthest boundaries of the source.

For distances less than 1km, which are those of most interest for dispersion from the cap, we can use the approximation:

$$\sigma_z = ax^b$$

Equation 4.15

(where a and b are as in Equation 4.2).
If L(x) is taken to be independent of x and equal to the mean projected width of the release area, L, then:

$$X_{(0,0)} = \frac{Q_0}{A_s\sqrt{2p}\,au_{10}}\left(\frac{L}{ab}\right)\left(x_{\min}^{\ -b} - x_{\max}^{\ -b}\right)$$

Equation 4.16

4.1.4 Output

Output from the off-site atmospheric dispersion module consists of annual average concentrations of the pollutant in air at the point of interest, and corresponding deposition levels on the ground, for emission rates from the flare, engine and cap, and the sums of the concentrations and deposition levels from the three types of source. The annual averages are, in all instances, derived by summing over the windrose and frequencies of stability categories.

4.2 Atmospheric dispersion on-site

For emissions from flares and engines the equations given in Section 4.1 for off-site dispersion from point sources are also applied to calculate concentrations of gases and particulates on-site. For gas emissions from capped areas of the landfill the time-averaged concentration in each release area is calculated using:

$$X = \sum_j \frac{f_j Q_0}{\left(\sqrt{\frac{4A_s}{p}}u_j l_j\right)}$$

Equation 4.17

where:

A_s release area
u_j mean wind speed for category j and
l_j the mixing height for category j.

This formulation assumes a circular release area and a uniform windrose, and is judged to be sufficiently accurate for making estimates of health risks to landfill workers.

Concentrations of dust in air in open areas of the landfill are not estimated in the current version of the code. They could be derived using dust loadings in air for various conditions, rather than by using any dispersion modelling.

4.3 Lateral migration under steady state conditions

The gas emission model for the steady state case assumes that there is a pressure gradient from inside the landfill to outside its liner, but implicitly assumes that there is no pressure gradient within the ground around the landfill. Lateral migration under steady state conditions is therefore modelled as a diffusive process. In one dimension the mass flux rate at a distance x from a source is given by:

$$\frac{dC}{dt} = D_s \frac{d^2C}{dx^2}$$

Equation 4.18

where:

D_s effective diffusivity of the gas in soil ($m^2\ s^{-1}$)

which for a boundary condition of zero concentration at infinite x has the solution:

$$C(x,t) = C_0\ \ \mathrm{erfc}\ [\ x/(4D_s t)^{1/2})]$$

Equation 4.19

Equation 4.18 and Equation 4.19 are used in the code to obtain the mass flux of gas at any distance of interest It is assumed that there is no biological oxidation of methane and no other attenuation or reaction process that reduces the concentration of any gas as it moves through the ground. The concentration of gas in the landfill (C_o) is taken from the emissions module and the user can select the maximum, minimum or average concentration for the period of interest. Other user input is the distance to the receptor, the average porosity of the zone from the soil surface to the unsaturated depth of the landfill, and the ground saturation. The code uses these latter two parameters to select the appropriate value for the effective diffusivity of the gas in soil.

4.4 Lateral migration in unusual conditions

The conditions to be considered are those in which gas migration rates, and gas generation rates, increase rapidly so that there is a potential for high concentrations of flammable and toxic gases to suddenly occur in buildings at some distance from a landfill. In such cases pressure in the landfill will higher than in steady state conditions and there will be pressure driven gas flow from the landfill through the ground. The approach used in the code is to estimate the probability that an unusual migration event will occur, given input by the user about the presence or absence of features of the landfill and its surroundings, and about the probabilities that various conditions exist or may do so in the future.

The features and conditions for which the user is asked to provide probabilities (as percentages) are as follows:

- landfill is unlined
- desiccation in cracks in clay liner
- gas collection system out of commission for more than one day
- no gas collection system
- pressure drop over user defined criterion occurs
- impermeable surface layer between landfill and receptor
- wet or frost period occurs after a dry period, leading to an impermeable surface layer
- wet or frost period occurs when gas collection sytem is out of order
- strata contain fractures
- fractures are linked to liner defects.

In the code these are grouped so as to obtain the probabilities that various scenarios will occur, and hence provides the user with a semi-quantitative indication of the risk of a migration event with severe consequences (eg an explosion in a dwelling).

5. EXPOSURE ASSESSMENT

The exposure assessment module will carry out two major functions:

- the calculation of intakes of pollutants by persons on the site or residents near the site; and
- the calculation of concentrations of pollutants in indoor air, as a result of atmospheric dispersion and lateral migration.

Figure 5.1 shows the information flow through these parts of the module and its interfaces with the environmental transport and impact assessment modules. Section 5.1 describes the models and parameter values to be used to calculate intakes of pollutants by inhalation, ingestion and dermal exposure routes. Section 5.2 briefly indicates the models for calculating pollutant concentrations in indoor air.

5.1 Intakes of pollutants by members of the public

In this module the exposure of residents adjacent to a landfill to chemicals in the air and via food is assessed using assumptions about their habits and relevant data derived from the literature. Exposure assessment of site workers could be made using the user defined 'maximally exposed individual', with a short distance for the dispersion calculations and an outdoor occupancy appropriate to the type of work.. However, exposure of site workers remains a health and safety at work issue rather than a public exposure issue.

In order to provide an idea of the potential range of exposures, the concepts of a "critical group" and of average persons are used in the exposure assessment. A critical group has been defined by the NRPB as "those members of the public who are most exposed from a given source " (NRPB 1996). This critical group, by way of its particular situation and habits, is potentially exposed to a greater extent than the average population, and this approach thus provides conservative estimates of exposure for assessment purposes. In addition, to provide greater flexibility, the exposure model will include a user defined "maximally exposed

For assessing the direct exposure of residents near a landfill, exposure time in and around the residence is of greatest importance, thus the critical group is comprised of housewives and young children at home, and the maximally exposed individual has been chosen to be an active retired person who spends much time gardening and little time away from home.

From this basis, the conceptual exposure model was derived for 7 types of person:

- average infant, child, and adult;
- critical infant, child and adult; and
- the maximally exposed individual.

All parts of the model are to be applied to each of these persons.

The exposure routes of concern to the general population living adjacent to the landfill were defined as inhalation exposure, ingestion exposure and dermal exposure. For each of these exposure routes, both indoor and outdoor exposures are considered and summed for each route.

The exposure from each route is provided as annual average exposure to the chemical and also as a lifetime exposure.

The chemicals to be considered in the exposure model are:

Bulk gases: methane, carbon dioxide, hydrogen.
Trace gases: vinyl chloride, trichloroethene, tetrachloroethene, methane thiol, hydrogen sulphide, dioxin, furans, chlorodifluoromethane, dichlorodifluoromethane, benzene, nitrogen oxides, sulfur oxides, hydrogen chloride, hydrogen fluoride, carbon monoxide.
Particulates: PM_{10}, dust from landfill operation (user defined characteristics).

5.1.1 Inhalation exposure model

All the above chemicals are to be considered for the inhalation and dermal exposure routes. The bulk gases and the nitrogen oxides, sulphur oxides, hydrogen chloride, hydrogen fluoride and carbon monoxide will not be considered for the ingestion route as they are unlikely to be transported unchanged through foodchains, thus human exposure to these chemicals is improbable via ingestion of food.

The basis for the inhalation exposure model is defined below:

$$\mathbf{E_I = Q_I \ . C_{AIR}}$$

Equation 5.1

where:

E_I	inhalation exposure (mg d^{-1})
Q_I	inhalation rate (m^3 d^{-1})
C_{AIR}	air concentration (mg m^{-3})

Pollutant concentrations for indoor and outdoor air will be provided from other parts of the model (see Figure 5.1).

Following examination of the literature, inhalation rates were taken from the ICRP Human Respiratory Tract Model (ICRP 1994), following NRPB recommendations. From the inhalation rate data in NRPB (1996), the values for 3 month and 1 year old infants have been averaged to provide the infant value for gas risk assessment. The 5, 10 and 15 year old data were averaged to provide a general child value. Where separate male and female values were provided for 15 year olds and adults, the values have been averaged, except for the case of the

maximally exposed individual where the male adult value was chosen to provide the maximum inhalation rates for any given activity. The inhalation data for various activities

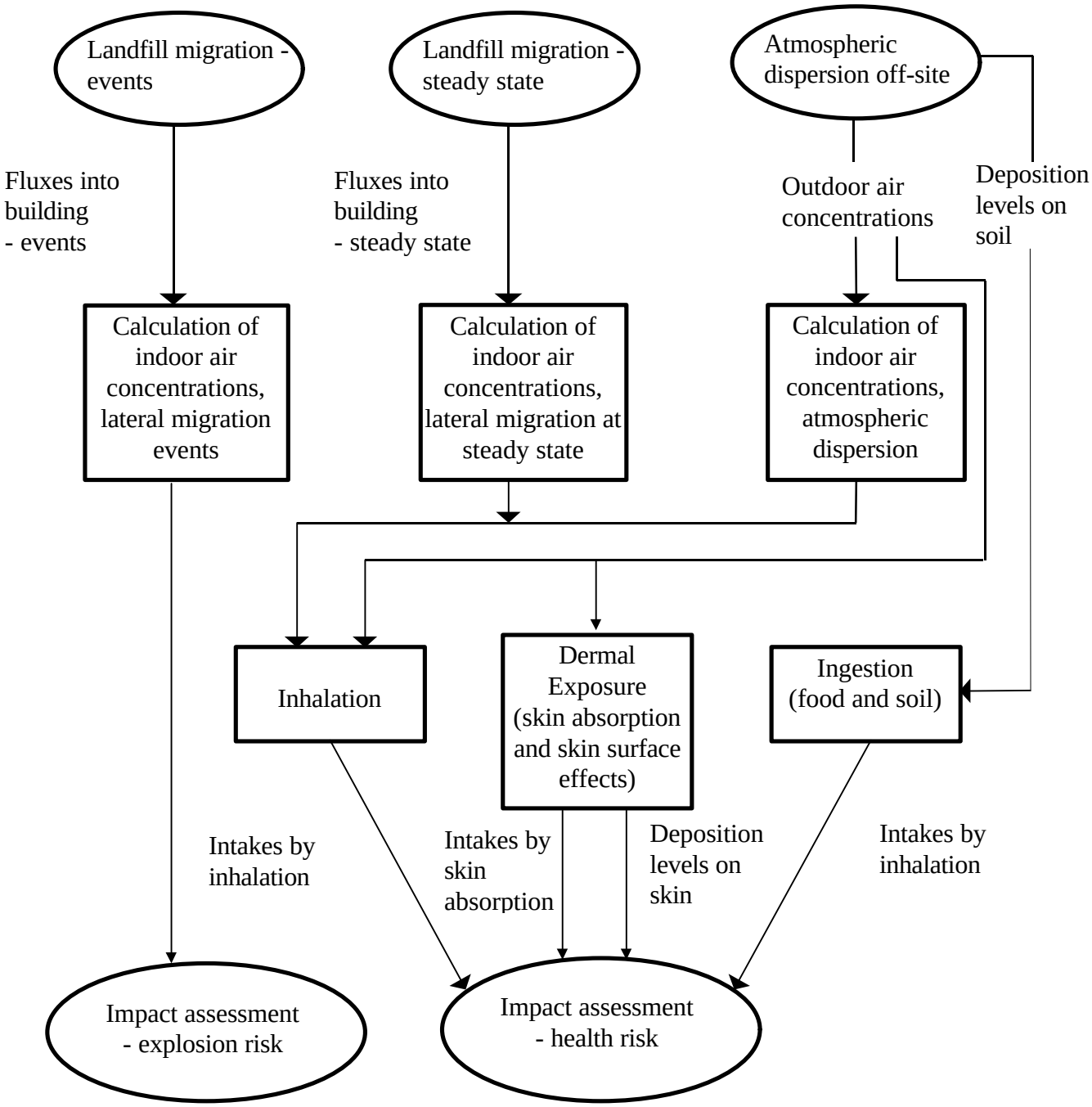

Figure 5.1 Exposure assessment module: members of the public

(sleeping, indoors, outdoors) match the categories required for gas risk assessment very well, and have been used directly apart from the averaging described above. Table 5.1 shows the inhalation rates included in the exposure assessment module.

Table 5.1 Inhalation rates (m^3hr^{-1})

Activity		Population						
		Average group			Critical group			Maximally
		Infant	Child	Adult	Infant	Child	Adult	exposed
		0-1 yr	1-16 yr	16-70 yr	0-1 yr	1-16 yr	16-70 yr	individual
Indoors at home	sleep	0.12	0.31	0.39	0.12	0.31	0.39	0.45
	other	0.25	0.75	1.07	0.25	0.75	1.07	1.18
Outdoors at home		0.31	0.94	1.11	0.31	0.94	1.11	1.69
(Away from home)		0.25	0.75	1.07	0.25	0.75	1.07	1.18

The above matrix of inhalation rates for various populations and activities (NRPB 1996) must be combined with estimates of occupancy times for each location and activity to provide inhalation data in units of m^3 per day. Occupancy data describing the time spent indoors or outdoors at home and away from home has been taken from NRPB (1987) utilising data derived from a BBC survey on population activity conducted in 1978 (BBC 1978). More recent data on domestic occupancy has not been found. The data in this report was used to ascertain that housewives would form the critical group for a pollution source adjacent to a domestic residence; young pre-school children would also have the same high domestic occupancy as the housewives. The critical group occupancy data has thus been derived from the housewife data in the report. The average population data has been derived from the report with some estimations made regarding the time spent outside at home for this group. The report also provides the data on sleeping time, school hours and time away from home for the relevant populations. The maximally exposed individual has been based on housewife occupancy data but with more time spent outdoors at home (e.g. gardening) rather than indoors or away from home, as this provides higher inhalation rates and probably greater exposure to higher outdoor air concentrations, though this may be chemical dependent. Table 5.2 shows the derived occupancy data to be used in the module.

Table 5.2 Occupancy rates (hr day^{-1})

Activity		Population						
		Average group			Critical group			Maximally
		Infant	Child	Adult	Infant	Child	Adult	exposed
		0-1 yr	1-16 yr	16-70 yr	0-1 yr	1-16 yr	16-70 yr	individual
Indoors at home	sleep	14	10	8	14	10	8	8
	other	7	9.5	11	7	9	12.5	12
Outdoors at home		0.5	0.5	0.5	1	1	1	3
(Away from home)		2.5	4	4.5	2	4	2.5	1

The data in these two tables can be combined for each population set to provide a table of activity weighted inhalation rates ($m^3 d^{-1}$) as follows:

$$\mathbf{Q_{IA} = A \,.\, Q_{I/hr}}$$

Equation 5.2

where:

Q_{IA}	activity weighted inhalation rate ($m^3 d^{-1}$)
A	activity ($hr\ d^{-1}$)
$Q_{I/hr}$	inhalation rate ($m^3 hr^{-1}$)

This provides values for average, activity weighted inhalation rates as shown in Table 5.3.

Table 5.3 Activity weighted inhalation at home (m^3 day^{-1})

Activity		**Population**						
		Average group			Critical group			Maximally
		Infant	Child	Adult	Infant	Child	Adult	exposed
		0-1 yr	1-16 yr	16-70 yr	0-1 yr	1-16 yr	16-70 yr	individual
Indoors at home	sleep	1.68	3.10	3.12	1.68	3.10	3.12	3.60
	other	1.75	7.13	11.77	1.75	6.75	13.38	14.16
Outdoors at home		0.16	0.47	0.56	0.31	0.94	1.11	5.07
(Away from home)		(0.63)	(3.00)	(4.82)	(0.50)	(3.00)	(2.68)	(1.18)
Total at home inhalation ($m^3 d^{-1}$)		**3.59**	**10.70**	**15.45**	**3.74**	**10.79**	**17.61**	**22.83**

The at home inhalation data can be multiplied by 365 to provide $m^3\ yr^{-1}$, which can then be combined with the indoor and outdoor annual average air concentrations for each chemical. Annual average ($mg\ yr^{-1}$) and cumulative lifetime ($mg\ lifetime^{-1}$) exposures via inhalation can then be derived for any of the population groups over any given time period of the landfill lifetime. A lifetime has been set at 70 years.

5.1.2 Ingestion exposure model

The ingestion exposure model includes ingestion of locally produced or home-grown foodstuffs and, additionally, inadvertent ingestion of soil and house dust. Ingestion exposure via foodstuffs can be described by

$$\mathbf{E_{IN} = Q_{IN\ local} \,.\, C_{\ food}}$$

Equation 5.3

where:

E_{IN}	ingestion exposure via foodstuffs (mg yr^{-1})
$Q_{IN\ local}$	ingestion rate of local foodstuffs (kg yr^{-1})
C_{food}	concentration in the local foodstuff (mg kg^{-1})

The population groups and the chemicals under consideration are exactly as defined in the inhalation model. The foodstuffs taken to be representative of home-grown produce are leafy green vegetables and root vegetables (cabbages and potatoes in winter, lettuces and potatoes in summer). These crops were selected on the basis that ingestion of them is likely to lead to the highest health risks. The leafy green vegetables will become contaminated primarily as a result of deposition from atmosphere, while contaminant concentrations in the root vegetables will reflect any build-up of pollutants in soils. (Other plants are likely to be considered in the part of the impact assessment module which deals with vegetation stress.)

Additionally, locally produced milk has been considered because of the importance of this foodstuff to infants and children. It is recognised that it is unlikely that milk from a farm adjacent to the landfill will reach the population living adjacent to the landfill in an undiluted form, however the potential for farmers' children drinking home-produced milk must be taken into account.

Data on ingestion rates of various foodstuffs has been taken from NRPB (1996) and based on an analysis by MAFF of three national dietary surveys examining infant, child and adult diets. These surveys were designed to provide a nationally representative sample of individual diets. The child survey was based on sampling of two age groups, 10-11 years and 14-15 years; the data for the 10-11 year old children have been used here as being most appropriate for the age range 1-16 years. Data are provided for potato and milk consumption, and the data for 'green vegetables' have been taken to be representative of lettuce and cabbage. Consumption data is provided for infants aged 6-12 months old and this has been used for the intakes of potatoes and green vegetables for the infant category, but for milk intake a value representing generalised milk intake over the whole first year of life has been used. Average intake data are provided and has been used directly for the average adult, child and infant categories, the 95th percentile data has been used for critical group categories, and the 97.5th percentile data has been used for the maximally exposed individual. Table 5.4 shows these data.

Table 5.4 Food consumption rates (kg person^{-1}.year^{-1})

Foodstuff	**Population**						
	Average group			Critical group			Maximally
	Infant	Child	Adult	Infant	Child	Adult	exposed
	0-1 yr	1-16 yr	16-70 yr	0-1 yr	1-16 yr	16-70 yr	individual
Milk	200	110	95	350	220	210	240
Potatoes	10	45	50	25	75	100	120
Green vegetables	2	4.5	15	95	15	35	45

Table 5.4 shows the annual average consumption of these foodstuffs. For these risk assessment purposes only locally produced food is taken into account and this will only be a proportion of the annual consumption of the foodstuff. For the maximally exposed individual

and the critical group, it may be prudent to assume that their total consumption of these foodstuffs is home-grown or local. For the average population it is suggested that 50% of total consumption is of home-grown or local produce (MAFF, personal communication, Walters, 1995). Thus local food consumption rates can be derived by multiplying the total food consumption rates by the proportion of this which is home-grown.

$$\mathbf{Q_{IN\ local} = Q_{IN} \cdot h}$$

Equation 5.4

where:

$Q_{IN\ local}$	ingestion rate of local foodstuffs (kg yr^{-1})
Q_{IN}	total food ingestion rate (kg yr^{-1})
h	proportion of home-grown produce (unitless)

These food consumption rates are then combined with the concentration of the chemical in particular foodstuffs to provide an ingestion exposure from home-grown vegetables and locally produced milk.

$$\mathbf{E_{IN} = Q_{IN\ local} \cdot C_{food}}$$

Equation 5.5

where:

E_{IN}	ingestion exposure via foodstuffs (mg yr^{-1})
$Q_{IN\ local}$	ingestion rate of local foodstuffs (kg yr^{-1})
C_{food}	concentration in the local foodstuff (mg kg^{-1})

In order to obtain data on the chemical contamination of the locally produced foodstuffs it is necessary to simulate the movement of the chemicals through to foodstuff following deposition from atmosphere. It is assumed that chemicals from the landfill will be deposited on both the soil and vegetation, and thus be present in garden produce via root uptake, stomatal uptake and direct contamination of the leaves. To obtain an estimate of the transfer of chemicals through the foodchain the concept of transfer factors are used where equilibrium concentrations of a chemical in soil is linked to concentrations in the vegetation growing on that soil by a linear factor. The factor is thus a method of taking all the potential transfer routes to vegetation into account in one equation.

$$\mathbf{B_v = C_{dry\ plant} / C_{dry\ soil}}$$

Equation 5.6

where:

B_v	transfer factor soil to plant
$C_{dry\ plant}$	concentration in dry plant (mg kg^{-1})
$C_{dry\ soil}$	concentration in dry soil (mg kg^{-1})

and

$$\mathbf{B_m = C_{dry\ milk} / DI}$$

Equation 5.7

where:

B_m	transfer factor plant to milk
$C_{dry\ milk}$	concentration in dry milk (mg kg^{-1})
DI	daily intake of chemical (mg d^{-1})

For various organic chemicals, a relationship between the octanol-water partition coefficient (K_{ow}) of the chemical and its measured transfer factor (B_v) to vegetation and to milk (B_m) has been derived by Travis and Arms (1988). These derived values have been used here to obtain transfer factors for the trace volatile organic chemicals which are released from landfills. Where it has been possible to obtain a value for the octanol-water partition coefficient of a chemical, this has been used to model the transfer of these chemicals through the soil to vegetation and then to milk using the following relationships derived from Travis and Arms (1988).

$$\mathbf{\log B_v = 1.588 - 0.578 \log K_{ow}}$$

Equation 5.8

and

$$\mathbf{\log B_m = -8.10 + \log K_{ow}}$$

Equation 5.9

Octanol-water partition coefficients have been determined for most of the volatile organic chemicals and these are shown in Table 5.5. When soil concentrations of the chemicals are available from the deposition model, the derived transfer factors, B_v and B_m, described above can be used to provide the chemical concentrations in the vegetation and then milk. These calculations have been included in the module. Soil concentrations will be provided from the deposition module for each chemical to be considered. Deposition of chemicals to soil (mg m^{-2}) will be averaged through the top 20 cm depth of soil (the rooting zone) to provide a concentration in the rooting zone (mg m^{-3} to 20 cm depth).

Table 5.5 Transfer coefficients based on octanol-water partition coefficients

Chemical	log Kow	log Bv	Bv	log Bm	Bm
vinyl chloride	1.36	0.80	6.34	-6.74	1.82E-07
trichloroethene	2.42	0.19	1.55	-5.68	2.09E-06
tetrachloroethene	1.66	0.63	4.25	-6.44	3.63E-07
methanethiol					
dioxin	6.02	-1.89	0.01	-2.08	8.32E-03
furans	1.34	0.81	6.51	-6.76	1.74E-07
chlorodifluoromethane					
dichlorodifluoromethane	2.16	0.34	2.19	-5.94	1.15E-06
benzene	2.15	0.35	2.21	-5.95	1.12E-06

For the bulk gases, methane, carbon dioxide and hydrogen, and the trace gases, hydrogen sulfide, nitrogen oxides, sulfur oxides, hydrogen chloride, hydrogen fluoride and carbon monoxide, octanol-water partition coefficients are not appropriate. These gases will not be considered in the ingestion model as they are unlikely to be transported through the food chain in their original form. Most of these gases would be chemically altered on being deposited to soil or on being absorbed through plant stomata, and would not be present in the edible plant part, or in milk.

The other part of the ingestion model considers inadvertent ingestion of soil and housedust. Soil and dust can be ingested via hand-to-mouth activity (infants and children sucking fingers, adults smoking or eating) or object-to-mouth activity, or in rare circumstances by direct ingestion, usually by children.

Data on the amount of soil and dust ingested by various sectors of the population have been derived from various experimental approaches and are reported in the literature. These range from observation of hand-mouth activity, soil loading on skin, and tracer experiments to monitor soil material ingested. The literature has been reviewed in the context of human risk assessment from contaminated soil by Ferguson and Marsh (1993), and data for average and critical soil and dust ingestion rates are derived in NRPB (1996). The NRPB values have been chosen as the most appropriate for this risk assessment. Table 5.6 shows these. The value for the maximally exposed individual is taken to represent a high or a deliberate consumer of soil and is consistent with the higher rates of ingestion recorded in the literature.

Table 5.6 Inadvertent soil/housedust ingestion

	Population						
	Average group			Critical group			Maximally
	Infant	Child	Adult	Infant	Child	Adult	exposed
	0-1 yr	1-16 yr	16-70 yr	0-1 yr	1-16 yr	16-70 yr	individual
Soil/housedust ingestion (mg day^{-1})	100	30	10	300	100	30	3000

These values of soil ingestion will be combined with the concentration of chemicals in the dust to provide information on the amount of chemical ingested per day and then per year.

5.1.3 Dermal exposure model

For the gases released from landfill, dermal exposure will be related to the concentration of the gas in air and to the deposition velocity of the gas concerned which is to be provided from other parts of the model, and also to the surface area of the skin available for deposition. For gases the assumption has been made that no attenuation of deposition would occur due to clothing. This may be conservative, but gases have the ability to permeate most materials. There would also have to be a time weighting for indoor and outdoor exposure depending on the occupancy rates provided in the inhalation model and the indoor and outdoor air concentration.

The adult skin area for an adult is provided as 18,150 cm^2 (average of male and female ages 20-30 years, USEPA 1988a), and for a child is provided as 9,400 cm^2 (average of male and female ages 3-12 years, USEPA 1988b).

For particulate releases from landfill, direct dermal exposure to PM_{10} may pose a health risk in the same way as gaseous dermal exposure and this can be assessed by the deposition velocity route outlined above. Additionally particulates may act as carriers for other chemicals such as heavy metals and other organic chemicals and this can be assessed using dust adherence data, chemical loading of the dust and exposed skin areas.

5.2 Calculation of pollutant concentrations in indoor air

As indicated in Figure 5.1, models are needed to calculate pollutant concentrations in indoor air resulting from atmospheric dispersion of emissions from the landfill cap, flares and utilisation plant, and from lateral migration of gases through the ground. In the migration case we need to consider steady state conditions and unusual conditions.

The current module enables the user to consider several types of design of houses, spanning the range from modern houses with slab floors to old houses with cellars. Two main types of house construction have been modelled, one is a slab based building, the other is a building with a suspended floor. The first type allows consideration of modern concrete floored buildings, but would also cover brick floors on soil in older houses and other forms of construction where there is no void space between the soil and the living space (Figure 5.2). The second type of model considers a space beneath a suspended floor and the air concentrations are calculated in the lower space as well as in the living space above (Figure 5.3). This methodology covers houses with cellars or access space beneath the building and those with suspended floors. Many older houses would fall into this category. Changing the input parameters regarding dimensions of the building allows the user to model different forms of building constructions with these two approaches.

Equations have been derived to calculate indoor concentrations from soil gas concentrations (available from the lateral migration model) and outdoor air concentrations (available from the atmospheric dispersion models). Data has been acquired for the calculations although it is recognised that derivation of parameter values for typical UK houses is likely to be a matter of judgement. Default parameter values are provided in the HELGA User Manual.

Slab based buildings

$$C_2 = \frac{(D_{12} + \alpha)C_1 + \beta C_3}{D_{12} + \beta}$$

Equation 5.10

where:

$\alpha = V_s PL/(S_a A)$

$\beta = D_{23(w)} (A_{wa} - A_{wd})/A + D_{23(c)} + E_x h$

C_1	concentration of contaminant in soil gas
C_2	concentration of contaminant in indoor air
C_3	concentration of contaminant in outdoor air
D_{12}	coefficient of molecular diffusion between the soil and the living space
$D_{23(w)}$	coefficient of molecular diffusion between the living space and outdoor air through building walls
$D_{23(c)}$	coefficient of molecular diffusion between the living space and outdoor air through building ceiling
V_s	suction flow velocity
P	perimeter length of house
L	character length over which suction flow is effective
S_a	air filled soil porosity
A	ground area of house
A_{wa}	area of house walls
A_{wd}	area of external windows and doors
E_x	air exchange rate in living space
h	height of living space

The equation for the suspended floor building is an extension of the slab based floor model described above. It includes a sub-floor space and calculates the diffusion between this volume and the house ground floor (Figure 5.3). Many of the input parameters are the same as those listed for the slab based floor equations, with additional information required for the dimensions of the sub-floor void.

For the case of lateral migration under unusual conditions the concern is to determine whether gas concentrations could build up to levels where the risk of explosion is high, or where there is a possibility of sudden, serious health effects (e.g. asphyxiation). The equations used for

steady state conditions can be adapted for use to calculate air concentrations in the unusual conditions of weather and lateral migration which are relevant.

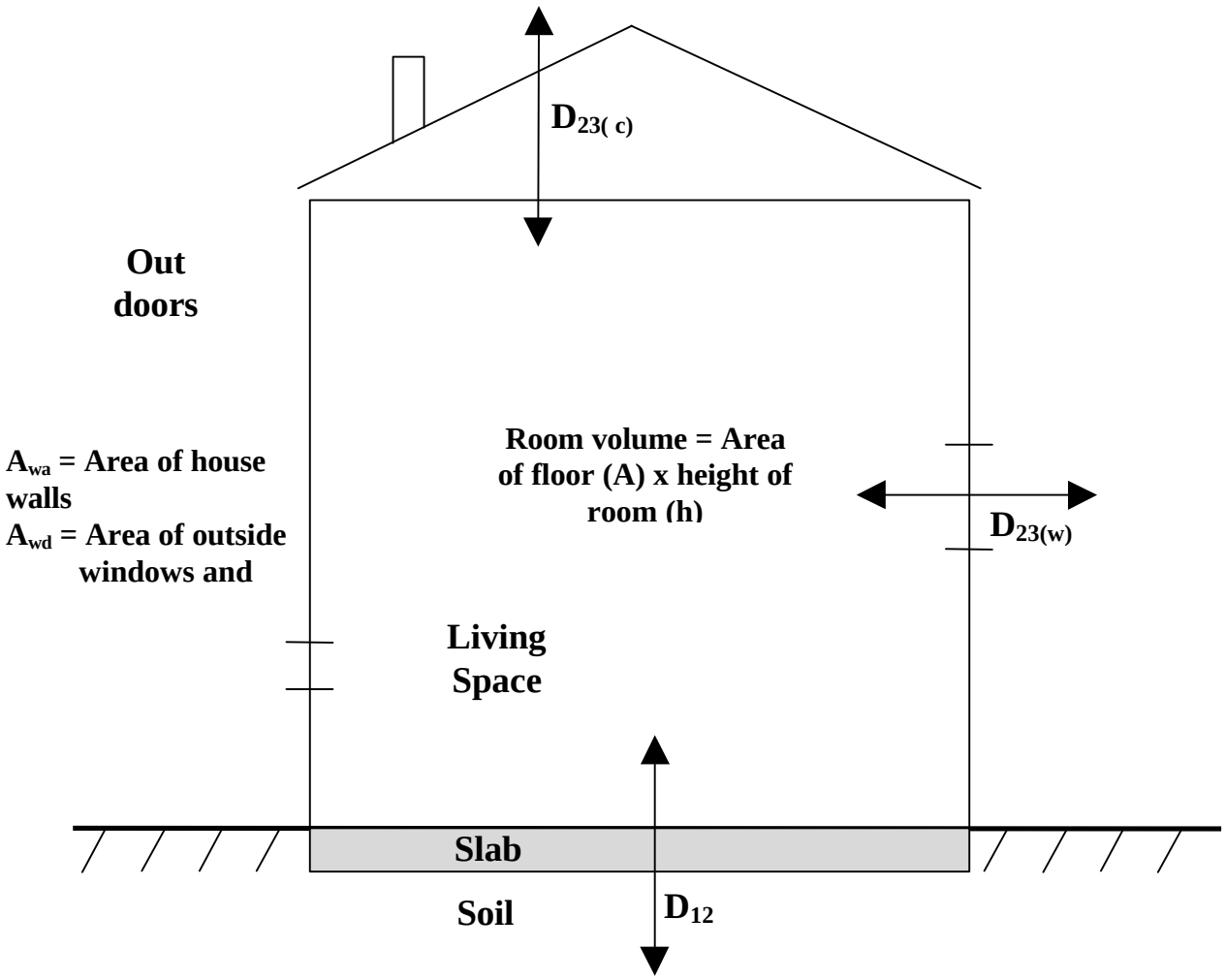

Figure 5-2. Diagrammatic representation of slab floored house

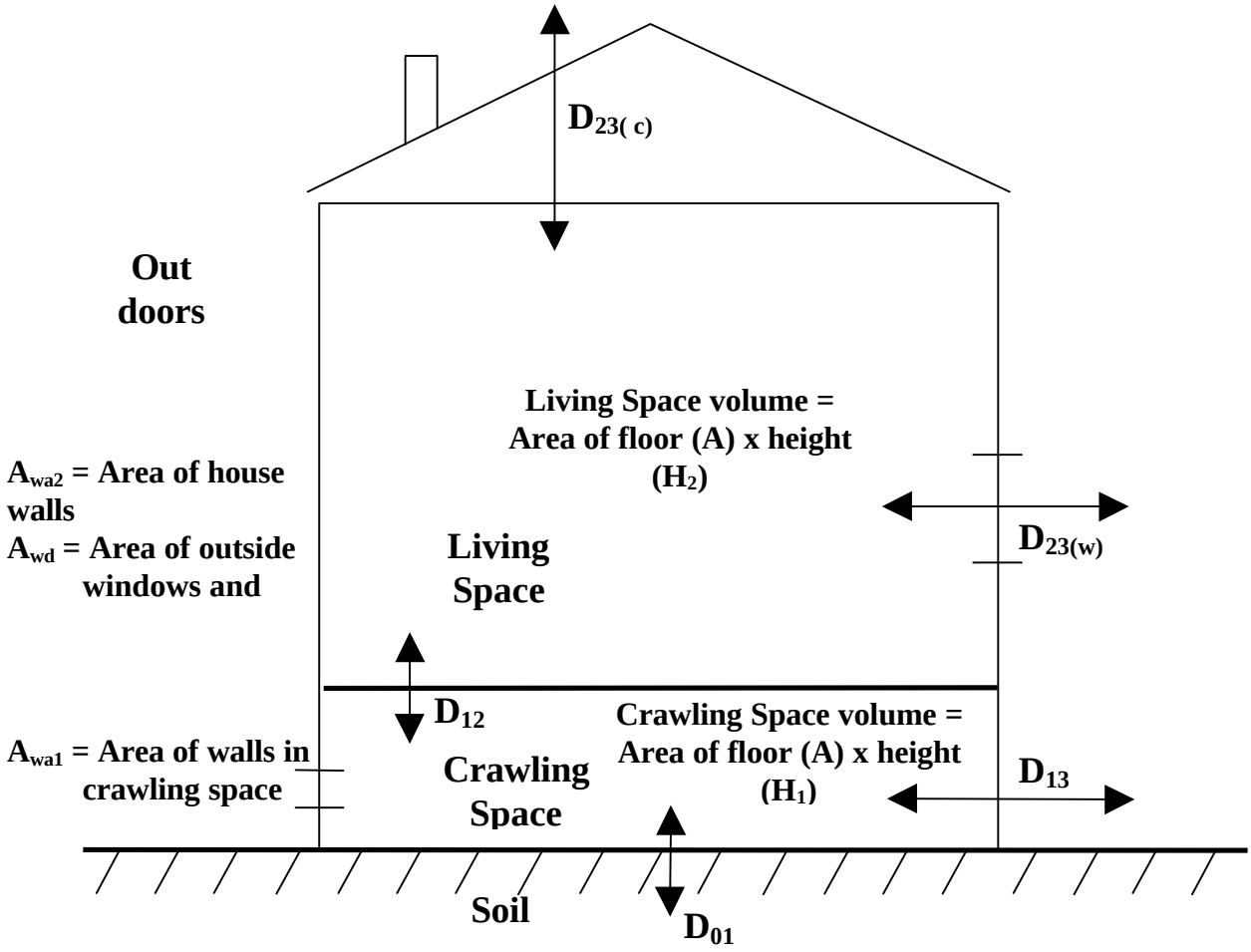

Figure 5-3. Diagrammatic representation of a suspended floor building

6. VALIDATION TESTS FOR THE HELGA MODULES

6.1 Introduction

In order to provide confirmation that the calibrated HELGA modules bear resemblance to actual behaviour, and can therefore be used with confidence to forecast behaviour at other landfill sites, a series of validation trials were carried out. The concept behind validation testing is that model forecast data are compared with data which have been derived by other means than modelling. The degree of consistency between the two data sets demonstrates the validity of the model forecasting capability.

It is not necessary to validate all aspects of the model on one site. Indeed, there is no single site which could provide sufficient data to test all emission pathways represented in the HELGA model. The approach adopted was to investigate each key module or pathway with reference to a well characterised set of site measurements. The validation tests concentrate on the modules which need to be tested, i.e. those which generate the concentration of the emitted pollutant under consideration at a given distance from the landfill. These modules are generally those which are concerned with generation, emission and migration. The impact assessment modules are all based on given exposure levels, and so cannot be validated in this fashion.

The following tests were performed (see Table 6.1).

Table 6.1. Validation tests for HELGA modules

Landfill Site	Module(s) evaluated	Description
Auchencarroch test cells	Gas generation	Well-monitored test cells were used to provide data for the gas generation (source-term) module of HELGA.
Unidentified Buckinghamshire landfill	Gas generation and Surface emissions - methane	Data from part of a well characterised site in Buckinghamshire were compared with equivalent data from other sites in the UK, to test the emissions module for methane.
Greene Valley landfill (US)	Surface emissions - VOCs	A suite of comprehensive monitoring data from this US landfill was compared with forecast emissions, to test the emissions module for VOCs.
Nant-y-Gwyddon landfill	Atmospheric dispersion	This site has been well characterised in terms of odour characteristics. Hydrogen sulphide dispersion modelling was compared with site monitoring data.
Foxhall landfill	Lateral migration	This well characterised site has demonstrated some lateral off-site gas and VOC migration. The model forecasts were compared to measured concentrations off site, along the line of the plume.

6.2 Validation of the gas generation module

6.2.1 Assumptions

The University of Strathclyde has been carrying out some detailed studies of gas generation under different conditions from test cells at Auchencarroch. The Auchencarroch test cells are shallow (approximately 10 m or less deep), filled in the space of 1 year, and subsequently monitored, on an hourly basis, for methane generation. Some cells were treated as control cells, whilst others accepted pulverised waste or were equipped with recirculation of leachate. The data used to validate the model applied to the sum of all the waste emplaced in all the test calls at Auchencarroch.

Data were available covering:

- Waste composition
- Waste mass
- Infiltration of water
- Recirculation
- Gas volume

These data were manipulated into a form that could be directly input or compared with the model forecasts. Data on gas production rates were available for years 2 and 3 after filling, and these were averaged over the years to give average production rates in $m^3.h^{-1}$.

The input data for the test cells used in the model are given Table 6.2 below.

Table 6.2. Input data for the gas generation validation scenario

Parameter	Value
Waste mass	3500 (t)
Fill time	1 (y)
Surface area	625 (m^2)
Waste density	0.75 ($t.m^{-3}$)
Waste depth	10 (m)
Infiltration rate	676 ($mm.y^{-1}$)
Leachate head	0.5 (m)
Recirculation	0.5 ($m^3.h^{-1}$)

The composition of the waste placed into these test cells is given in Table 6.3. This shows that the waste composition is similar to that from the National Household Waste Analysis Programme (DoE, 1994), which forms the default for the degradable carbon data used in the model. We have not therefore changed the waste parameters to suit the test cell composition.

Table 6.3. Waste composition placed in the test cells and from the National Household Waste Analysis Programme (NHWAP. DoE, 1994).

Waste Category	Untreated	Pulverised	NHWAP
Paper/Card	27.29	32.65	33.49
Plastic Film	5.64	7.25	5.09
Dense Plastic	5.20	8.35	5.34
Textiles	3.67	3.65	2.36
Misc. Combustibles	3.54	3.45	7.94
Misc. Non-combustibles	0.50	1.75	2.02
Glass	4.67	6.40	8.63
Putrescibles	38.40	24.65	20.79
Ferrous Metals	5.88	8.05	6.32
Non-ferrous Metals	0.87	1.55	1.44
Fines	4.39	2.20	7.11

6.2.2 Validation Results

The range of modelled LFG production rates for years 2 and 3 are shown in Table 6.4. These data can be compared with the experimental results for the LFG production in the test cells, which are given in Table 6.5.

Table 6.4. Modelled LFG production rates from the test cells (m^3 h^{-1})

Year	Max	Mean	Min	Range
1	19.5	15	10.5	9.0
2	9.7	8	6.3	3.4
3	5.4	4.8	4.1	1.3

Table 6.5. Experimentally determined LFG production rates from the test cells (m^3 h^{-1})

Year	Cell 1	Cell 2	Cell 3	Cell 4
2	8.47	5.80	5.68	5.48
3	5.27	3.67	3.52	5.51

Figure shows the model output, with the experimental data overlain. The figure shows the mean LFG production rate from the test cells (black dot), the range of results (rectangular box) and one standard deviation either side of the mean (black bar line). The HELGA forecast data are shown as three curves (mean - square symbols; 5^{th} percentile - triangles; 95^{th} percentile - diamonds).

Degradation rates have been chosen which are quite rapid, to reflect recirculation of leachate and pulverisation of the waste prior to landfilling. The results show that the model and experimental ranges overlap for years 2 and 3. This therefore indicates that the model

produces results that are within the range of the experimental data. This is encouraging, as gas generation in the early years has been notoriously difficult both to forecast, and measure.

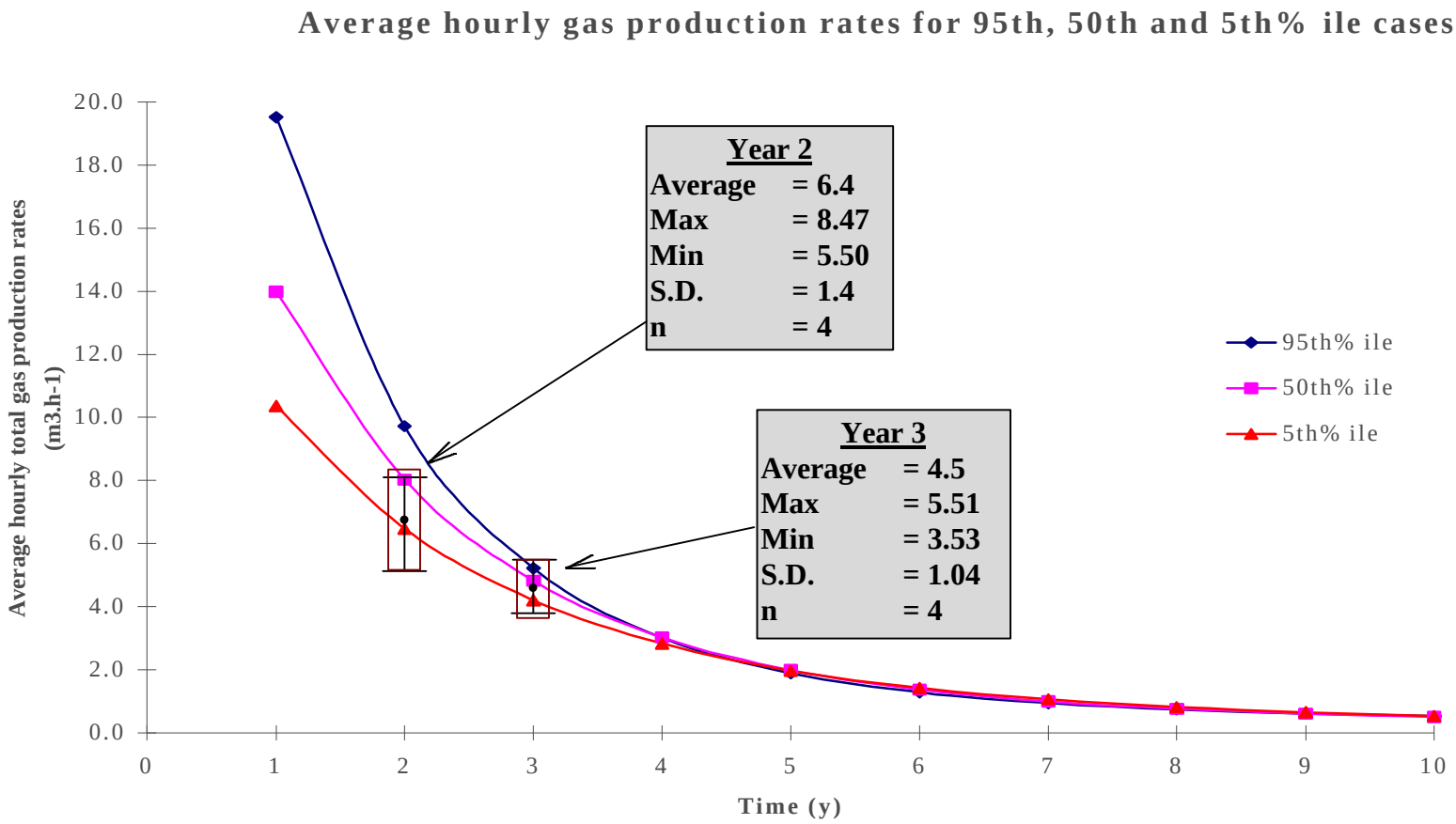

Figure 6.1. Auchencarroch Test Cells: Model Output, with Experimental Data Overlain.

6.3 Validation of gas generation module and surface emission of methane

6.3.1 Assumptions

This Buckinghamshire landfill (otherwise unidentified) has accepted predominantly domestic waste for many years. For the phase of landfilling under consideration, waste was emplaced between 1978 and 1985. Table 6.6 gives the model input data for this scenario.

Table 6.6. Input data for the methane surface emissions scenario

Parameter	Value
Volume of waste into site	2,000,000 (t)
Waste composition	100% domestic
Filling of site	1978 to 1985
Waste type for model (Era)	2 (current)
Fill regime (average for years):	
78/79	200,000 ($t.y^{-1}$)
80/81	200,000 ($t.y^{-1}$)
82/83	260,000 ($t.y^{-1}$)
84/85	333,000 ($t.y^{-1}$)
Saturation of waste	wet
Surface capping	1m clay and 0.8m soil for agricultural purposes
Landfill gas (LFG) collection from area modelled (in 1997)	700 to 1000 ($m^3.h^{-1}$)

6.3.2 Validation results

Landfill gas production

Two model interpolations have been carried out. The first simulation uses the pseudo-probabilistic version of the HELGA model, as delivered to the Environment Agency, which is not dependent upon Crystal Ball™ add-in software. The second uses the fully probabilistic mode, which is expected to be used in subsequent versions of the model. The pseudo probabilistic mode built into the framework model allows HELGA to be used without the separate Crystal Ball™ probability sampling package.

Figure 6.2 shows the pseudo probabilistic model output for the first 30 years. The forecast range of LFG production rates for the time period 18 to 20 years after filling commenced is shown by the box labelled ‘forecast data’. The actual site LFG production (assuming gas collection = gas production) is shown by the box labelled ‘observed data’. Figure 6.2 therefore shows that, in this case, the HELGA model is underestimating the LFG production rate by about 28%.

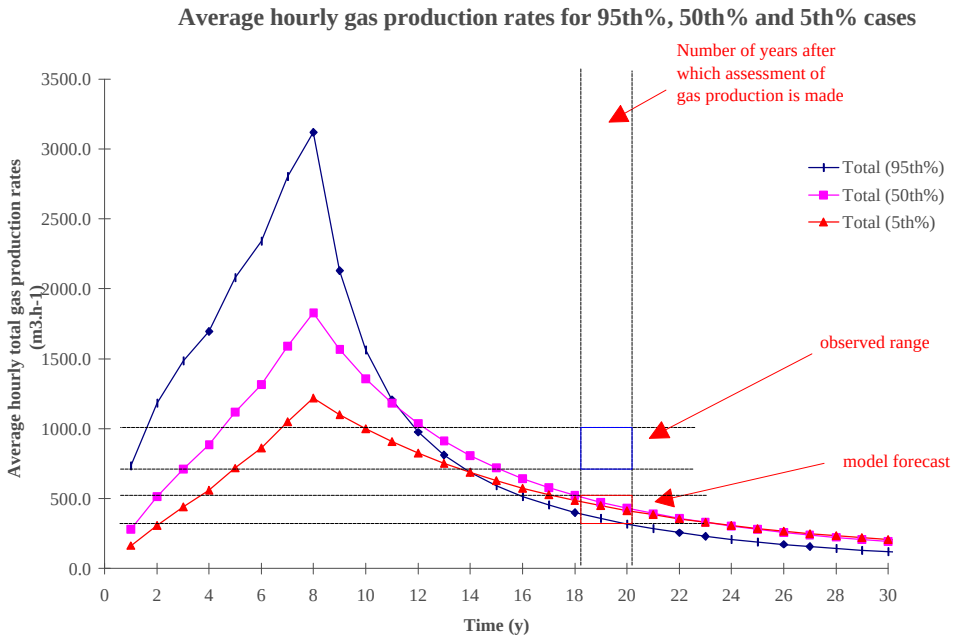

Figure 6.2. Pseudo-probabilistic output, comparing landfill gas production after 18 to 20 years (observed range) and the modelled landfill gas production rate (model forecast)).

If, however, the fully probabilistic Crystal Ball ™ mode is used (Figure 6.3), the estimated range of LFG production from the site and the modelled range overlap. This limited validation indicates that both the pseudo-probabilistic model and the fully probabilistic model produce results that are reasonably close to field data.

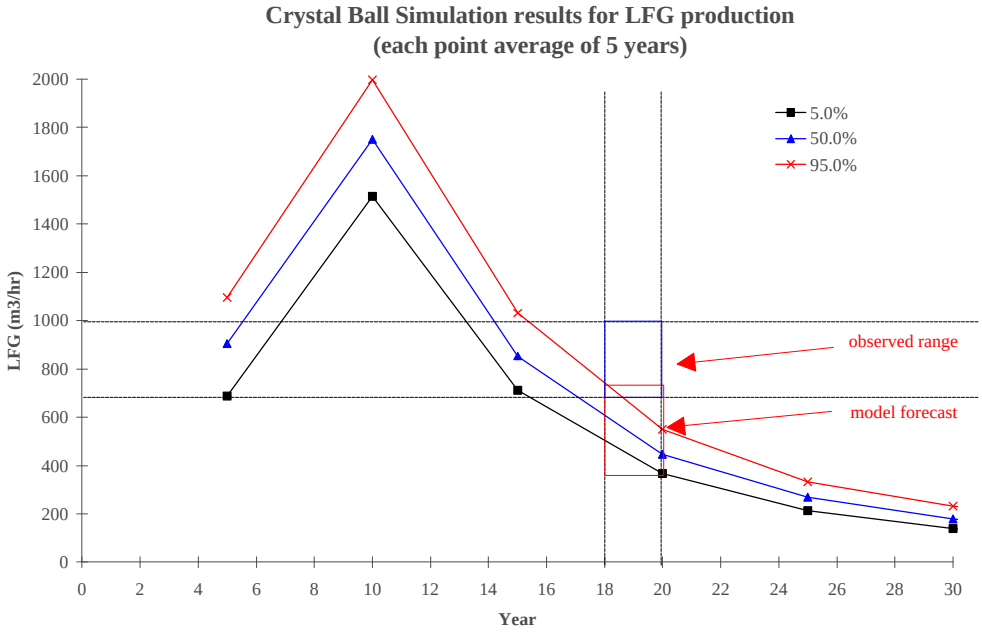

Figure 6.3. Fully probabilistic output, with landfill gas production after 18 to 20 years (observed range) and modelled landfill gas production rates (model forecast).

As would be expected, the fully probabilistic model appears to deal better with uncertainties in input data and assumptions to produce a range that matches better the field data.

Surface methane emissions

Surface methane emissions from the Buckinghamshire site have also been determined in the model for the selected time frame (18 to 20 years after filling commenced). The two scenarios considered below are:

- Scenario 1: 85% LFG collection efficiency and 70% biological oxidation of fugitive methane in the cap.
- Scenario 2: 95% LFG collection efficiency and 90% biological oxidation of fugitive methane in the cap.

The HELGA model calculates average net surface methane emissions after allowing for LFG collection and biological methane oxidation. The model output indicates the average surface emissions from this site would be between 10^{-2} mg.m^2.s^{-1} (Scenario 1) and 10^{-3} mg.m^2.s^{-1} (Scenario 2) (Figure 6.4). Although site measurements were not available for this landfill, field measurements of methane flux from a number of other, similar, sites indicate that for a landfill with an engineered cap and gas collection scheme the average net emissions are in the range of 10^{-4} to 1 mg.m^2.s^{-1} (Gregory et al., 1998; Milton et al., 1997) This range of measured emissions is consistent with other published studies (Bogner et al., 1997a).

Figure 6.4 compares the range of measured data with modelled data. The ranges overlap. This suggests that (1) the HELGA model is calculating results within the expected ranges, and (2) more work is required to characterise and understand the different results produced by different methane flux protocols.

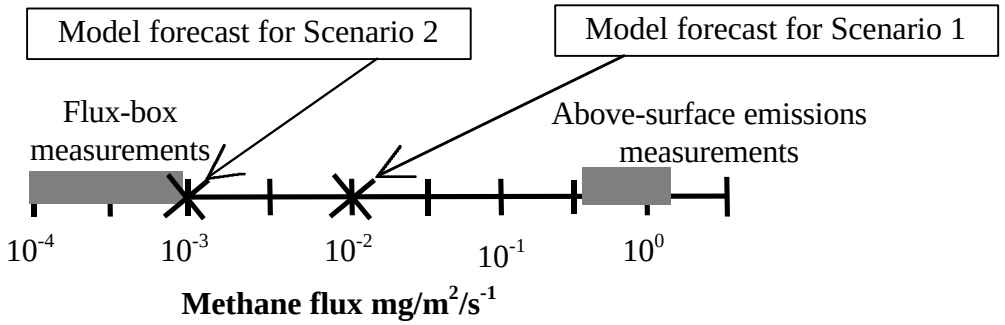

Figure 6.4. Surface emissions data modelled for site scenarios 1 and 2 (black crosses) superimposed on field results for similar sites (WS Atkins flux box measurements, and NPL above-surface emissions measurements).

6.4 Validation of surface emissions module for VOCs

6.4.1 Assumptions

Bogner et al. (1997b) monitored the surface emissions of a number of volatile organic compounds (VOCs) from Greene Valley landfill site (USA). The HELGA model was tested against measured emission rates of benzene, tetrachloroethene, trichloroethene and vinyl chloride. Table 6.7 shows the input parameters for this surface emissions scenario.

Table 6.7. Input data for the VOC surface emissions scenario

Parameters	Values
Site commenced filling:	1974 (22 years from commencement of waste deposition to assessment)
Total volume of waste:	32,262,000 (t)
Model input has five 2 year phases	
Phase 1	1,400,000 ($t.y^{-1}$)
Phase 2	1,400,000 ($t.y^{-1}$)
Phase 3	1,400,000 ($t.y^{-1}$)
Phase 4	1,400,000 ($t.y^{-1}$)
Phase 5	560,000 ($t.y^{-1}$)
Waste type	Mainly domestic (model type 2)
Waste saturation	Dry
LFG collection system operating	7000 ($m^3.h^{-1}$)
Landfill flare capacity	7000 ($m^3.h^{-1}$)
Landfill engine capacity	4700 ($m^3.h^{-1}$)
Surface cap	Clay approx. 1 m and soil approx 1 m

6.4.2 Validation results

For model forecasting, default concentrations of VOC in LFG were used, as provided in the HELGA model. These were compared with the measured range of surface emissions from Greene Valley landfill site, given in Table 6.8.

Table 6.8. Measured fluxes of specific VOC from surface of Greene Valley landfill (Bogner *et al.*, 1997b)

VOC	Maximum flux ($mg.m^{-2}.s^{-1}$)	Minimum flux ($mg.m^{-2}.s^{-1}$)	Highest negative flux ($mg.m^{-2}.s^{-1}$)
benzene	5.37×10^{-5}	0	-1.15×10^{-3}
tetrachloroethene	1.23×10^{-5}	3.99×10^{-7}	
trichloroethene	3.10×10^{-6}	4.50×10^{-10}	-4.92×10^{-5}
vinyl chloride	3.18×10^{-5}	9.61×10^{-6}	-8.68×10^{-3}

Table 6.9 presents the output ranges from the model of VOC surface emissions for a mean default value of VOC represented in the model. The shaded boxes in Figures 4.1-4.4 show this forecast range. The range represents the forecast VOC range for maximum and minimum values of LFG production.

Table 6.9. Modelled surface emissions for mean default VOC concentration in LFG and mean, maximum and minimum LFG production.

VOC	Surface emissions ($mg.m^{-2}.s^{-1}$)		
	Maximum LFG production	**Mean LFG production**	**Minimum LFG production**
benzene	$1.39x10^{-5}$	$7.08x10^{-6}$	$1.51x10^{-6}$
tetrachloroethene	$6.89x10^{-5}$	$3.51x10^{-5}$	$7.51x10^{-6}$
trichloroethene	$3.79x10^{-5}$	$1.93x10^{-5}$	$4.13x10^{-6}$
vinyl chloride	$3.49x10^{-5}$	$1.78x10^{-5}$	$3.8x10^{-6}$

Table 6.10 shows the output range from the model using the maximum and minimum default range of VOC concentrations, supplied in the model, as opposed to the mean concentration which was used to calculate Table 6.9. Maximum emissions are derived from maximum VOC concentrations and maximum LFG production. Minimum emissions are derived from minimum VOC concentrations and minimum LFG production. This range is represented by the thick dashed line bar on Figure 4.1 - 4.4. Field observations (Table 6.8) are represented by the dashed box in Figure 6.5 - 6.8.

Table 6.10. Model output for the maximum default VOC concentration in LFG and maximum LFG production; and minimum default VOC concentration in LFG and minimum LFG production.

VOC	Surface emissions ($mg.m^{-2}.s^{-1}$)	
	Maximum emission(1)	**Minimum emission(2)**
benzene	$9.05x10^{-5}$	$8.96x10^{-11}$
tetrachloroethene	$5.12x10^{-4}$	$2.91x10^{-10}$
trichloroethene	$2.9x10^{-4}$	$2.46x10^{-9}$
vinyl chloride	$2.53x10^{-4}$	$2.96x10^{-8}$

1. Calculated for the maximum LFG production rate and maximum VOC concentration in the default range.
2. Calculated for the minimum LFG production rate and minimum VOC concentration in the default range.

There is excellent agreement for all VOCs, except trichloroethene, between the mean modelled value and the range of field measurements observed. The trichloroethene data are within half an order of magnitude, and are within the maximum/minimum range of default emissions data provided in the HELGA model.

From this validation procedure , it is clear that the model outputs for surface emissions agree well with observations collected in the field.

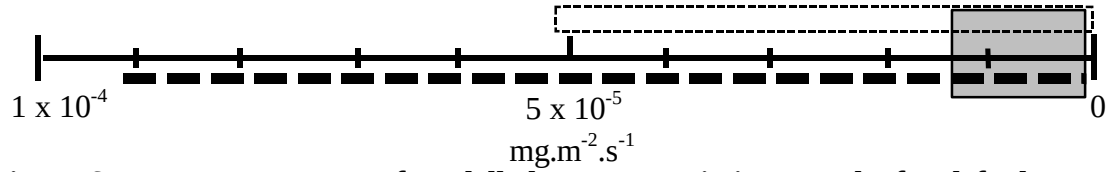

Figure 6.5. Benzene: Range of modelled average emissions results for default mean benzene concentrations (shaded box), maximum–minimum range produced by the model for full range of benzene concentrations (thick dashed line) and field emissions data range (dashed box).

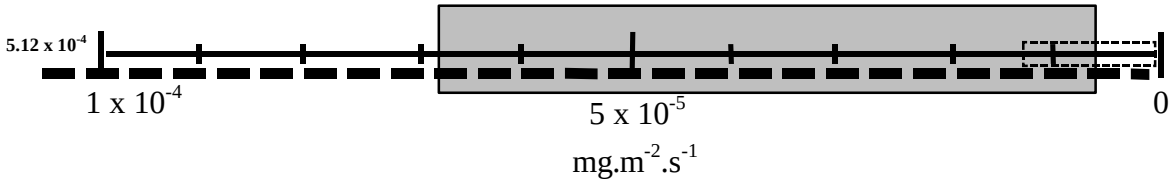

Figure 6.6. Tetrachloroethene: Range of modelled average emissions results for default mean tetrachloroethene concentrations (shaded box), maximum–minimum range produced by the model for full range of tetrachloroethene concentrations (thick dashed line) and field emissions data range (dashed box).

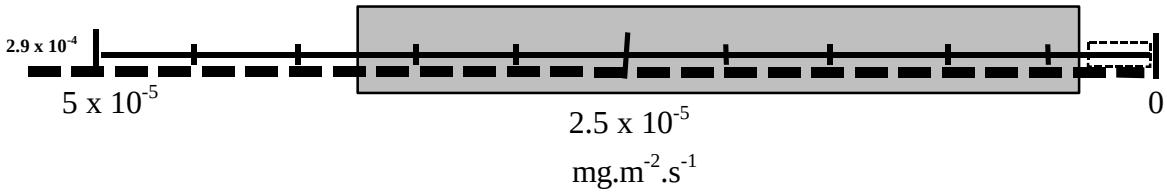

Figure 6.7. Trichloroethene: Range of modelled average emissions results for default mean trichloroethene concentrations (shaded box), maximum–minimum range produced by the model for full range of trichloroethene concentrations (thick dashed line) and field emissions data range (dashed box).

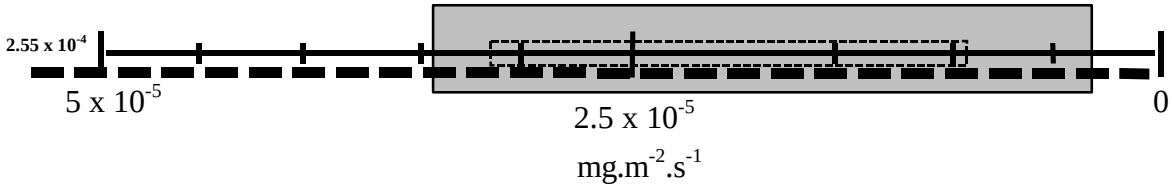

Figure 6.8. Vinyl chloride: Model average emissions results range for default mean VOC concentrations (shaded box), maximum–minimum range produced by the model for full range of VOC concentrations (thick dashed line) and field emissions data range (dashed box).

6.5 Validation of atmospheric dispersion module

6.5.1 Assumptions

Scott et al. (1997) monitored the concentration in air of various LFG trace components at Nant-y-Gwyddon landfill in response to complaints of odours allegedly arising from the site. The atmospheric dispersion module in the HELGA model was validated against actual ambient air quality measurements of hydrogen sulphide various distances from the landfill site. The hydrogen sulphide concentration in the raw LFG was an average 2000 ppm (~3000 $mg.m^{-3}$), with a maximum recorded concentration of 6000 ppm (~9100 $mg.m^{-3}$). The reason for the high hydrogen sulphide concentrations detected in the LFG is thought to be due to disposal of high sulfate containing wastes with domestic waste.

Table 6.11 shows the input parameters for the modelling of the Nant-y-Gwyddon atmospheric dispersion scenario.

Table 6.11. Input data for the atmospheric dispersion scenario

Parameter	Value
Site commenced filling:	1988 (9 years from commencement of waste deposition to assessment)
Total volume of waste:	850 000 (t)
Model input has five 2 year phases	
Phase 1	52 000 ($t.y^{-1}$)
Phase 2	52 000 ($t.y^{-1}$)
Phase 3	52 000 ($t.y^{-1}$)
Phase 4	178 000 ($t.y^{-1}$)
Phase 5	178 000 ($t.y^{-1}$)
Waste input type	Thought to be mainly domestic (except for calcium sulphate waste).
Saturation of waste	Average
Surface capping	None of any significance (at the time of monitoring)
Landfill gas (LFG) collection from area in 1997	None (at the time of monitoring)
Distance to receptor	500 to 1000 (m)
Windrose conditions	User defined, direction 1, value for direction 1 = 1 (i.e. wind blowing in that direction, which is correct for an instantaneous effect like odour)

6.5.2 Validation results

Scott *et al*. (1997) measured hydrogen sulphide at a concentration of 4.5×10^{-3} $mg.m^{-3}$ at the receptor (Blean Clydach), which is located between 500 to 1000 m from the site.

Figure 6.9 show the outputs from the model for hydrogen sulphide in the air at receptors ranging from 250 to 1250 m from the site boundary, for the maximum, mean and minimum LFG production rates forecast by the HELGA model. The output curves are derived from a range of hydrogen sulphide concentrations in LFG (500 and 9500 $mg.m^{-3}$) observed at the site and input in the emissions module of the HELGA model, overriding the default data already present in the model.

Superimposed on Figure 6.9 are the odour threshold limit (4.7×10^{-4} $mg.m^{-3}$), the concentration of H_2S detected in the air at the receptor (4.5×10^{-3} $mg.m^{-3}$) and the range of possible distances to the receptor (500 to 1000 m).

The range of model forecast outputs for hydrogen sulphide concentrations in the air between 500 and 1000 m from the site boundary is $9 \times 10^{-4} – 8.3 \times 10^{-3}$ $mg.m^{-3}$. These are above the odour threshold and bracket the concentration measured in the field (4.5×10^{-3} $mg.m^{-3}$).

The model predicts that hydrogen sulphide migrating offsite would be observed at concentrations above the odour threshold at the receptor when site specific source term data are used in the HELGA model. For this scenario, the model produces results that are in excellent agreement with field data.

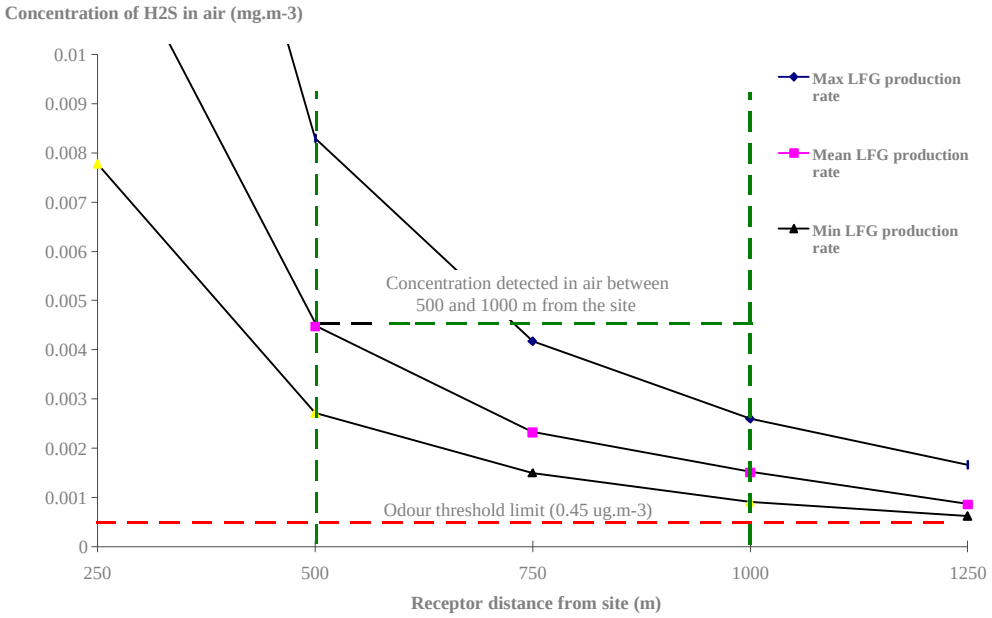

Figure 6.9. Modelled concentrations of H_2S in the air at receptors 250 to 1250 m from the site. The three lines represent different source terms for maximum, mean and minimum production rates of hydrogen sulphide in LFG, derived from the average site-specific hydrogen sulphide concentration in LFG emanating from the site.

6.6 Validation of Lateral Migration

6.6.1 Assumptions

The lateral migration module has been validated against data from Foxhall landfill site, which has been well characterised and monitored for VOCs in a lateral emission plume from part of the site (Ward et al., 1996). Table 6.12 shows the module input parameters for this scenario.

Table 6.12. Input data for the lateral migration scenario.

Parameter	Value
Ground porosity	40 % (assume the geology is sandy gravel, taken from published data)
Assume at field capacity	10 % (assume a well drained unsaturated material)
Ground saturation	25 %
VOC concentrations in LFG	model defaults have been used

Table 6.13 shows the measured concentration of three VOCs detected in the ground at 5m depth, 40m away from the site.

Table 6.13. VOC concentrations at 5m depth, 40 m from the site boundary.

VOC	Maximum concentration in LFG at the site boundary (ppm)	Measured concentrations at 40 m offsite (ppm)
Vinyl chloride	4.25	15.4
Dichlorodifluromethane	0	13.7
Chlorodifluromethane	11.54	3

6.6.2 Model outputs

Figures 6.10 - 6.12 show the range of model forecasts for concentrations of VOCs at 40m from the site boundary (shaded box), with the detected concentration superimposed (black cross) for the three VOCs considered: vinyl chloride, dichlorodifluromethane and chlorodifluoro-methane. The range of concentrations calculated in the model bracket the concentrations detected in the field investigation.

The lateral dispersion module operates outside the probabilistic framework, but a range of VOC concentrations has been used to determine the model forecast range. The VOC concentrations at 40 m are derived from the range of VOC concentrations in LFG provided as model defaults before the plume migrates from the site. No biochemical or chemical reactions are simulated during migration, which is simulated as a diffusion-only system. The results

confirm that the ranges of concentration of these VOCs selected for the model are appropriate for a diffusion-driven system. Ward et al (1996) have analysed the data closely, and have suggested that a combined diffusion-advection model best fits the data. Advective flow has not been built into the HELGA model in this version, but nevertheless the results are encouraging.

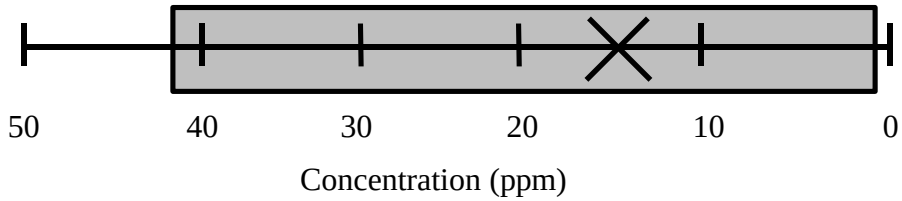

Figure 6.10. Forecast model output range for vinyl chloride in the ground 40m from the site (shaded box), with detected concentration (X) 40m from the site (Ward et al., 1996).

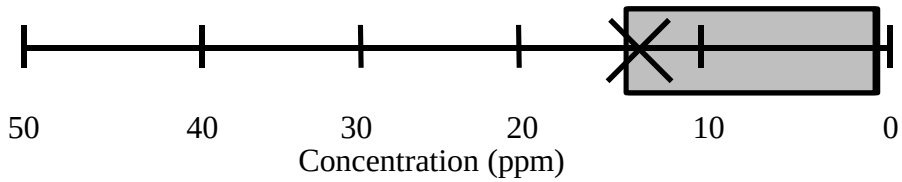

Figure 6.11. Forecast model output range for dichlorodifluromethane in the ground 40m from the site (shaded box), with detected concentration (X) 40m from the site (Ward et al., 1996).

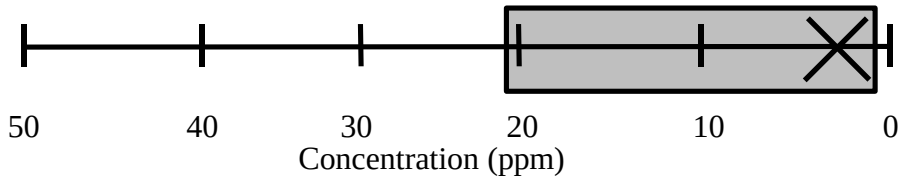

Figure 6.12. Forecast model output range for chlorodifluromethane in the ground 40m from the site (shaded box), with detected concentration (X) 40m from the site (Ward et al., 1996).

6.7 Conclusions from validation tests

6.7.1 Comparison with observations

The findings of the validation tests performed on the HELGA model are encouraging. Not only do the key modules produce forecasts which are generally in accordance with field observations, but they do so when driven by a relatively small data requirement. This small data requirement is important.

The HELGA model was conceived for use in the planning of landfill gas management for new-build landfills, but could be equally effective when applied to existing sites for landfill gas health and environmental risk assessments. In both instances, the availability of reliable data with which to drive the model has a direct effect on the forecasting capability of the decision tool. For many existing landfill sites, and certainly for new build landfills, much data will be best estimates, or model defaults. It is encouraging to observe that when data are scarce or non-existent, the forecast range of results from the HELGA model, using model default data, overlap with actual site measurements.

6.7.2 Uncertainties and deficiencies in the model

As the source-term module determines the amount of landfill gas produced, and the rate at which this amount is generated, the user should acquire as much site-specific waste and landfill design data as is available.

Model default values for VOCs are acceptable for emissions, but the database for trace landfill gas components and VOCs would benefit from more data to determine the probability density functions for these species. This will be essential for when the model is coded as a free-standing probabilistic decision tool.

Waste composition data for commercial and industrial waste streams are still poorly characterised today, so the ability to forecast emissions from landfills which accept these wastes is limited by the lack of data.

The steady state lateral migration model uses only diffusion driven flow. Advective flow, to simulate flow in fractures, could be added to enhance the model's forecasting abilities.

The migration event module is not as sophisticated as other modules in the model, and does not sit comfortably within a probabilistic decision tool. We would suggest that this module is omitted from future developments of the code.

7. LFG EMISSIONS MANAGEMENT OPTIONS

7.1 Introduction

The primary purpose of the HELGA decision tool is to aid the implementation of appropriate landfill gas management methods at the planning and subsequent stages of operation of a modern-day landfill. In order to demonstrate the flexibility of the HELGA model to do this, four scenarios have been simulated which demonstrate the effect of different cap designs on a landfill site, and the effect of different landfill gas management options employed on the site.

All the scenarios considered apply to a notional site in eastern England accepting 5Mt household waste over a ten-year period. The scenarios considered are as follows:

- **Scenario 1**. A minimal soil cap of 0.3m thickness, and no other gas controls.
- **Scenario 2**. A 1m clay cap with 0.8m soil cover, and no other gas controls.
- **Scenario 3**. As Scenario 2 with the addition of gas collection and flaring.
- **Scenario 4**. As Scenario 2 with the addition of gas collection, flaring and gas utilisation.

For each scenario, we have considered the effect on emissions 12 years after the start of site operations, i.e. 2 years after completion of filling, when gas generation and control will be an important environmental concern. HELGA has the ability to produce a vast array of useful information for each year after commencement of filling (up to 150 years after start of landfilling), for landfill gas and each VOC on the database. The choice of 2 years after completion of filling allows for a like-for-like comparison between the scenarios. We have chosen to compare the following indicative parameters for each scenario.

- **Gas generation**.
    - Carbon dioxide and methane generation rate.
    - Landfill gas migration through the cap and liner.
    - Methane oxidation in the cap.

- **VOC emissions through the cap**.
    - Comparison of emission rates of hydrogen sulphide, methanethiol, benzene, vinyl chloride, dioxins, hydrogen chloride and NOx.

- **Site Worker Exposure**.
    - Comparison of air concentrations on-site with LTELs for hydrogen sulphide, methanethiol, benzene, vinyl chloride, dioxins, hydrogen chloride and NOx.

- **Offsite Inhalation Exposure**.
    - The scenarios consider a suspended floor single storey house located 200m WSW from the landfill site.
    - Indoor and outdoor concentrations of VOCs hydrogen sulphide, methanethiol, benzene, vinyl chloride, dioxins, hydrogen chloride and NOx are evaluated.
    - Average annual exposure to the maximally exposed individuals are determined.

- Comparison is made to the inhalation exposure limit (if any).

Table 7.1 below gives all the base case simulation data that remain constant throughout the four model scenarios. Table 7.2 sets out the variables for the four scenarios compared.

Table 7.1 Simulation data common to all scenarios

Parameter	Value	Units of measurement
Source Term		
Waste composition	100% domestic	%
Fill rate	500,000	tonnes per year
Fill period	10	years
Site capacity/void space	5,000,000	m^3
Landfill gas composition	50% methane	%
Adsorbtive capacity of waste	10	%
Effective waste porosity	10	%
Hydraulic conductivity of waste	1×10^{-6}	$m\ s^{-1}$
Waste conductivity to gas	9.8×10^{1}	$m\ s^{-1}$
Liner and ground conditions		
Surface area	25	Ha
Site dimensions	500 x 500 x 20	m
Basal clay liner thickness	1	m
Gas conductivity of basal liner	9.8×10^{-5}	$m\ s^{-1}$
Soil porosity (for lateral migration)	0.1	unitless (i.e. 10%)
Ground saturation	10	%
Leachate recirculation	none	
Receptor details		
Distance to receptor	250	m
House perimeter	35	m
Ground floor area	75	m^2
Area of windows and doors	20	m^2
Height of living space	2.5	m
Height of suspended floor area/cellar	0.5	m
Area of walls in living space	320	m^2
Area of walls in suspended floor area/cellar	186	m^2
Receptor target height above ground level	2	m
Pollutant/VOC release height	0	m
Pollutant/VOC characteristics	non-reactive	
Wind rose location	east coast	
Vector of property from landfill site	WSW	
Year of interest	12	years after site commenced filling

Note: Many of the parameters listed here which are not site specific can be used as defaults in the absence of site-specific data.

Table 7.2 Key variables in the four scenarios

Parameter	Scenario 1: Sandy soil cap, no gas collection	Scenario 2: Clay cap, no gas collection	Scenario 3: Clay cap with gas flaring	Scenario 4: Clay cap with gas utilisation	Units of measurement
Cap details					
Soil Thickness	0.3	0.8	0.8	0.8	m
Clay thickness	0.0	1.0	1.0	1.0	m
Thickness of layer with lowest gas conductivity	0.3	1.0	1.0	1.0	m
Gas conductivity of this layer	1×10^{2}	9.8×10^{-5}	9.8×10^{-5}	9.8×10^{-5}	$m\ s^{-1}$
Infiltration	100	50	50	50	$mm\ y^{-1}$
Leachate head	6	1	1	1	m
Summary of site water balance conditions	average	dry	dry	dry	Calculated from data on infiltration and leachate head
Gas collection system details					
Flare details					
Utilisation scheme details					

It should be noted that the database of VOCs and trace gases used to derive the ranges of emissions reported below is not complete, although it does comprise an accurate record of the UK data available at the time of construction of the HELGA model. In order to provide even more confidence in the HELGA forecasts, new data should be added to the database, as it becomes available.

7.2 Results of gas generation simulations

Gas generation, migration and methane oxidation rates for the four scenarios are shown in Table 7.3 below.

7.2.1 Gas generation

Results for the mean (50^{th} percentile) and one standard deviation either side of the mean (5^{th} percentile and 95^{th} percentile) are given for each of the four scenarios. These data show a wide range of potential gas generation rates possible for the quantities of waste emplaced. This is because the relatively poorly understood mechanisms of gas generation, and other site-specific factors, have to be represented in a model of this nature by probability density functions, or their equivalents.

Table 7.3 shows the total quantities of landfill gas produced, and the rates of landfill gas production per year. The landfill gas generation profile is identical for Scenarios 2-4. This is because these three scenarios had the same water infiltration and waste degradation conditions, and were calculated by the model to be analogous to a 'dry' site (the model allows dry, average and wet sites to be simulated, and will also calculate this from infiltration and leachate head data). The landfill gas generation profile for Scenario 1 shows higher gas generation rates in the early years of the site's gas profile. Infiltration and water content of the waste is a key parameter in regulating the rate of decomposition of landfilled waste, and because infiltration through the soil cap will be higher than that for a clay cap, the consequent rate of gas generation was raised to that of 'average' moisture content. Figure 7.1 shows the gas production curves for Scenario 1, and Figure 7.2 for the other three scenarios.

7.2.2 Potential for gas migration through cap and liner

The potential for gas migration through the cap or liner is proportional to the thickness and permeability of each liner. Table 7.3 shows that Scenario 1, with the soil cap, and no other forms of gas control, performs worst of all, with all gas generated migrating through the cap. Scenario 2, with a 1m clay cap, also loses most of the gas generated through the cover materials. Only Scenarios 3 and 4, where gas collection and flaring/utilisation is simulated, reduces surface emissions significantly, compared with the base case.

In these examples, Scenario 4 shows most reduction in emissions. This need not be the case, however. The absolute value of emissions reduction in Scenarios 3 and 4 for any particular year (note that this is year 12) will depend upon the sizing of flare and/or utilisation scheme employed on the site. This sizing must be done by examining the base case gas generation

profile over a number of years, and selecting a flare and/or utilisation scheme combination which fits best the gas generation profile.

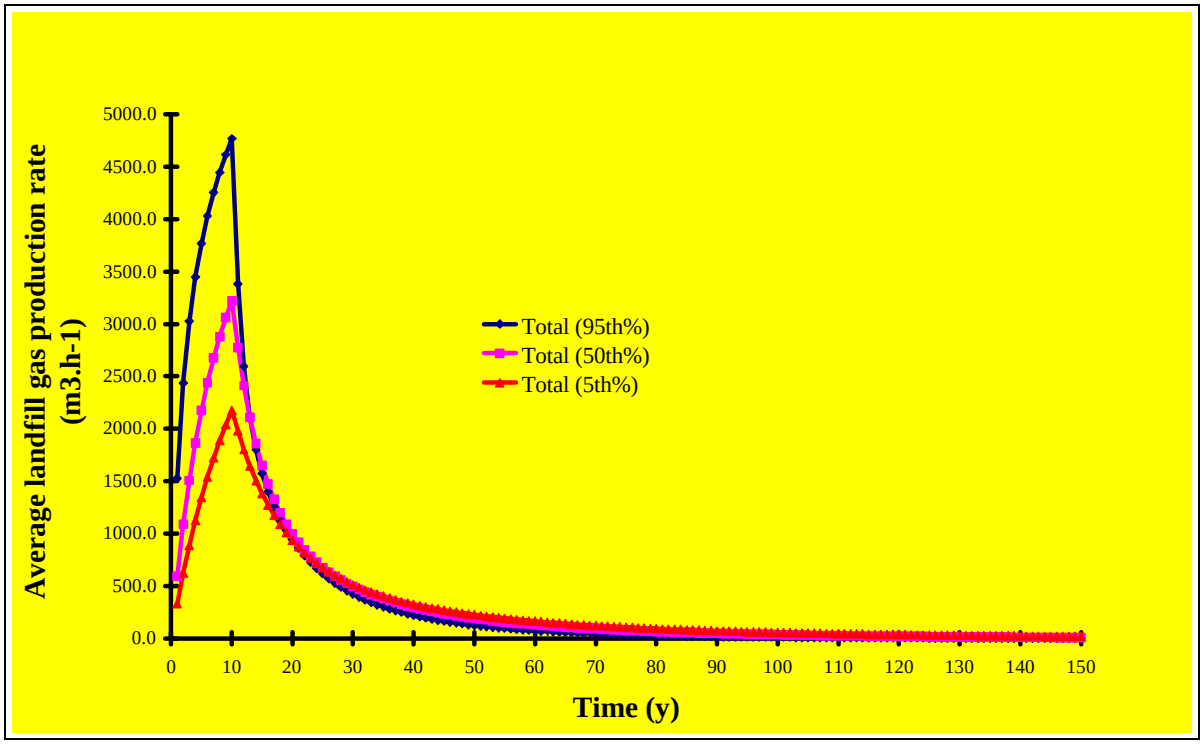

Figure 7.1. Landfill gas generation profiles for Scenario 1.

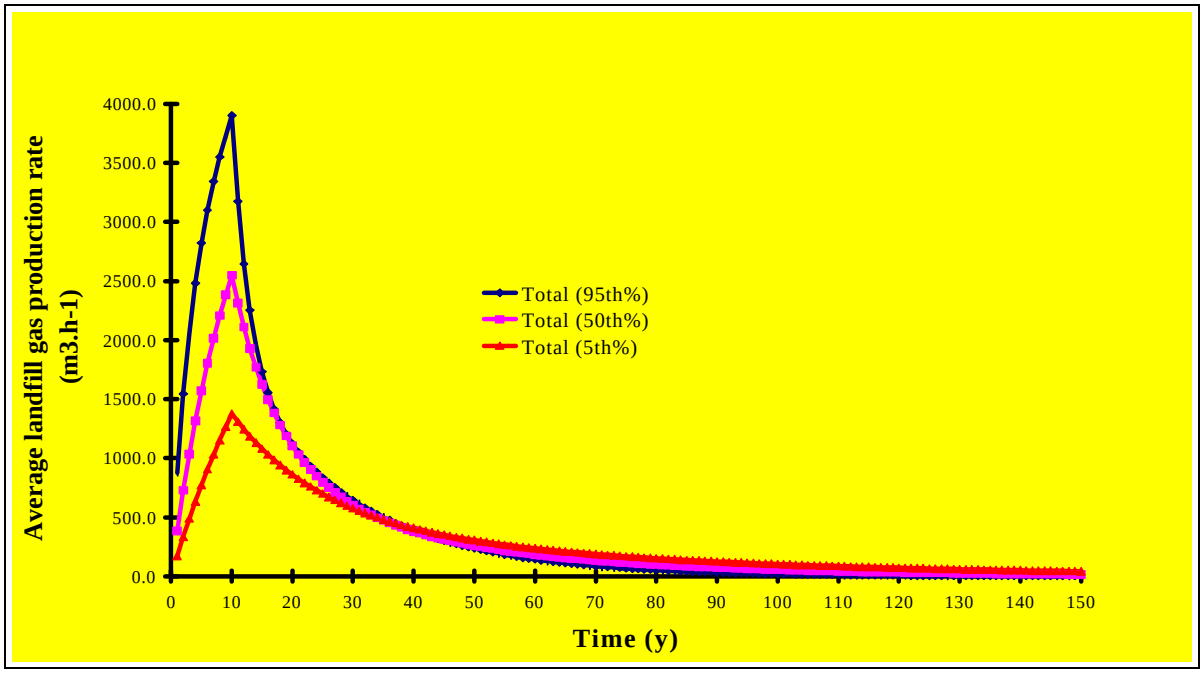

Figure 7.2. Landfill gas generation profiles for Scenarios 2-4

Table 7.3 Gas generation, migration and methane oxidation rates

Parameter	Scenario 1: Sandy soil cap, no gas collection			Scenario 2: Clay cap, no gas collection			Scenario 3: Clay cap with gas flaring			Scenario 4: Clay cap with gas utilisation		
	5th %ile	50th %ile	95th %ile	5th %ile	50th %ile	95th %ile	5th %ile	50th %ile	95th %ile	5th %ile	50th %ile	95th %ile
LFG generation												
LFG generation in year 12 ($m^3 h^{-1}$)	1800	2410	2596	1244	2110	2644	1244	2110	2644	1244	2110	2644
methane content (%)	50	50	50	50	50	50	50	50	50	50	50	50
LFG migration potential												
Through cap ($m^3 h^{-1}$)	1800	2410	2596	1236	2095	2625	618	1048	1313	740	605	640
Through liner ($m^3 h^{-1}$)	0	0	0	9	15	19	5	8	9	5	4	5
Methane oxidation in the cap												
Methane flux at base of cap ($m^3 h^{-1}$)	900	1205	1298	618	1047	1312	309	524	656	370	303	320
Methane flux at surface ($m^3 h^{-1}$)	720	964	1038	370	838	1050	185	314	525	222	182	192
Methane oxidation (%)	20	20	20	40	20	20	40	40	20	40	40	40

7.2.3 Methane oxidation in the cap

The degree of methane oxidation in the cap is a function of the rate of transmission of landfill gas through the cap thickness, which is driven by the rate of gas generation (after collection of a fraction of the gas for flaring and/or utilisation. If the rate of gas generation is sufficiently high that the movement of gas through the cap takes less than one second (an arbitrary value, but one which appears to work well and mimic observed behaviour), then the degree of methane oxidation observed is 20%. If gas movement takes longer than one second, then the degree of methane oxidation observed is 40%. These values of 20% and 40% are again arbitrary, as there are no data to confirm these values, but again, the pattern of behaviour and the results produced agree well with observed, but unquantified, gas behaviour.

The scenarios in Table 7.3 show a steady increase in the likelihood of high levels of methane oxidation in the capping layers as the quantity of landfill gas which is collected and flared or otherwise utilised increases. This means that the more gas diverted to flare or utilisation, away from the cap, the lower the 'loading' on the cap, and the higher the opportunity for methane oxidising bacteria to cope with the flux of uncontrolled gas.

These figures will also impact on global environmental burdens (global warming potential and ozone depleting potential. See section 7.3 below.

7.3 Global environmental burdens

The HELGA model takes the emissions data and calculates the global warming potential (GWP) (in tonne equivalents of carbon dioxide), and the ozone depletion potential (ODP) (in tonne equivalents of fluoro-trichloromethane (CCl_3F)). The results of the simulations (for the 50^{th} percentile gas generation rates) are shown in Table 7.4.

These results clearly show that for any given site that generates landfill gas, the effects of capping, flaring and gas utilisation progressively reduce the global environmental burden due to that particular site. Obviously, these figures only apply to year 12. Over the site's entire life, a reduction in GWP and ODP of over 70%, compared to the base case, will not be attained, as flaring and gas utilisation are only appropriate over the most productive phases of gas generation. However, since flaring and utilisation can manage the bulk of the gas, the benefits to the environment of these landfill gas management systems are obvious.

Table 7.4. Global environmental burdens

	Scenario 1: Sandy soil cap, no gas collection	Scenario 2: Clay cap, no gas collection	Scenario 3: Clay cap with gas flaring	Scenario 4: Clay cap with gas utilisation
GWP (tonnes equivalent CO_2)	130,000	113,000	47,000	30,500
Percentage reduction from base case	0	13	64	77
ODP (tonnes equivalent CCl_3F)	0.35	0.30	0.15	0.09
Percentage reduction from base case	0	14	57	74

Note: The base case is Scenario 1

7.4 VOC emissions

VOC and trace gas emissions through the cap, flare and utilisation scheme have been calculated for the following substances:

- benzene
- hydrogen sulphide
- methanethiol
- vinyl chloride
- dioxins
- hydrogen chloride
- nitrogen oxides

The HELGA model generates mean, minimum and maximum forecast values for each of the 5^{th}, 50^{th} and 95^{th} percentile gas generation rates. The data given in Table 7.5 below were derived using the 50^{th} percentile gas generation rate. Not all the compounds listed above are released via each emission pathway, and it should be noted that the quantities of VOCs released via each pathway are directly proportional to the volumes of landfill gas emitted via each pathway. All dioxin forecasts should be treated with great care, as only one data value for surface emissions, flare and engine emissions exist in the HELGA database.

The data in Table 7.5 only show the total site surface emissions, and emissions from the flare or utilisation scheme. They should not be interpreted as exposures. Site worker exposure and offsite inhalation exposures are discussed in Sections 7.5 and 7.6 respectively.

Table 7.5. VOC emissions from the surface, flare and engine for the 50th percentile gas generation rate

Emissions ($mg.s^{-1}$)	Scenario 1: Sandy soil cap, no gas collection			Scenario 2: Clay cap, no gas collection			Scenario 3: Clay cap with gas flaring			Scenario 4: Clay cap with gas utilisation		
	min	**mean**	**max**	**min**	**mean**	**max**	**min**	**mean**	**max**	**min**	**mean**	**max**
Emissions through the cap												
benzene	3×10^{-4}	4	30	2×10^{-4}	4	26	1×10^{-4}	2	13	7×10^{-5}	1	7
hydrogen sulphide	3×10^{-3}	8	37	3×10^{-3}	7	32	1×10^{-3}	4	16	8×10^{-4}	2	9
methane thiol	7×10^{-2}	60	290	6×10^{-2}	53	250	3×10^{-2}	26	125	2×10^{-2}	15	72
vinyl chloride	9×10^{-2}	11	82	8×10^{-2}	10	72	4×10^{-2}	5	36	2×10^{-2}	3	22
dioxin	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}	1×10^{-6}	1×10^{-6}	1×10^{-6}	6×10^{-7}	6×10^{-7}	6×10^{-7}
Emissions from the flare												
benzene							6×10^{-1}	26	51			
vinyl chloride							0	4×10^{-1}	9×10^{-1}			
dioxin							8×10^{-7}	8×10^{-7}	8×10^{-7}			
hydrogen chloride							7	29	72			
nitrogen oxides							36	160	370			
Emissions from the engine												
dioxin										2	2	2
hydrogen chloride										37	66	95
nitrogen oxides										150	2000	3300
Total emissions												
benzene	3×10^{-4}	4	30	2×10^{-4}	4	26	6×10^{-1}	26	51	7×10^{-5}	1	7
hydrogen sulphide	3×10^{-3}	8	37	3×10^{-3}	7	32	1×10^{-3}	4	16	8×10^{-4}	2	9
methane thiol	7×10^{-2}	60	290	6×10^{-2}	53	250	3×10^{-2}	26	125	2×10^{-2}	15	72
vinyl chloride	9×10^{-2}	11	82	8×10^{-2}	10	72	4×10^{-2}	5	36	2×10^{-2}	3	22
dioxin	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}	2×10^{-6}	2	2	2
hydrogen chloride							7	29	72	37	66	95
nitrogen oxides							36	160	370	150	2000	3300

What these data do show is the relationship between emissions due to natural landfill gas emissions, the effect of flaring or gas utilisation on these natural emissions, and the additional combustion products resulting from flaring or gas utilisation.

The emissions data show the following.

- Increasing the level of gas collection and flaring or utilisation reduces the uncontrolled surface emissions of VOCs proportionately.
- The available data for VOC emissions show wide uncertainty ranges (or wide variations in landfill gas trace gas compositions) for some components. The forecast emissions of benzene, for example, could vary over six orders of magnitude. Additional VOC emissions measurements should be made to drive this model if reliable forecasts are to be made.
- Some results will be unreliable because of the lack of sufficient monitoring data (e.g. dioxins).
- Flaring or combustion destroys compounds to different degrees. Hydrogen sulphide and methanethiol, for example, have not been recorded in significant concentrations from flare or gas engine emissions. The dioxin content of flared landfill gas is comparable to the unflared gas.
- Some flare or gas engine combustion products (hydrogen chloride, nitrogen oxides) occur in much higher concentrations that the landfill trace gases or VOCs represented in the model. This is because they are derived from combustion of many other VOCs not represented in the model, and more than one atom of the combustion products are produced from each VOC molecule, i.e. there are more of them per cubic metre than the VOCs they are derived from.

7.5 Results of site worker exposure simulations

Comparisons of the concentrations in air on site of the selected compounds with long-term exposure limits (LTELs) are made in Table 7.6. All exposure concentrations are very low, and where LTELs exist, are below the LTEL by between 4 and 5 orders of magnitude.

It is clear from the simulations that the use of flaring and/or gas utilisation diverts VOCs from direct emission through the cap, and these combustion processes destroy a fraction of the VOCs sent to the flare or gas engine, thereby reducing the total emissions of landfill-sourced VOCs released. However, combustion products from the gas engines are in significantly higher concentrations than the naturally emitted landfill VOCs.

Table 7.6. Site worker exposure to VOC emissions from the surface, flare and engine for the 50th percentile gas generation rate

Airborne concentrations ($mg.m^{-3}$)	Scenario 1: Sandy soil cap, no gas collection	Scenario 2: Clay cap, no gas collection	Scenario 3: Clay cap with gas flaring	Scenario 4: Clay cap with gas utilisation	Long term exposure limit (LTEL)
benzene	6×10^{-4}	5×10^{-4}	3×10^{-4}	2×10^{-4}	16
hydrogen sulphide	1×10^{-3}	1×10^{-3}	5×10^{-4}	3×10^{-4}	14
methane thiol	8×10^{-3}	7×10^{-3}	4×10^{-3}	2×10^{-3}	7
vinyl chloride	2×10^{-3}	1×10^{-3}	7×10^{-4}	4×10^{-4}	1
dioxin	3×10^{-10}	3×10^{-10}	1×10^{-10}	4×10^{-4}	
hydrogen chloride				2×10^{-2}	
nitrogen oxides				5×10^{-1}	

7.6 Results of offsite inhalation exposure simulations

Offsite inhalation exposure here considers the average annual exposure, from indoor and outdoor exposure, for the most highly exposed individual living in a property with a suspended floor 250m from the landfill. The wind rose for eastern England has been used, and the property is downwind of the prevailing wind direction. The results of these simulations are given in Table 7.7.

Table 7.7. Offsite inhalation exposure scenarios

Scenario/VOC	Concentration outdoors ($mg.m^3$)	Concentration indoors ($mg.m^3$)	Average annual exposure ($mg.y^{-1}$)	Is inhalation exposure limit exceeded?
Scenario 1: sandy soil cap, no gas collection				
Benzene	2 x 10-6	0	4 x 10-3	
Hydrogen sulphide	4 x 10-6	7 x 10-7	1 x 10-2	no
Methanethiol	3 x 10-5	6 x 10-6	9 x 10-2	
Vinyl chloride	5 x 10-6	0	9 x 10-3	
Dioxins	1 x 10-12	0	2 x 10-9	
Scenario 2: clay cap, no gas collection				
Benzene	2 x 10-6	0	3 x 10-3	
Hydrogen sulphide	3 x 10-6	7 x 10-7	1 x 10-2	no
Methanethiol	2 x 10-5	6 x 10-6	8 x 10-2	
Vinyl chloride	4 x 10-6	0	8 x 10-3	
Dioxins	9 x 10-13	0	2 x 10-9	
Scenario 3: Clay cap with gas flaring				
Benzene	9 x 10-7	0	2 x 10-3	
Hydrogen sulphide	2 x 10-6	7 x 10-7	8 x 10-3	no
Methanethiol	1 x 10-5	6 x 10-6	6 x 10-2	
Vinyl chloride	2 x 10-6	0	4 x 10-3	
Dioxins	4 x 10-13	0	8 x 10-10	
Scenario 4: clay cap with gas utilisation				
Benzene	5 x 10-7	0	9 x 10-4	
Hydrogen sulphide	9 x 10-7	7 x 10-7	7 x 10-3	no
Methanethiol	7 x 10-6	6 x 10-6	5 x 10-2	
Vinyl chloride	1 x 10-6	0	2 x 10-3	
Dioxins	2 x 10-6	0	4 x 10-3	
Hydrogen chloride	9 x 10-5	0	2 x 10-1	no
Nitrogen oxides	3 x 10-3	0	5	

These results mimic the pattern shown for workers above, but because of distance from the landfill, the outdoor concentrations are typically two to three orders of magnitude lower than those over the site. It is unlikely that any exposures will exceed the inhalation exposure limit.

Again, it is clear from the simulations that the use of flaring and/or gas utilisation diverts VOCs from direct emission through the cap, and both flaring and gas utilisation plant destroy a fraction of the VOCs, thereby reducing the human exposure to landfill-sourced VOCs. However, combustion products from the gas engines are in significantly higher concentrations than the naturally emitted landfill VOCs. The absence of inhalation exposure limits for many substances makes further interpretation of the values difficult, but it is obvious that emissions are of a low order.

7.7 Conclusions

The aim of constructing the four scenarios set out above was to demonstrate the effect of changing cap type and employing gas collection, flaring and utilisation as landfill gas management techniques. To date there has been little in the way of quantitative measurements on the need or effectiveness of landfill gas management techniques. Whilst the data in these scenarios apply to a notional landfill site, the main findings will apply to all landfills which accept biodegradable waste.

These findings are summarised as follows.

- The gas generation rate for Scenario 1, the sandy soil capped site, was higher than the rate for any of the clay capped site scenarios (Scenarios 2-4). This was due to a combination of a higher rate of rainfall infiltration into the site, and a higher standing head of leachate within the site. This increased the net water content of the waste, and therefore accelerating decomposition of the waste.

- The stepwise effect of improving cap quality on the site, from a soil cap (Scenario 1) to a clay cap (Scenario 2), introducing gas collection and flaring (Scenario 3) or gas utilisation (Scenario 4) has the following benefits:
    - surface emissions are reduced; and
    - as more gas is collected and flared or utilised, the fraction of landfill gas remaining which can undergo methane oxidation increases, because the net methane flux is reduced.

- The global warming potential (GWP) and ozone depleting potential (ODP) results clearly show that for any given site which generates landfill gas, the effects of capping, flaring and gas utilisation progressively reduce the global environmental burden due to that particular site. In year 12 of the site's life, a reduction in GWP and ODP of over 70% could be attained. This percentage will not be sustained over the site's entire life, but since the bulk of the landfill gas generated within the site can be managed by flaring and utilisation, the benefits to the environment of these landfill gas management systems are obvious.

- VOC emissions from the surface of the site are proportional to the rate of bulk landfill gas emissions, and so the quantities of VOCs emitted from the landfill are reduced by the addition of a clay cap (Scenario 2), introduction of gas collection and flaring (Scenario 3) or gas utilisation (Scenario 4).

- Site worker exposures to landfill gas VOC emissions are reduced by flaring or gas utilisation (Scenarios 3 and 4). The emissions of all trace gas components are well below permitted levels of exposure (where exposure limits exist) in all scenarios, although emissions from landfill gas engines are, as would be expected, in higher concentrations than the uncollected landfill gas emitted from the site.

- Maximally exposed individual exposures to landfill gas VOC emissions are also reduced by flaring or gas utilisation (Scenarios 3 and 4). Although combustion products are produced from the landfill gas engine, the emissions of all trace gas components are well below permitted levels of exposure (where exposure limits exist) in all scenarios.

On balance, taking into account uncertainties and omissions of data from the landfill gas and VOC database, the scenarios modelled offer the following interpretation for gas management at this notional landfill site, which can be applied to the majority of modern landfills.

The provision of an engineered cap on a landfill has been shown to reduce annual landfill gas emissions, but this is due to changes in waste degradation rates rather than positively destroying trace gases or VOCs.

However, landfill gas flaring and/or gas utilisation provide positive steps to reducing trace gas and VOC emissions, by collecting a significant fraction of the landfill gas generated by an individual landfill site, and destroying a high percentage of the bulk and trace landfill gas constituents in the combustion process. These combustion processes are not without their own environmental burdens, and low temperature combustion processes, particularly those from landfill gas engines, generate higher concentrations of emission by-products such as hydrogen chloride and nitrogen oxides.

Landfill gas flaring and/or gas utilisation provides significant global environmental protection, as these gas management options reduce the quantities of landfill gas emitted to atmosphere, and consequently reduce the landfill site's individual GWP and ODP.

The interpretation of the environmental impact of landfill gas flaring and/or gas utilisation in terms of local human health effects is difficult to quantify, as destruction of some trace gases and VOCs results in formation of different combustion products. Exposure limit standards or health risk data are not available for many of the components in landfill gas, so it is difficult to determine whether these emission products are a significant risk. All the data show that where exposure limit data are available, the emissions for all scenarios considered do not exceed exposure limits.

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