DEVELOPMENT OF A LANDFILL GAS RISK ASSESSMENT MODEL: GASSIM

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ABSTRACT
The emissions of bulk and trace gases from landfills created either directly from waste decomposition or from the combustion of landfill gas (LFG) during flaring and/or gas utilisation, have the potential to:

- impact the global atmosphere by ozone depletion and global warming;
- impact the local environment by odour and vegetation stress; and
- expose humans to trace concentrations of LFG components and combustion products.

The risk of these processes occurring is normally assessed using a mixture of experience, calculation and computer models. GasSim assesses the risk of these processes and the magnitude of the impacts and considers the uncertainty in processes, models and parameters, using a Monte Carlo Simulation. GasSim aids LFG risk assessment, enables the processes of LFG generation, emissions, migration/ dispersion and impact / exposure to be assessed in a reproducible manner by those familiar with the subject but without the need to build multiple models.

GasSim determines the generation of methane, carbon dioxide and hydrogen produced from the waste mass, waste composition and moisture content using a multi-phase first order decay equation, for both methanogenic and acetogenic decay. The definition of the waste composition is highly flexible allowing the model to be tailored to individual landfills. The generation of trace gases, including half-life decay, is calculated from 'user' defined or 'typical' concentrations per m^3 of LFG. Additionally the model includes a single phase first order equation to emulate the LandGem model functionality.

The bulk and trace LFG emissions from the cap and through the liner are simulated using information on the gas collection system, flare, engine, engineered barriers (cap and liner), and biological methane oxidation. Flare and engine emissions of non-combustion products are determined from the volume of gas collected, and a destruction efficiency for the engines / flares. The emissions of combustion products, generated in the flare/engine, is simulated using either 'user' defined or 'typical' concentrations per m^3 of combusted gas exhaust, or by simulating evolution from parent substances e.g. hydrochloric acid from chloride containing substances.

Environmental transport is simulated for terrestrial lateral migration by a one dimensional advection-diffusion equation, and for atmospheric dispersion using the NRPB R91 (Gaussian plume) model. These models determine the concentrations of the various species in the unsaturated subsurface and in the air, including wet and dry deposition for on-site and off-site receptors at various vectors plotted on a wind rose.

GasSim assesses the environmental impact of the bulk and trace species in LFG on the:

- global atmosphere by determining the global warming potential and ozone depletion potential of the relevant species;
- local environment using the odour thresholds and the distribution of odorous compounds generated by the atmospheric dispersion module, and using a vegetation stress threshold and lateral migration concentrations of bulk gases; and
- exposure to humans from atmospheric dispersion and lateral migration, by a series of exposure scenarios, each of which has a set of defined exposure pathways and exposure factors for the critical groups.

To demonstrate the suitability of the model GasSim has been verified against other computer models and validated against published field measurements. The results of LFG generation using GasSim have been verified against its precursor model HELGA (Gregory et al., 1999), a spreadsheet framework model which was produced for the Environment Agency of England and Wales (the Environment Agency), and LandGem (Pelt et al., 1998), which was produced for the USEPA. GasSim compared very well to spreadsheet calculations using the HELGA framework (within 0.5%) and fairly well with the LandGem model (within 4%). Additionally, the single degradation rate equation model, designed to emulate LandGem, has been compared to the LandGem model, with these models agreeing within 2.6% overall.

Validation of the source and emissions modules has been carried out against UK test cells and landfills.

The Environment Agency of England and Wales (the Environment Agency) has funded the development of the model to allow risk assessment for LFG impacting receptors at the planning stage and at the operational stage to aid decision making.

BACKGROUND

The principal drivers behind the development of GasSim were the considerable interest concerning the potential health effects of living near and working on landfills, and the need to substantiate these, as well as the need for a management tool to help the UK meet international agreements to reduce the emissions of greenhouse gases to the environment. UK Government sponsored research (Elliott et al, 2001) has indicated a statistical (but not necessarily causal) relationship between an adverse effect on human health, e.g. birth defects, and landfill emissions. Additionally, under the Kyoto agreement, the UK is obliged to reduce emissions of greenhouse gases. Methane is potentially the second most important anthropogenic greenhouse gas, after carbon dioxide, and is emitted from landfills in significant quantities.

These concerns have lead to the introduction of new European Union (EU) Directives, which apply to the generation and management of landfill gas:

- the European Union Waste Framework Directive (EC, 1991) requires that waste is recovered or disposed without using methods that could endanger human health or harm the environment;
- the Landfill Directive (EC, 1999) requires waste operators to control the accumulation and migration of LFG, to collect and flare or utilise LFG from landfills receiving biodegradable waste, and minimise damage or deterioration of the environment;
- the Integrated Pollution Prevention and Control (IPPC) Directive (EC, 1996) requires preventative measures are taken against pollution through flaring and utilisation.

These regulations cover the design, construction, operation and maintenance of the landfill gas management systems and require:

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

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

- health from trace components and combustion products;
- the local environment by odour and vegetation stress; and
- global atmosphere by ozone depletion and global warming.

The risk of these processes occurring is normally assessed using a mixture of experience, calculations and computer models. GasSim has been developed to provide a standard risk assessment methodology for the Environment Agency, operators and consultants. In order to quantitatively evaluate the risks of these processes and the magnitude of the impacts, GasSim considers the uncertainty in input parameters using a Monte Carlo Simulation. GasSim is designed to aid LFG risk assessment, by enabling LFG generation, emissions, migration / dispersion and impact / exposure to be assessed in a reproducible manner by those familiar with the subject, but without the need to build multiple models.

GasSim has been developed using the HELGA framework (Gregory et al., 1999), which was also developed for the Environment Agency. To provide a model to assess implication of different LFG management options on the environment.

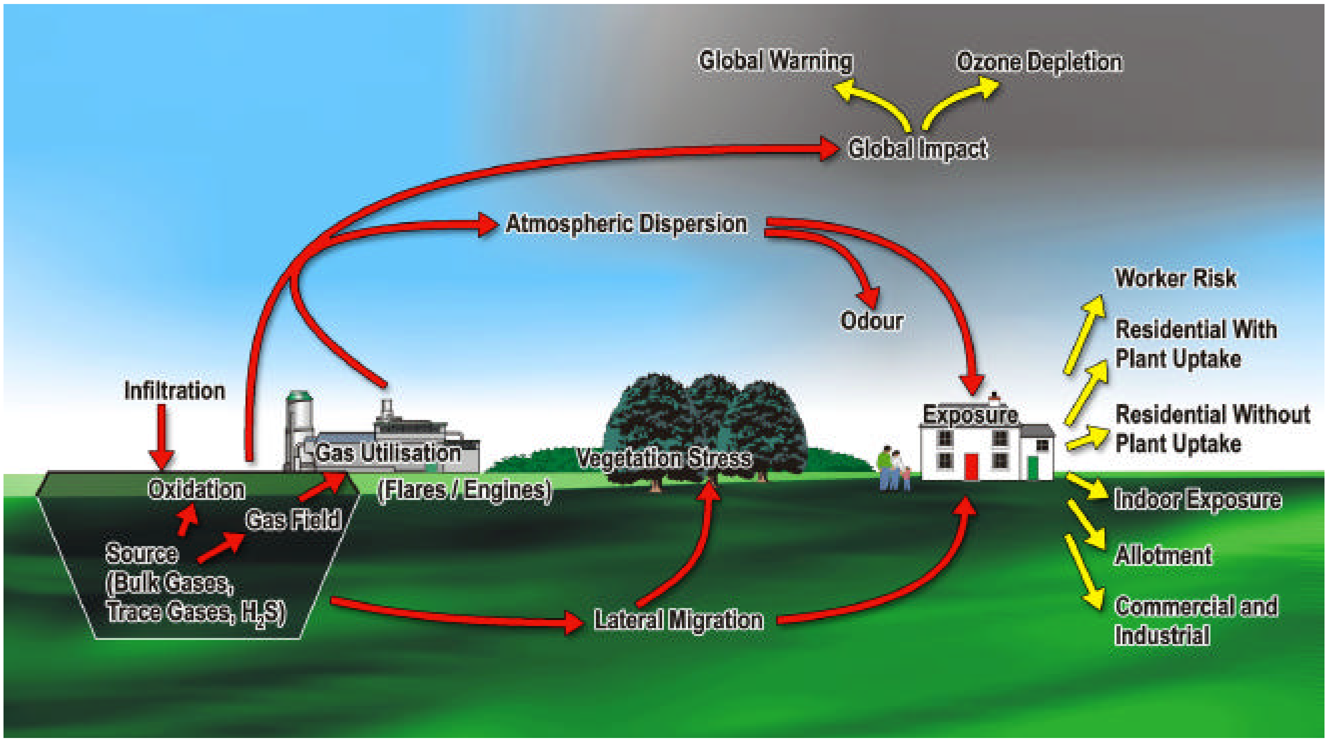

FIGURE 1. THE GASSIM CONCEPTUAL MODEL

CONCEPTUAL MODEL

The conceptual model (Figure 1) has a modular structure. Each module incorporates the effects of additional processes. Progression to successive modules is only necessary if this information is required, e.g. LFG generation and emissions can be determined without proceeding through subsequent modules to optimise time and data collection constraints.

GasSim is divided into 4 main modules, described in detail below:

- source term;
- emissions;
- environmental transport; and
- exposure/impact

GasSim does not simulate:

- catastrophic impacts associated with inundation of floodwater, earthquake or collapse of mine workings;
- the movement of landfill leachate or LFG dissolved in water; and
- acute events associated with sudden drops in atmospheric pressure resulting in lateral migration.
- acute exposure e.g. asphyxiation and also acute health effects by exposure to VOCs

Source

Bulk gases: The heart of the model is the source term, which simulates the generation of methane, carbon dioxide, hydrogen, and hydrogen sulphide produced from the following waste characteristics:

- the waste breakdown, the mix of different waste streams e.g. domestic, civic amenity and commercial waste;
- the waste composition, the fractionation or make-up of the waste e.g. the proportion of paper, textiles and putrescible materials. The waste fractions are defined by the percentage of the material that can decompose, the proportion of cellulose and hemi-cellulose, and the moisture content of the fraction (Table 1);
- the waste moisture content, from the infiltration, leachate management, and waste physical parameters; and
- the biodegradability of the waste fractions, the rate of decay of cellulose in the waste fractions.

The definition of these input parameters allows the model to be highly flexible and tailored to individual landfill sites, taking account of specific waste streams, filling/deposition rates and environmental conditions.

TABLE 1. COMPOSITION OF 1980 TO 2010 WASTE STREAMS

Waste Fraction		Domestic (%)	Civic Amenity (%)	Commercial (%)	Sewage sludge (%)	Composted organic material (%)	Incinerator ash	Water content (%)	Cellulose (%)	Hemi-cellulose (%)	Decomposition (%)
Paper/Card	Newspapers	11.38		10				30	48.5	9	35
	Magazines	4.87						30	42.3	9.4	46
	Other paper	10.07	12.7	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	3.6					25	20	20	50
Miscellaneous	Disposable nappies	4.35						20	25	25	50
Combustible	Other misc. combustibles	3.6						20	25	25	50
Putrescible	Garden waste	2.41						65	25.7	13	62
	Other putrescible	18.38	15	15				65	55.4	7.2	76
Fines	10mm fines	7.11	15					40	25	25	50
Sewage sludge					100			70	14	14	75
Composted organic material						100		30	(1)	(1)	57
Incinerator ash							100	30	(2)	(2)	57
Non-Degradable		28.86	31.3	24.6	0	0	0	0	0	0	0

The proportion of different material in waste have been taken from the HELGA framework (Gregory et al., 1999),
* assumed to be garden wastes by comparison with the HELGA framework data.
(1) Uniform distribution of minimum 7.47 and 9.59 maximum.
(2) Triangular distribution of minimum 0.5, most likely 0.7, maximum 1.5.

The methanogenic degradation of carbon is simulated by dividing the waste make-up of the different waste streams into three waste fractions (Table 2), which degrade slowly (newspaper), moderately (Miscellaneous combustible) and rapidly (putrescibles). The gas generation is then calculated using a highly flexible multi-phase equation (Equation 1).

TABLE 2. DEGRADATION RATE ASSIGNED TO EACH WASTE FRACTION

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

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

and $$C_x = C_t - C_{t-1}$$

(Equation 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 (1, 2, 3, rapidly, moderately and slowly degradable respectfully (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)

In addition to the multi-phase equation GasSim includes a simpler approach using a single phase equation following the LandGem approach (Pelt et al., 1998). This determines the quantity of methane generated using the methane generation capacity and the mass of carbon deposited to determine quantity of carbon available for degradation and thus the quantity of methane generated (Equation 2).

$$C_t = C_0 - \left(C_{o,1}e^{(-kt)}\right)$$

and $$C_x = C_t - C_{t-1}$$

(Equation 2)

where:

C_t mass of degradable carbon degraded up to time t (tonnes)

C_0 mass of degradable carbon at time t = 0 (tonnes)

$C_{o,1}$ mass of degradable carbon at time t = 0 no. in equation

C_x mass of carbon degraded in year t (tonnes)

t time between waste emplacement and LFG generation (years)

k degradation rate constant of degradable carbon or methane generation rate (per year)

The composition of the generated gas and the ratio of methane to carbon dioxide, is defined for both equations by the user.

The decay equations (1 and 2) only determine quantity of available carbon, which are used to determine the generation of methane and carbon dioxide, using the methane to carbon dioxide ratio.

GasSim also simulates the generation of hydrogen, for both decay equations, by allowing 1% of the waste deposited in that year to undergo acetogenic decay, as described in Equation 3.

$$C_6H_{12}O_6 \xrightarrow{\text{Acetogenes is}} 2CH_3COOH + 4H_2 + 2CO_2$$

(Equation 3)

<u>**Trace Gases:**</u> The generation of trace gases is simulated by the user defining the concentration of the trace gas or selecting a typical value (mg/m^3) within the bulk landfill gas. GasSim determines the quantity of trace gas generated by proportioning the concentration of the trace gas species to the LFG generation rate. Additionally GasSim allows the option to reduce the trace gas concentration over time, using a half-life decay declining source term.

The default rate of the defining source term has been defined by examining the emissions of VOCs in landfill gas from a number of landfills from studies by Knox (1990), Scott et al. (1988a), Allen et al. (1997), Young and Parker (1983), Emberton and Scott (1987), Jones et al. (1988), and Scott et al. (1988b). The generated data has been analysed (Figure 2) using the FITCURVE routine to fit a standard non-linear regression model. This estimates the model's only non-linear parameter, r, which defines the rate of exponential decrease of VOCs with time. The other linear parameters (a and b) are estimated by linear regression at each stage of an iterative search for the best estimate of the decay.

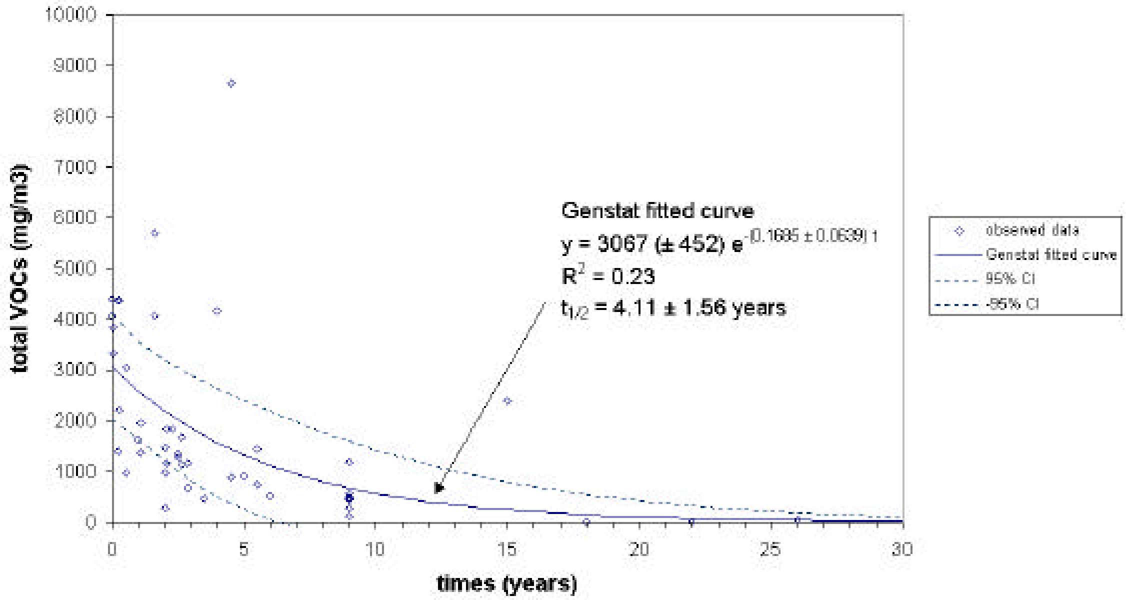

FIGURE 2. VOC TRACE GAS DECAY

Emissions

Emissions from a landfill are normally, but not always, controlled by engineering measures, e.g. the installation of engineered barriers (cap and liner) and gas collection system. The gas collected can then be flared or utilised. GasSim simulates emissions from flares and/or gas utilisation, using information on the collection system.

The model assumes that any LFG generated and not collected will be emitted through the landfill cap or liner at a steady state. The proportion of emissions through the cap compared to the liner is determined, using landfill construction details and the corresponding surface areas. GasSim also assumes that gas generated from an uncapped area, is not collected, and will be released through the surface to the atmosphere, without methane oxidation.

Flares/Gas Utilisation Emissions:

The emissions from engines and/or flares are determined from the quantity of gas abstracted and the:

- concentration of the species in LFG and/or the combustion emissions;
- concentration of a parent species, which reacts to form the emitted species, in LFG; or
- the monitored concentration of the emissions.

The information required depends on whether the species is a combustion product or is destroyed during the combustion process.

The quantity of gas that is abstracted for the capped area is calculated using the:

- available engine and flare capacity per year;
- gas collection system efficiency; and
- proportion of the landfill that is capped.

The collection efficiency for the gas management system can be user defined. However, it is assumed that gas collection is unlikely to be 100% efficient and therefore some small quality of methane will normally be emitted in an uncontrolled fashion.

The available engine and flare capacities are determined by the commissioning and decommissioning times of the flares/engines and the available capacity. Flares are defined using an operational range, a minimum and maximum capacity, and engines are defined by a single capacity. Engines are only simulated to operate when collected gas is available above their nominal capacity, and flares will fail if gas is collected below their minimum capacity. Therefore at low gas generation rates, insufficient gas may be available to operate the flare and/or engines. Conversely at high gas generation rates the specified flare and/or engine capacity may be insufficient, and therefore unable to abstract all the gas available.

The different operational practices of the gas management systems are simulated using four options:

- engine and flares are operated in the order that they are entered into the model;
- engines are operated in the optimum order, with excess LFG being flared;
- flares are operated in the optimum order, with excess LG. being utilised by the engines;

- engines and flares are not operated.

The method by which the concentration of the species emitted by the engine/flare is calculated is dependant on whether the species is formed as a result of combustion or is destroyed by the combustion process. For the purposed of these equations GasSim assumes that all flares are enclosed, which reflects current best UK practice.

Where the gas is destroyed by the combustion process, the emitted concentration is determined using Equation 4. The destruction efficiency should be defined for each gas, using default or site-specific information.

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

(Equation 4)

where:

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

This equation is used by GasSim to determine the atmospheric emissions from engines and flare of all bulk and trace gas species, except for those listed below that have modified equations.

- carbon dioxide (Equation 5);
- hydrogen chloride (Equations 6 and 7);
- nitrogen oxides (Equation 6);
- sulphur dioxide (Equations 6 and 7);
- carbon monoxide (Equation 6);
- dioxins and furans (Equation 6),
- PAHs (Equation 6);
- total non-methane VOCs (Equation 6 and 7);
- hydrogen fluoride (Equations 6 and 7);
- nitric acid (Equation 6);
- total phosphates (Equation 6).

GasSim assumes that carbon dioxide is created from the combustion of VOCs and methane. Therefore the quantity of carbon dioxide generated is dependant on the destruction efficiency of these two species, including a carbon mass balance correction (Equation 5). GasSim assumes that the average unit of VOC unit has a relative molecular mass of 44, based on a generic formula C_nH_2.

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

(Equation 5)

where:

R_{CO2c} release of carbon dioxide by combustion (mg/hr)
Q_{engine} landfill gas to engine (m^3/hr)
Q_{flare} landfill gas to flare (m^3/hr)
G_{CH4} concentration of methane within raw landfill gas (mg/m^3)
G_{VOC} concentration of total VOCs (as organic C) within raw landfill gas (mg/m^3)
DE% destruction efficiency of the gas flare or engine

The emissions of combustion products are determined either using post-combustion monitoring data or by determining the combustion of a parent species into the daughter species, which is emitted.

The emissions of hydrogen chloride, hydrogen fluoride, dioxins & furans, nitrogen oxides, sulphur dioxide, nitric acid, total phosphates, carbon monoxide, PAHs and non methane VOCs using the monitored emissions that have been scaled up to take into account the air to fuel (landfill gas) ratio in the gas engine or flare (Equation 6).

$$R_{pc} = \cdot(AF + 1) \cdot \left(\left[F_p\right] \cdot F + \left[E_p\right] \cdot E \right)$$

(Equation 6)

where:

R_{pc} release of species by combustion (mg/hr)
E landfill gas engine (m^3/hr)
F landfill gas flare (m^3/hr)
F_P concentration of species P within flare stack (mg/m^3)
E_P concentration of species P within engine exhaust (mg/m^3)
AF air to fuel ratio (unitless)

This equation assumes that:

- for measured flare stack emissions, correction to standard oxygen and to dry gas has not been possible because there is no systematic reporting of the data available to allow such corrections to be made However, this will be possible in the future after additional Environment Agency Research has been undertaken; and
- for engine emissions data the reported values were expressed for reference conditions of 15% oxygen content and dry gas.

Alternative methods are available determining the emissions of HCl, HF and SO_2 from combustion (Equation 7). This determines the emissions of the daughter species from their respective parent species, e.g. total chlorine, fluorine, and an estimate of the reduced sulphur content in landfill gas. The parent species are simulated as a trace gas, as described above, and the emissions are determined using Equation 7, which is based on equations presented in AP-42 (US EPA, 1998). The equation also requires a correction factor for the ratio of molecular mass.

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

(Equation 7)

where:

- R_D release of daughter species by combustion e.g. hydrogen chloride (mg/hr)
- Q_{engine} landfill gas to engine (m^3/hr)
- Q_{flare} landfill gas to flare (m^3/hr)
- G_P total concentration of daughter species within raw landfill gas e.g. chlorine (mg/m^3)
- MM ratio of molecular mass e.g. of HCl to Cl = 1.03
- DE% destruction efficiency of the emitted from the gas flare or engine e.g. HCl (this value cannot be set to 0%)

Surface and Lateral Emissions:

GasSim is a steady state model that assumes that all the gas generated is emitted by some pathway or another. This gas will be collected and used by flares and/or engines or lost uncontrollably through the surface or the liner. The surface emissions are determined by a combination of the emissions for the capped and operational, uncapped area. This differentiation is made since GasSim assumes that gas generated from the uncapped area is emitted directly through the surface. It is assumed the open surface of the waste will be far more permeable that the sides of the landfill, which may or may not be engineered. The surface emissions are calculated using the percentage of the uncapped area and the gas generation. Therefore this percentage is defined as a fractional tonnage of waste in place, since using an area would assume the waste has a uniform thickness, which is unlikely to be the case during filling.

For the engineered surfaces, the proportion of emissions lost laterally through the side liner, compared to the proportion lost through the capped surface is calculated and partitioned using the permeability and thickness of the most impervious layers, of each. GasSim assumes that gas movement is via plug flow and that both the cap and liner are homogenous and isotropic, even though in practice poor cap/liner construction and maintenance can result in cracks and micro-fractures. Although these may be locally important, their net effect on the emissions will be averaged out across the site.

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

The emissions of LFG through the cap and the liner can be calculated using Darcy's law, for a homogeneous medium (Equation 8).

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

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

(Equation 8)

where:

- Q_c flux from cap (l = liner)
- Q_{res} residual LFG production
- K_c effective permeability of medium of cap
- d_c thickness of cap in direction of flow
- A_c surface area of cap in the direction of flow (l = liner)

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

GasSim also allows the option to reduce the emissions of methane through the cap by biological methane oxidation by simulating the quantity of emission that pass though that cap (and are subject to oxidative processes) compared to that which passes unoxidised through fissures. The model allows the use of the IPCC methodology (IPCC 1996a, 1996b), or a user defined approach. Here, the emissions through the cap are simulated to reduce by a user defined or default percentage if more that 30 cm of soil is present above the cap, and the amount of fissuring can be specifically modelled. The surface emissions are subject to a maximum oxidative capacity which has been calculated by reference to a number of studies, beyond which methane oxidation does not take place (Borjesson and Svensson (1997); Borjesson et al (1998, 2000); Haarstad (1997), Scharff et al (2001).

GasSim simulates the surface and lateral emission of trace gases using the concentration of the species per m^3 of LFG and the LFG emission rate, by proportioning the quantity of trace gas generated along the same lines as the as the bulk gases.

Environmental Transport

Contaminant transport laterally through the geosphere is simulated using an advection-dispersion equation. Dispersion through the atmosphere is simulated using frequencies of different wind speeds and stability categories occurring.

Lateral Migration: This is simulated simplistically assuming one-dimensional plug flow, which is emitted uniformly from all sites of the landfill. The module uses an advection and dispersion equation (Equation 9) to determine the migration of gas emitted through the landfill liner, this is similar to the equation used for the migration of contaminant in groundwater by LandSim II (Environment Agency, 2001). The advection term is determined by the pressure in the landfill, which is proportional to the quantity of gas that migrates laterally. We assume that the landfill is at steady state. Therefore the velocity at which the gas escapes the landfill can be determined. The dispersion term simulates the concentration gradient, using the dispersivity of the gas in air with corrections for the soil porosity and moisture content.

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

(Equation 9)

where

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

t = time (s)

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

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

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

D_L = the longitudinal coefficient of dispersion (that is, parallel to the direction of gas flow) (m^2s^{-1}), this is determined from the dispersivity of gas in air, the geosphere porosity, the geosphere moisture content, and the dispersion due to movement

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

- the diffusion coefficient for each component is constant;
- partitioning to any dissolved or solid phases present is neglected; and
- movement of dissolved components is neglected.

GasSim assumes that there is no biological oxidation of methane, dispersion, retardation or other attenuation/ reaction processes that reduce the concentration of any gas as it moves through the ground. This will result in an overly conservative approach. Additionally GasSim does not simulate the migration of dissolved gases.

Atmospheric Dispersion: Atmospheric dispersion of the emissions from the engines, flares and the surface is simulated using the NRPB R91 gaussian plume model (NRPB, 1995). This takes into account the effects of thermal plume rise associated with flares and simulates the removal of gases for the atmosphere by both wet and dry deposition. GasSim assumes that the emissions from the landfill represent a point source.

The module simulates the dispersion of the gases using meteorological data, e.g. the wind rose, the frequency of different Pasquill stability conditions, and the average wind speeds and mixing layer heights for each of the stability conditions.

Impact/Exposure

The impact of the emissions can be assessed in four different ways, by determining the:

- global warming and ozone depletion potential (GWP and ODP);
- vegetation stress at a given distance;
- distance from the landfill of the odour threshold; and
- on-site worker, and off-site indoor and outdoor exposure.

Climate change: The contribution that the landfill has on climate change is determined by calculating the GWP and ODP, of the emissions from engines, flares and through the surface. The emissions through the lateral liner are not included as this is an unintentional release pathway. The model allows the user the option to edit the default GWPs and ODPs of species known to contribute to climate change.

Vegetation stress: The impact of methane and carbon dioxide emitted from the landfill on the vegetation in the local environment can also be simulated. This is undertaken by determining the point at which the laterally migrated gases reduces below a default or user defined level above which vegetation stress is known to occur.

Odour: The impact of odour is assessed in two ways, the first determines the point at which the concentrations of odorous species fall below the Odour Threshold Value. This is simulated using the atmospheric distribution of the odorous species. The second method simulates the emissions of European Odour Units from the uncapped, capped and discrete features e.g. passive venting wells and fissures. The atmospheric dispersion of these emissions is then simulated in the same manner as a trace gas, and the point at which the concentrations of an individual odorous species falls below the Odour Threshold Value is determined.

Exposure: Exposure to humans is determined for a number of set scenarios:

- Residential with plant uptake;
- Residential without plant uptake;
- Allotments;
- Commercial & Industrial; and
- Worker exposure.

Each of these exposure scenarios has a set number of exposure pathways, from the following:

- Inhalation of vapour (indoor and outdoor);
- Inhalation of fugitive soil and dust (indoor and outdoor);
- Dermal dust contact (indoor and outdoor);
- Ingestion of contaminated vegetables;
- Ingestion of soil; and
- Ingestion of soil attached to contaminated vegetables.

Each pathway has a default set of exposure factors based on a member of the critical group, and each contaminant considered has a contaminant specific set of physico-chemical properties associated with it.

GasSim primarily undertakes this exposure assessment following the approach used in the CLEA model (Environment Agency, 2002), with some minor modifications for pathways not represented in CLEA.

Although much of the data input is readily available through landfill monitoring and from the site operator, GasSim incorporates a database of values for those parameters not normally determined on a site-specific basis. This data has been obtained for a number of research projects funded by the Environment Agency of England and Wales.

REPRESENTING UNCERTAINTY

The basic idea in all probabilistic assessments is that a probability can represent a judgement about uncertainty. Many of the model inputs have a wide range of uncertainty due to measurement techniques and natural variations. Parameter uncertainty (and to some extent model uncertainty) is dealt with by allowing specification of a range of values for each input parameter rather than a single number, using probability density functions (PDFs). GasSim allows most of the inputs to be defined as single values or a number of distributions, e.g. Uniform, Triangular, Log Uniform, Log Triangular Distribution, Normal and Log Normal Distribution. The model is then simulated using a Monte Carlo simulation selecting different input parameters, from the input PDFs, for each iteration and reporting the outputs statistically.

Thus choice of input distribution may have a profound effect on the predicted results, and it is important that the distribution type you use is justified based on the available data.

DATA INPUTS AND MODEL VERIFICATION

The model verification has included comparing the GasSim multi-phase equation with equations from the HELGA framework and LandGem, using the scenario listed in Table 3. GasSim was first compared to HELGA using the three decay rates: fast - 0.044 (6 years); medium - 0.076 (9 years); and slow - 0.116 (15 years). The methane to carbon dioxide ratio was set at 50:50 and the simulation carried out using a domestic waste stream. This scenario was also compared to LandGem, using a methane generation rate of 0.077 (9 years) and a typical UK cumulative methane generation capacity of ~64 m^3/t.

The comparison of the models is shown in Figure 3 and the cumulative gas generated per tonne during the 150 years simulation has been tabulated in Table 4. The GasSim model compares very well to spreadsheet calculations using the HELGA framework (within 0.5%) and to LandGem (4%).

TABLE 3. VERIFICATION - WASTE TONNAGES

Year	Waste Input (tonnes)
1	500,000
2	700,000
3	800,000
4	800,000
5	500,000

TABLE 4. VERIFICATION - UK SCENARIO

Model	CH_4 (m^3/t)	CO_2 (m^3/t)	Total LFG (m^3/t)
GasSim	63.7	63.7	127.5
LandGem	66.3	66.3	132.5
HELGA	63.8	63.8	127.6

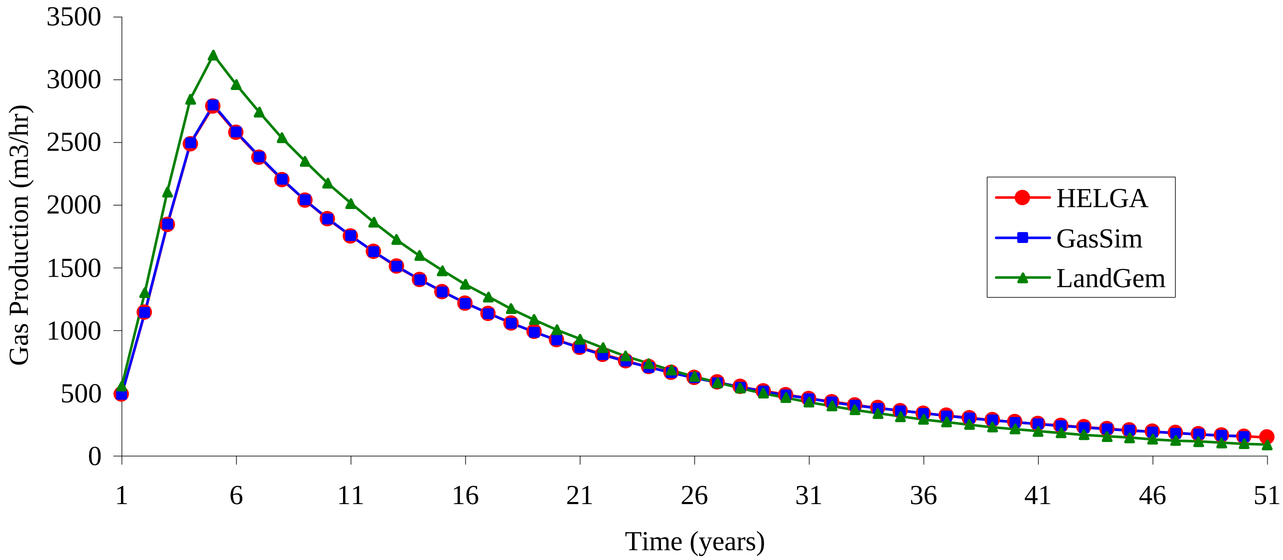

FIGURE 3. COMPARISON OF GASSIM, LANDGEM AND HELGA SIMULATIONS

Additionally the single phase equation in GasSim has been compared to LandGem for the same scenario using the LandGem CAA and AP42 default inputs. The comparison of the total gas generated per tonne during the 150 years simulation have been tabulated in Table 5. The models agree within 2.6%.

TABLE 5. VERIFICATION – AP42 AND CAA DEFAULT SCENARIOS

Model	CH_4 (m^3/t)	CO_2 (m^3/t)	Total LFG (m^3/t)
LandGem AP42	99.6	99.6	199.3
GasSim AP42	101.7	101.7	203.5
LandGem CAA	169.7	169.7	339.5
GasSim CAA	174.2	174,2	348.4

MODEL VALIDATION

In order for any model to be used with confidence it is essential that its represents reality. Therefore a series of validation trails have been undertaken, a selection of which are included here.

Validation of LFG Generation Against Test Cells

The bulk gas source generation term has been validated against the LFG production data collected by the University of Strathclyde from the Auchencarroch Test cells. These shallow cells (approximately 10m deep) were filled over 1 year and subsequently monitored for methane generation under an Environment Agency contract. The cells had received a range of treatments and therefore the sum of all the emplaced waste for the gas produced 2 and 3 years after filling has been used to validate the model.

The monitored gas productions have been overlain on the simulated gas production curve (Figure 4) and the range of LFG production reported by the cells for years 2 and 3 (Table 6) has been compared to the predicted results. The simulation has calculated the waste moisture content within the cells as wet, which will lead to rapid degradation of the waste. The results show that the simulated gas production curve lies within the monitoring data.

Validation of LFG Generation Against a UK Landfill

The bulk gas source generation module has also been validated against a landfill in the UK, which has received 2 million tonnes of domestic waste over an eight year period. The input data simulated is detailed below (Table 7). The simulated data were compared to monitoring data obtained 18 to 20 years after filling commenced.

TABLE 6. MEASURED AND PREDICTED LFG PRODUCTION, AUCHENCARROCH TEST CELLS

Year	Cell 1 ($m^3 h^{-1}$)	Cell 2 ($m^3 h^{-1}$)	Cell 3 ($m^3 h^{-1}$)	Cell 4 ($m^3 h^{-1}$)	GasSim Simulation ($m^3 h^{-1}$)
2	8.47	5.8	5.68	5.48	6.84
3	5.27	3.67	3.52	5.51	4.76

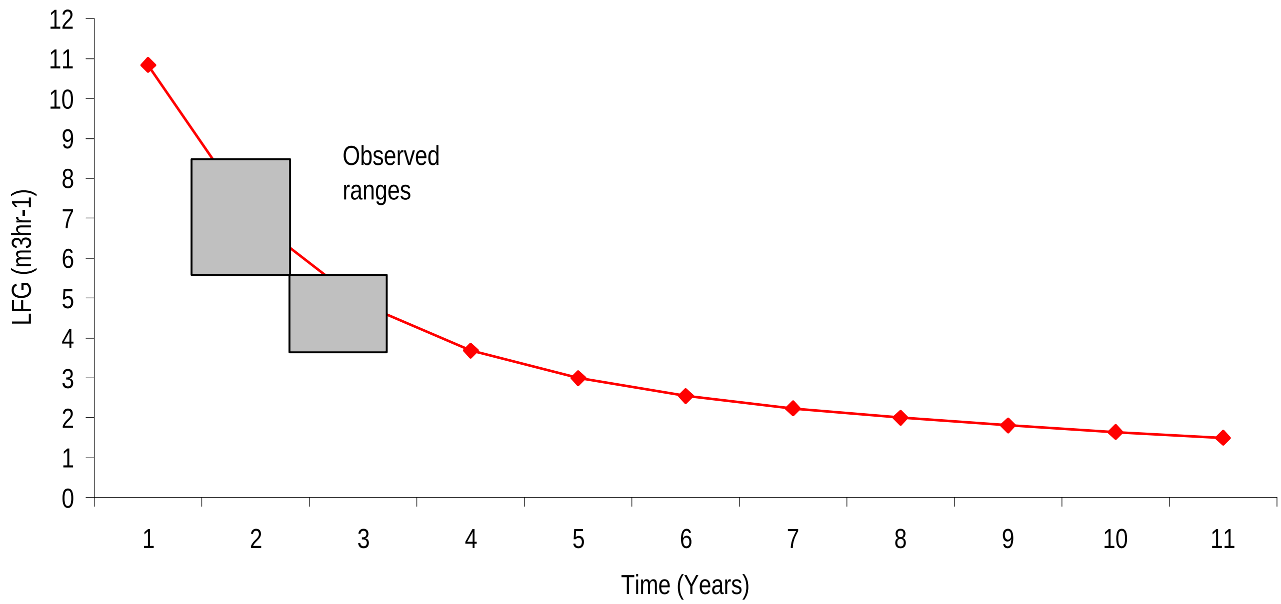

FIGURE 4. AUCHENCARROCH TEST CELLS: MODELLED DATA OVERLAIN BY OBSERVED RANGE

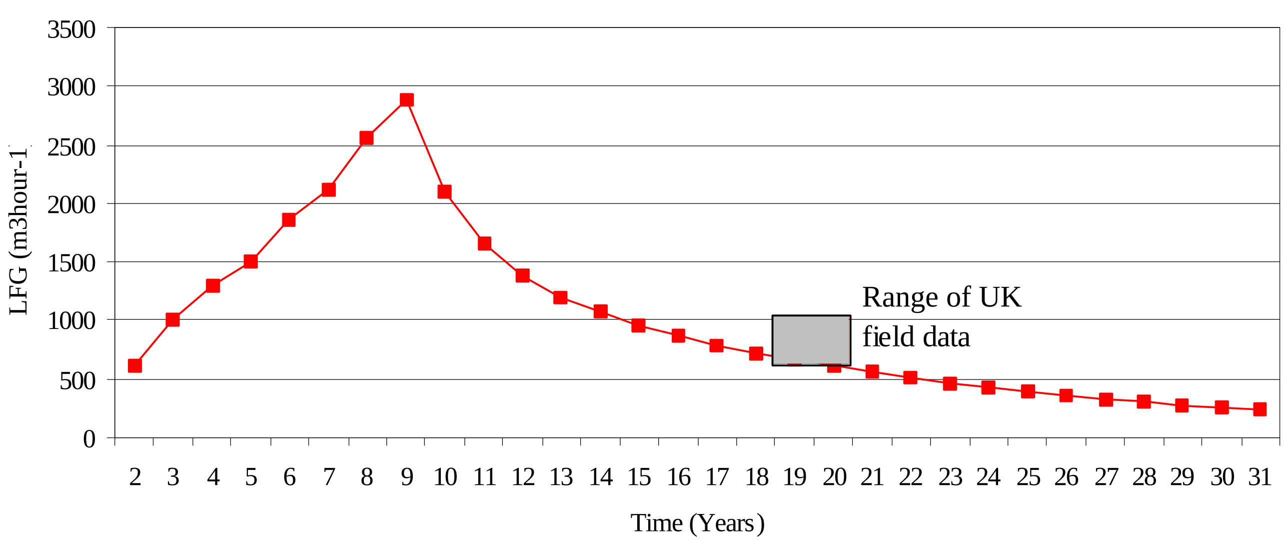

FIGURE 5 UK LANDFILL: MODELLED DATA OVERLAIN BY THE OBSERVED RANGE

TABLE 7 UK LANDFILL WASTE TONNAGES

Year	Waste Input (tonnes)
1978	200,000
1979	200,000
1980	200,000
1981	200,000
1982	260,000
1983	260,000
1984	333,000
1985	333,000

The monitored gas productions have been overlain on the simulated gas production curve and the range of LFG production reported for years 18 to 20 (Figure 5) has been compared to the predicted results. The simulation has simulated the waste moisture content within the cells as wet, which will lead to rapid degradation of the waste. The results show that the simulated gas production curve lies within the monitoring data.

CONCLUSIONS VALIDATING THE MODEL

The GasSim model was designed to allow the risks for LFG to be assessed during both at the planning, operational and post operational stages of a landfill. This assessment includes a quantitative assessment of the risks to humans, vegetation, the atmosphere, and the extent of odour releases.

The landfill can be simulated using site-specific data or generic data provided in the model, which covers information that operators are unlikely to have, e.g. for trace gas concentrations, destruction efficiencies of flares and composition of different waste streams. The model has been designed carry out simulations with a limited amount of site-specific data, with uncertainties in the data sets modelled using probability distribution functions and Monte Carlo simulation.

The verification trails have demonstrated that the GasSim model produces results that agree with other models, namely LandGem, and the equations used in HELGA framework.

The initial validation trails are encouraging with the source model simulating gas production in accordance with reality. The surface, engine and flare emissions; lateral migration and atmospheric dispersion modules are currently undergoing validation.

GasSim can be used to assess the risk of LFG impacting local receptors at the planning stage and during the operation stages to aid decision making, to minimise the impact on local receptors, by allowing the simulation of different capping designs and flare/engine combinations.

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