Applications of Computer Modelling to Landfill Processes.

DoE Report Number : CWM 039B/92.

(Summary of DoE Report Number : CWM 039A/92)

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Contents.

Chapter 1 : Executive Summary.

This summary describes the results of a 3-year research project funded by the Department of the Environment. Its aim has been to gain an improved understanding of landfill behaviour through the development of mathematical models, and to apply these to specific problems in site management.

It is our firm contention that all the mechanisms involved in regulating landfill degradation interact and cannot ultimately be considered in isolation from each other. The model results support this belief and we advocate a more holistic approach to landfill management, rather than concentrating on one or two supposedly key parameters as most previous studies have done. Computer simulations are used to demonstrate the interactions of various factors within landfills and to offer insights into feasible management strategies.

The theory that has been developed is sufficiently comprehensive to allow many of the physical, chemical and microbiological characteristics of landfills to be better understood. It also provides a powerful tool for the accurate modelling of gas extraction systems. The models which have been produced are capable of being applied to a wide range of underground pollution problems, though most of the practical emphasis of the present project has been directed specifically towards landfill gas. A major benefit of the approach adopted has been the highlighting of deficiencies in current knowledge and consequent recommendations for data acquisition.

The illustrations in this summary are all taken from comprehensive worked examples in the main report, and it recommended that any interested parties refer to the full document, which is available from

Wastes Technical Division,
P1/145,
2 Marsham Street,
London, SW1P 3EB.

A short report (CWM040/92) aimed at providing advice on management strategies to site operators has also been compiled, and is available from the same address.

Chapter 2 : Project Background.

Immediately following its deposition within a landfill most of the organic fraction of waste will begin to undergo degradation through chemical and bacterial action. In the earliest phase this takes place via aerobic metabolic pathways, but as more material is added and overlying strata begin to significantly impede the flow of oxygen into the landfill then the dominant reactions within the interior will become anaerobic. After the first year or so of decomposition the major gaseous products are normally carbon dioxide and methane, and the reactions producing them will continue at a gradually decreasing rate for at least fifteen, and often upwards of fifty, years. It is during this latter phase that the majority of the degradable waste will decompose.

The onset of large-scale methane production is of great importance when managing a site, both in terms of its environmental impact and financial opportunities for exploitation. Before this occurs the gas vented is largely carbon dioxide with an admixture of hydrogen, and the leachate is highly acidic. When the methane producing phase is entered, hydrogen ceases to be found in the gas, and the leachate becomes much less acidic (and consequently less harmful in the event it escapes past the site walls).

The aim of this project was to produce a mathematical model for landfill processes which could be implemented on computers to produce predictions of site behaviour.

It is our firm contention that all the mechanisms involved in regulating landfill degradation interact and cannot ultimately be considered in isolation from each other. However the number of variables involved makes the production of a single unified model difficult, and it is initially necessary to separate out the primary aspects and to develop and verify them individually. Hence this report describes a modular set of models which could eventually be combined to produce a single scheme.

The difficulties in gathering data regarding the contents of a particular site make it difficult to produce specific predictions of the site future behaviour — in addition to which the amount of computer time required for some aspects would be prohibitive. Most of our effort was therefore concentrated on producing generic models to identify the primary in-situ interactions and any feasible methods of controlling them. The advantage of modelling over experimentation for these purposes is that there are no uncontrollable factors and full information is available when trying to understand simulation results.

A significant by-product of the modelling process has been the identification of areas in which fundamental data is lacking, and of the need to perform experiments before further progress can be made.

2.1 Structure of the Report and Summary.

The Chapter headings in this summary are identical to those in the main report. Extensive use of graphical techniques has been made throughout the main report (which contains over 100 figures and graphs) to illustrate the simulation results, and a small number of these have been incorporated into this summary.

Chapter 3 : Mathematical Techniques.

In the main report the mathematical discussions have been gathered together as a single Chapter so that a general reader can omit them without detracting from the overall arguments and results. None of the mathematical details are presented in this summary.

Most of the models are based on continuum hypotheses and phrased in terms of coupled sets of partial differential equations (PDEs), and these are solved either analytically or by Finite Element Methods (FEM) or Alternating Direction Implicit (ADI) algorithms. The numerical techniques are explained further in Appendices to the main report.

The ecosystem model of Chapter 6 is described in terms of ordinary differential equations (ODEs), and solved using Gear's method. The network extraction program of Chapter 5 is represented as a set of simultaneous non-linear algebraic equations and solved using a Newton-Raphson scheme.

Chapter 4 : Gas Composition and Migration.

Current practise in landfill gas monitoring relies on measuring gas composition to assess environmental safety and the internal state of a landfill. However, measurements of emissions from a single site frequently show large variations in chemical composition and magnitude, often on the same time scale as the monitoring interval, and these have been generally ascribed to faulty instrumentation or mysterious alterations in the internal biological processes. Such data will eventually be used as evidence to determine when a site deserves a Certificate of Completion, and it is important to know to what extent it can be trusted. The model has shown that the present methods are both intrinsically unreliable and inaccurate as presently applied.

Results from the model, and a supporting field experiment, show that gas flux and composition is affected by changes in atmospheric pressure. In particular the size of gas emissions is linearly related to the rate at which the surface pressure is changing, and has little correlation with the actual value of atmospheric pressure as is often supposed. The model demonstrates how factors such as pH, void fraction, moisture distribution, depth, permeability, and gas evolution/production rates affect these changes. It is shown that the void fractions are much more important than the permeability. A experimental investigation was conducted and found to agree with the model.

Amongst our conclusions are that gas monitoring should be done much more frequently than at present (at least daily), that atmospheric pressure changes must be taken into account, and that monitoring for safety purposes is especially important during periods when atmospheric pressure is falling rapidly. Variations in gas concentration are largest near the surface of a site, with changes in the actual flux being much larger. We were unable to find suitable instruments for either continuous monitoring of gas composition or flux, and their development should be regarded as a priority.

Simple statistical tests for analysing gas data are demonstrated, and a new method of graphically presenting monitoring data has been developed. It is recommend that these become part of standard site characterisation practises.

Some recent experimental evidence has suggested that there is a linkage between atmospheric pressure effects and the quantity and composition of landfill gas. Chapter 4 explored this issue to determine to what extent current gas monitoring practices represent a reliable method of determining the status and safety of a site. The model demonstrated a fundamental physical mechanism, common to all sites, which is able to cause such changes even though gas production is constant.

The main theme of this Chapter was to demonstrate that the rate of change of atmospheric pressure is much more important than the actual pressure itself.

4.1 Volumetric Changes.

The model's results show that the void fraction is more important than the permeability for determining changes in gas yield, and that differing values for the horizontal and vertical permeabilities influence where the gas escapes rather than how much is vented. The simulations give the following results for changes in volumetric gas yield:

{1} When the atmospheric pressure is steady, the rate of gas venting is constant and independent of the pressure.

{2} When the atmospheric pressure is rising, the rate of venting decreases by an amount proportional to the rate at which the pressure is rising.

{3} When the atmospheric pressure is falling, the rate of venting increases by an amount proportional to the rate at which the pressure is falling.

The implications of these results are that gas emissions on or adjacent to landfill sites are highest during times of rapid atmospheric pressure decrease. Also, the total amount of extra gas vented over any period is proportional to the total decrease in pressure. This effect will enhance the build up of methane and carbon dioxide concentrations in confined or poorly ventilated spaces during such periods, increasing the risk of explosion or asphyxiation.

4.2 Compositional Changes.

A more complex model was used to investigate compositional changes in landfill gas due to variations in atmospheric pressure. The following main conclusions were drawn from the results of the computer simulations

[1] The composition of vented gas can exhibit large fluctuations even though the internal generation rates are steady.

[2] Although the effects are complex, the size of the changes is likely to increase as the moisture content of the site rises, the pH of the leachate increases, or the void fraction decreases.

[3] The size of the compositional fluctuations will increase as gas production decreases. This means that gas composition measurements from older sites and regions adjacent to landfills are especially prone to mis-interpretation.

[4] The size of the compositional fluctuations is greatest near to the site surface.

[5] Gas composition exhibits hysteresis — it has a 'history' which must be known to make sense of any new measurement.

[6] It is impossible to gauge the state of degradation of a site from measurements of gas composition taken at a single time or at too infrequent intervals.

[7] The frequency with which much historical gas data has been gathered renders it of little value for risk assessment purposes.

[8] Future monitoring programmes must make provision for a period of frequent (at least daily) monitoring of gas composition and external weather to evaluate the variability at each monitoring location.

Figures 4.1 and 4.2 show part of one of the example simulations from the main report, illustrating the fashion in which the total and individual fluxes of gas being vented from the surface of a landfill are affected by changes in atmospheric pressure.

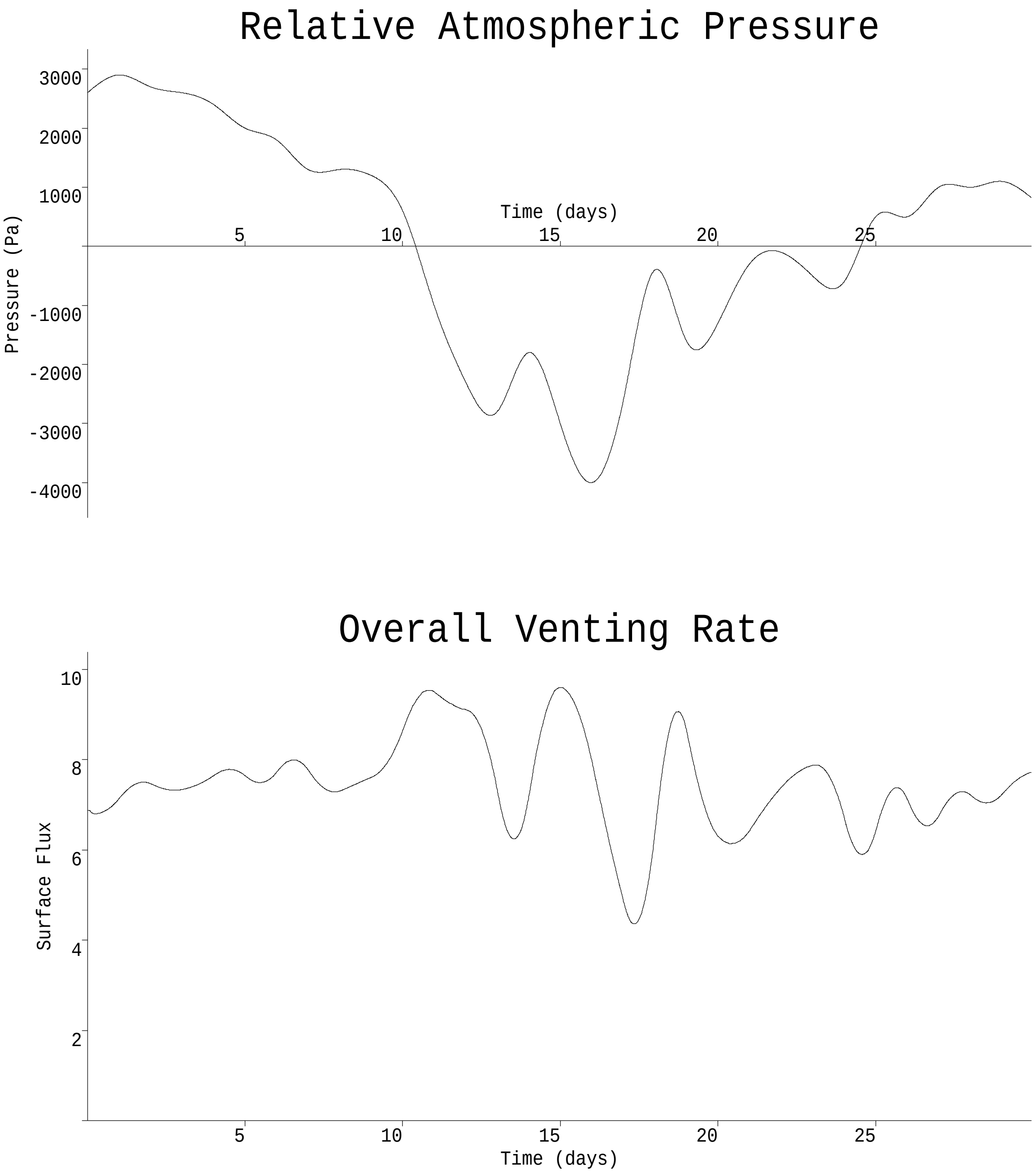


Figure 4.1 : Atmospheric pressure and predicted flux during December.

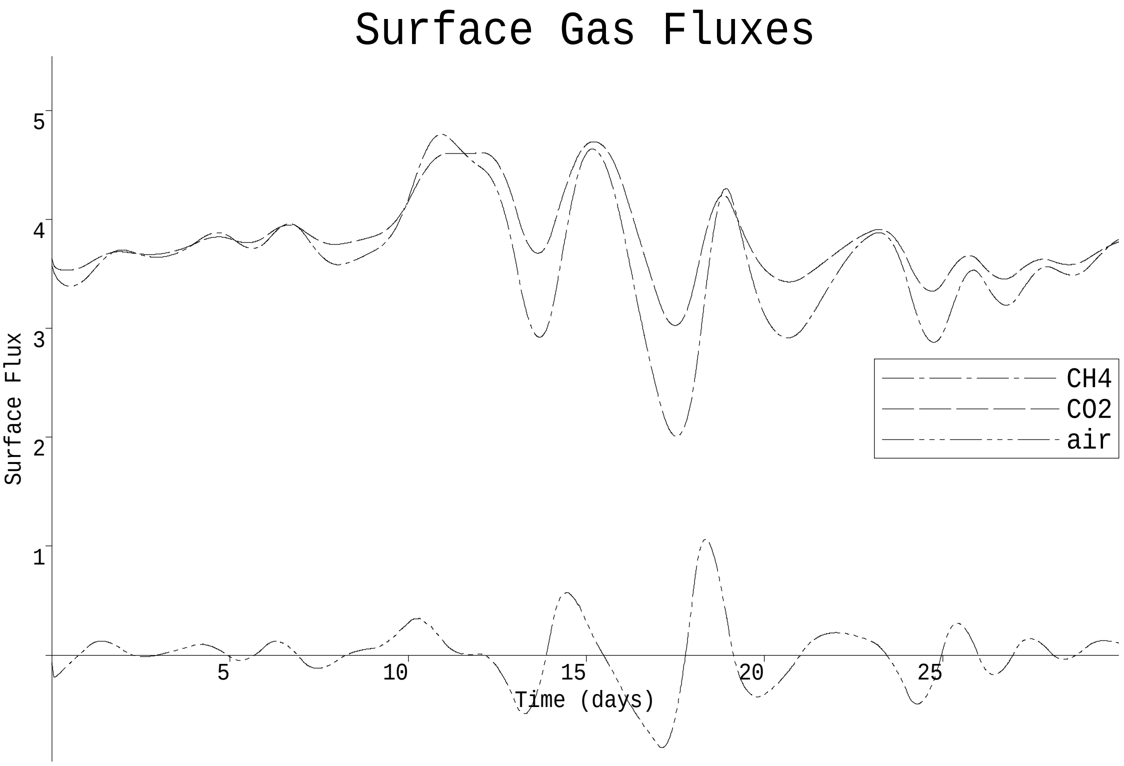


Figure 4.2 : Individual fluxes in vented gas.

A field experiment was conducted at Sleap landfill in which the atmospheric pressure and the concentrations of methane, carbon dioxide and oxygen were measured at 12 hour intervals. Monitoring was carried out at depths of 1 m, 2 m and 5 m. The recorded behaviour of the 1 m borehole is shown in Figure 4.3 below.

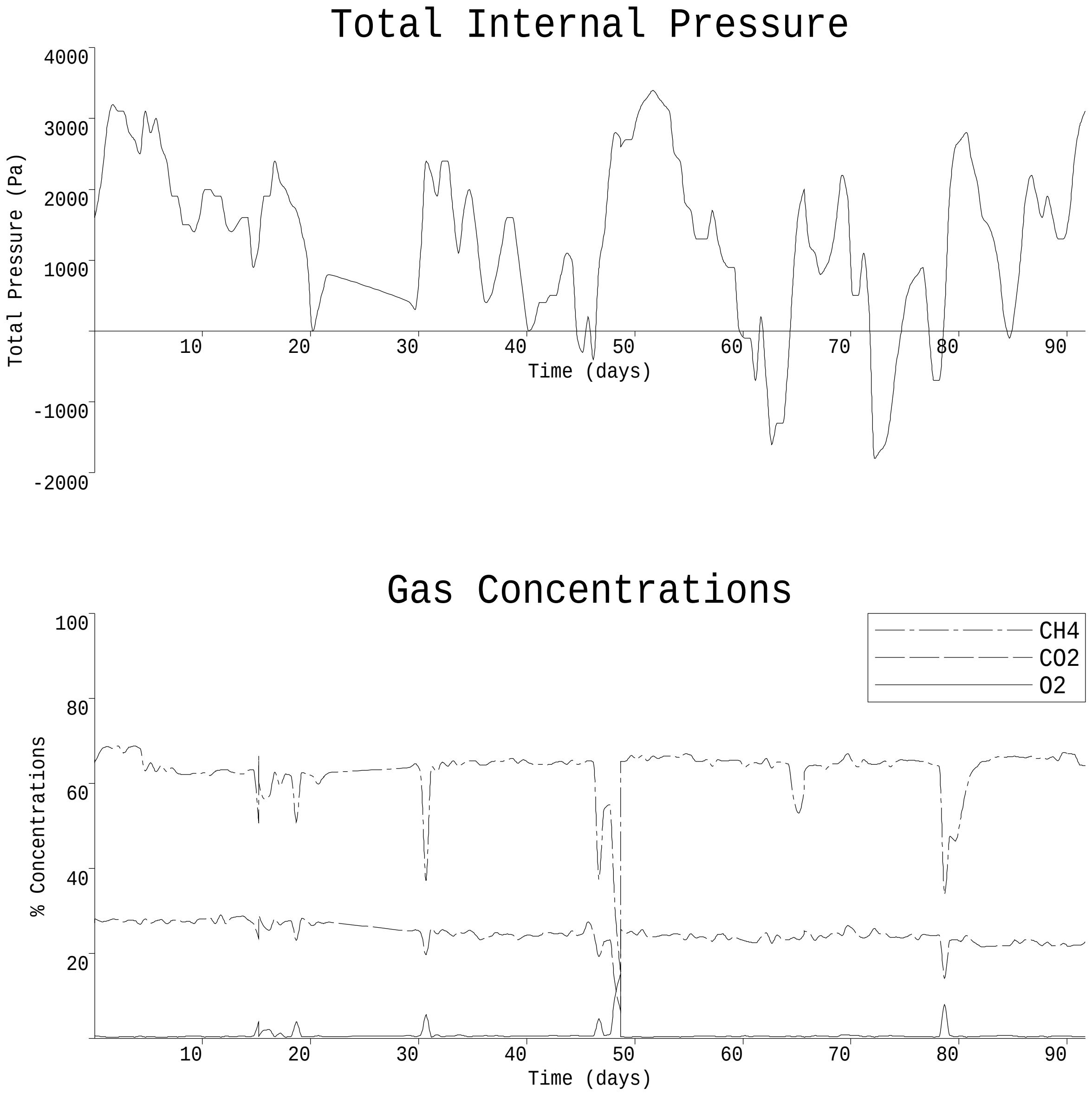


Figure 4.3 : Sleap 1 m.

Several graphical methods were investigated for presenting the monitoring data, and scatterplots were chosen as being the most effective. Figure 4.4 illustrates the methane concentration at 12-hourly intervals in the 1 m borehole. The use of a scatterplot to display how the concentration varies against both surface pressure and rate of change of surface pressure shows the trends and ranges of behaviour much more clearly than any other pictorial method.

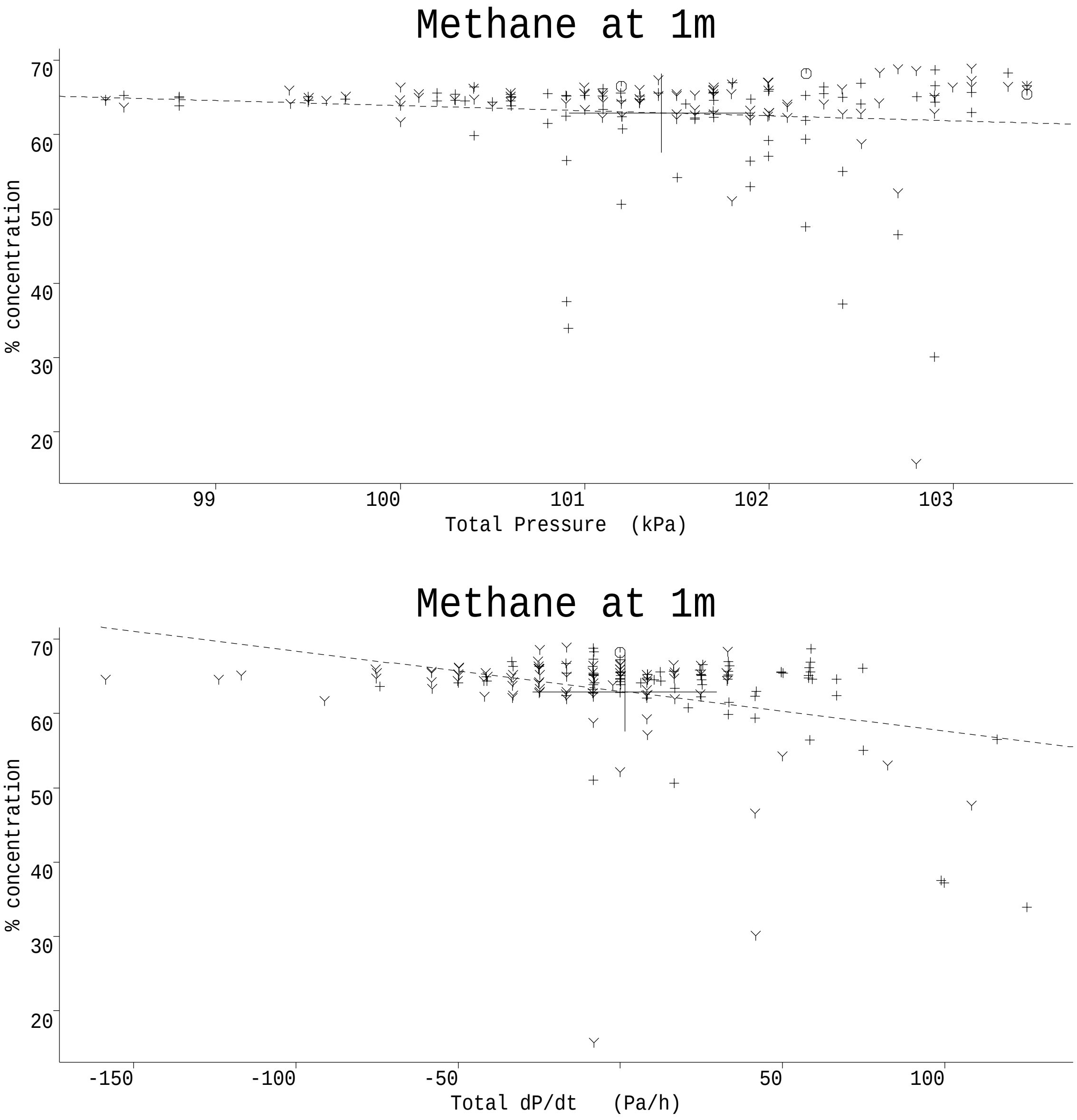


Figure 4.4 : Methane at 1 m depth.

The field experiment agreed with the model predictions regarding points [1], [4], [5], [6], [7] and [8] above, but could say nothing about the other items. However, the degree of agreement between the model and the tested predictions leads us to believe that [2] and [3] are essentially correct also.

In particular, in accordance with the field data, the model results show that the same rate of change of atmospheric pressure (for instance 50 $\mathrm{Pa\,hr^{-1}}$) can be associated with a wide variety of concentration levels, that the Sleap site does not produce peaks of concentration, and furthermore that all instances of low LFG concentrations occur during periods of rising atmospheric pressure (high LFG concentrations being impossible due to the nature of the site). The similarity between the models behaviour and the sub-surface field data gives us confidence that the much larger predicted changes in surface flux are real.

Note that the permeability makes little difference to the stoichiometric behaviour, because it affects only the gas velocity, and cannot cause the individual molecules to be vented in a different order. The gas composition is influenced not just by the instantaneous pressure changes, but also by the history of the weather over the preceding days or weeks which determines the initial position of the molecules of the individual component gases. As a result, the time-scale for gas composition to approach equilibrium under steady external conditions is several weeks, whereas the net internal pressure reaches equilibrium within a matter of hours.

It would be useful to repeat the Sleap experiment on site with lower gas generation rates using monitoring points nearer to the surface. A method of measuring surface flux should be found, since this may vary drastically even when the internal concentrations are almost constantly at ‘saturation’ levels. A laboratory experiment to investigate the tortuosity coefficient for waste would be useful.

4.3 Recommendations for Future Monitoring Practises.

The existence of these short term variations mean that the prevailing barometric conditions should always be taken into account when using field data to assess gas generation rates and pollution hazards, and pressure data must be collected simultaneously with other readings. Since continuous barometric pressure monitors are cheap, all sites ought to have one installed immediately. As a general guideline, the model suggests that if only a small number of measurements can be made then they should be conducted during periods when the atmospheric pressure is falling — ideally when it has been falling for several days to allow CH_4 and CO_2 to migrate to the surface. With more resources, a period of frequent monitoring should be undertaken to assess the range of behaviours possible to a site, covering an interval sufficiently long that there are several rapid falls and rises in atmospheric pressure. Ideally some form of continuous (at least daily) monitoring should be installed in sites for the majority of their active phase.

Any trace gases produced within the landfill are subject to the same mechanisms as the CO_2 and CH_4 molecules, and will therefore show analogous alterations in concentration. Highly soluble gases, such as H_2S, should show less variation than relatively insoluble gases like H_2. Since the compositional variations decrease with depth, to assess the actual relative fractions of gas being generated it is necessary to draw samples from deep within a landfill.

Predictions of internal gas concentration based on χ^2 methods were shown to be inadequate for the Sleap data-set. It is currently normal practice to attempt to infer gas production rates from much smaller data-sets (or even single measurements), and this experiment has proven that such procedures are unreliable. The only way to assess a site properly is to gather a large data-set (at least the size of our Sleap data) and perform a simple statistical analysis in terms of means, extrema, standard deviations, and (for the near surface) correlation coefficients.

Our graphical method of illustrating gas concentrations as scatterplots is a very useful way of characterizing site emissions — although it may initially seem more confusing than tabulated data. I would recommend that it be adopted as a standard supplementary method of presenting monitoring results.

4.4 The Effect of Aquifers within a Site.

The model simulations indicated that the presence of aquifers can cause enrichment of the methane content and some lowering of internal pressure within a landfill (observations which have occasionally been made but not satisfactorily explained in a number of sites). Spatial variations in the concentration of carbon dioxide (particularly an increase in the ratio of $CH_4 : CO_2$ partial pressures towards the lower regions) are suggested as a diagnostic test for the existence of aquifers. The magnitudes of the enrichment effects cannot be determined without additional experimental evidence, particularly the rate at which gas molecules pass into and out of aqueous solution.

Chapter 5 : Gas Extraction Systems.

Gas extraction systems are currently designed on a rule-of-thumb basis using the radius of influence of a gas well as a single parameter relating gas yield to applied suction, and ignoring the interactions between wells and surface equipment. The model has been used to develop a parameter (the yield reduction coefficient, YRC) which quantifies part of these interactions. The use of YRCs reduces the need for underground gas flow computations which has previously hindered the prediction of extraction network performance.

The model allows systems composed of any number of pumps, pipes and wells to be assessed before installing them on a site, and can predict the effect of component failures on gas recovery. This section describes a computer program developed for use by site designers and operators to assess the efficiency of a gas extraction system while a site is still in the planning stage. An illustrative example is given, consisting of 28 wells, 2 pumps and 62 pipes, which took under 2 seconds to compute on a Vax6000 — making the system fast enough for interactive design use by landfill engineers.

5.1 Yield Reduction Coefficients.

Most practical extraction schemes consist of several wells, which will interact with each other, so that the effective radius of influence of a well depends on the status of any neighbouring wells. We have quantified this interaction by introducing a parameter called the 'yield reduction coefficient' (YRC), which enables the flux through any single well to be expressed as a function of the suction pressures at all of the wells (μ_{AB} measures the extend to which well B reduces the yield from well A). For instance, if the YRC at well A due well B is 0.15 ($\mu_{AB} = 0.15$) then an increase in extraction pressure of 100 Pa at well B causes the same decrease in flux at well A as if the suction at the latter were reduced by 15 Pa.

The YRCs depend only on the physical properties of the site, and are not affected by the rate of gas generation. The model predicts the following properties for the YRCs between two identical wells, labelled A and B:

[1] As the separation of the wells increases, the YRCs decrease.

[2] Increasing the depth of the perforated sections (but not their overall length) results in the YRCs increasing.

[3] If well A is situated nearer to an impermeable landfill boundary than well B then well B has a greater influence on well A than vice versa ($\mu_{AB} > \mu_{BA}$).

[4] As the vertical permeability decreases, the YRCs increase.

[5] As the horizontal permeability decreases, the YRCs decrease.

[6] If the perforated section of well A is located at a shallower depth than that of well B then well B has a greater influence on well A than vice versa ($\mu_{AB} > \mu_{BA}$).

[7] If the length of the perforated section of well A increases then μ_{AB} increases slightly while μ_{BA} increases by a much larger factor.

[8] If the radius of the perforated section of well A increases then μ_{AB} increases slightly while μ_{BA} increases by a much larger factor.

[9] If the thickness of the cap is increased, or its permeability decreased, then the YRCs increase.

When the two wells are sufficiently distant from the site boundaries, it is possible to formulate these relationships in a more precise manner. Firstly, the YRCs decrease exponentially with distance, except when the wells are extremely close together, or when they are near to impermeable boundaries. The YRCs increase linearly with increasing horizontal permeability, and are inversely proportional to the vertical permeability of the landfill strata. There is a linear increase in the YRC as the resistance to flow of the cap decreases.

As extra wells are introduced into a landfill, all of the YRCs will change — generally decreasing, this effect being greatest for those wells nearest to the new one. Conversely the YRCs will increase when one of the wells is removed or blocked.

To precisely determine the YRCs for a real site by experimentation would require as many pumping trials as there are wells, which would be impractical on a site having many wells, though the problem is reduced if the wells are connected in clusters, (assuming each cluster is at the same extraction pressure). Additionally a well/cluster will only be significantly affected by its nearest neighbours, so simultaneous pumping trials could be carried out on different regions within the site.

Our quantification of changes in YRC with respect to separation, location, permeability and well construction should enable landfill operators to transfer field experience gained from present sites to future ones with more accuracy. However, we feel that a field trial (involving say 3 wells and 5 pumping tests) is required to validate the model, so that engineers have sufficient confidence in it to use the generated predictions.

5.2 Comparison of Surface Installations.

The Network Pumping model allows different gas extraction schemes to be compared before installation, and the effects of changing gas production and component failures to be assessed in advance. Without the concept of YRCs developed in this project, limitations in computer power would make it impractical to predict the gas fluxes within an extraction system.

To fully exploit the power of the model requires more detailed attention to monitoring individual extraction wells that is common practice. However, if the user can estimate the well yield parameters roughly (either from measurements or previous experience) then the program will be able to produce valuable information about the comparative effectiveness of various installations. For instance, in addition to illustrating the program, the simulation results demonstrate the usefulness of installing relief pipes — both for everyday use and as a contingency against failures elsewhere. We feel that it would be useful to perform a further series of model calculations to compare generic site layouts (such as 'radial', 'daisy chain', 'clustered' and 'herring-bone').

Figure 5.1 shows a plan for a hypothetical landfill analysed in the main report, consisting of 2 pumps, 28 wells and 61 pipes connected via a ring main with an additional central relief pipe straddling the site. Calculating the fluxes and pressures at every point within the site required less than 2 seconds on a Vax6000 (which translates to under 10 seconds on a 33MHz IBM486 PC).

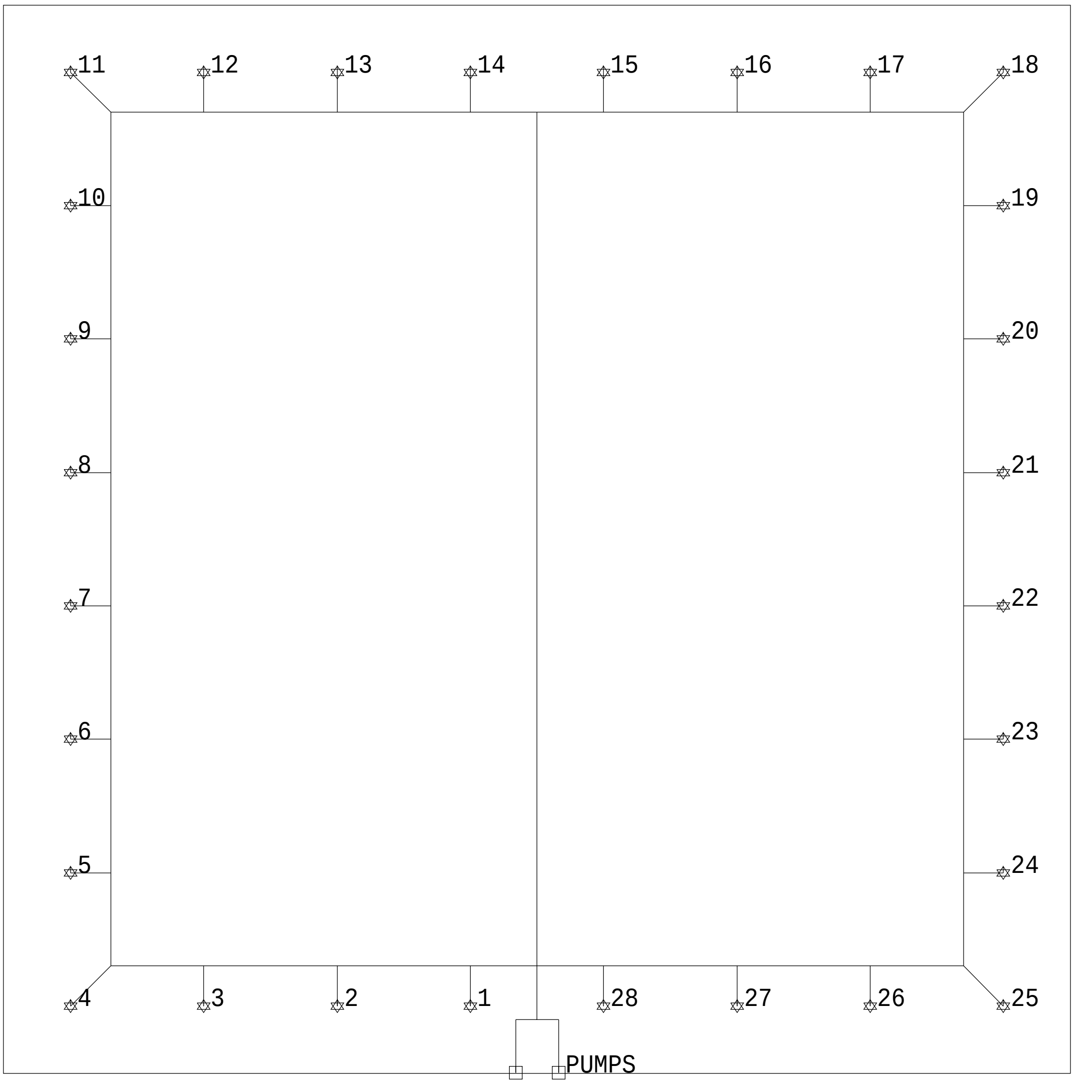


Figure 5.1 : Site configuration for extraction calculations.

Figure 5.2 shows the fluxes of gas being produced by each well within the site (assuming, for simplicity of comparison, that each has identical characteristics).

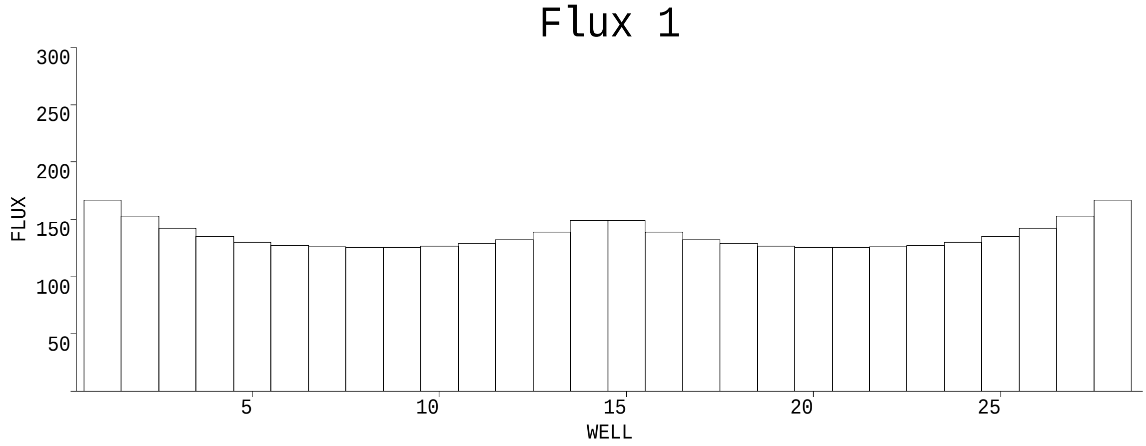


Figure 5.2 : Full site.

The main report demonstrates how the fluxes change under a number of circumstances involving component failures, and figure 5.3 demonstrates the effect of simultaneous blockages in the central relief pipe and the link between wells 1 and 2. Of particular interest is the way in which the increased suction at well 1 has enabled it to 'steal' gas from the region of well 2, and it is probable that it is now also drawing oxygenated air into the site.

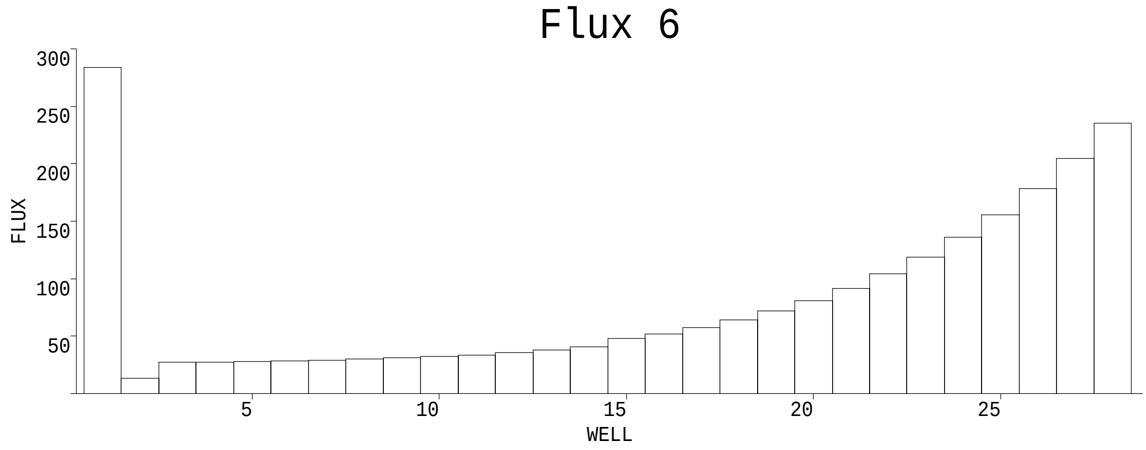


Figure 5.3: Failure of relief pipe and link between wells 1 and 2.

Several extensions are possible to the basic model, and these would require calibration experiments if manufacturers where unable to supply the relevant data. For instance, attaching generators causes a back-pressure, booster pumps may be used to aid gas flow through very long routes, condensation 'knock-out pots', valves and flame traps cause pressure drops, and entrained water may interfere with flow. In long pipes some condensation may take place in cold weather, but since the gas velocity is known at all points it would be possible to calculate the rate at which it cools on the way to the pumps, and hence to determine the amount of condensation likely to take place at any location (and thus the potential for blockages and ice-plugs).

There is no theoretical limit to the complexity of a site which can be modelled by the computer program. Without modification the procedure can cope with multiple networks being installed on the same site — for instance a utilisation scheme surrounded by a second un-connected network which over-sucks to prevent gas excursion. The program devised during the project is fast enough to be used by engineers on an interactive basis. With additional development work and the creation of a larger database describing landfill components this system would be an invaluable tool for site planners and operators.

Chapter 6 : Methanogenic Ecosystem.

Waste management policies in Europe and the UK are placing pressure on packaging wastes, encouraging higher recycling rates and the development of energy reclamation schemes. These changes will have a profound influence on the nature of the residual materials requiring landfill disposal, and the subsequent course of events within sites.

In studying the biochemical degradation of landfills and the establishment of the methanogenic ecosystem, the primary aim has been to predict the conditions under which methanogenesis is able to become established, the time scales required for this to happen, and ways of influencing the processes. The main influences on anaerobic bacterial activity are temperature, pH, Eh, substrate availability, and moisture level. These, together with their associated rate controlling factors are taken into account in the model. To provide flexibility in specifying composition, waste is divided into 10 separate categories. The methanogenic bacteria are considered as two separate species: acetoclasts and hydrogen consumers. A special laboratory study was conducted at Strathclyde University to provide data on the pH and temperature behaviour of methanogens, and it was found that the bacteria are more tolerant of low pH values than is usually assumed.

Low alkali metal concentrations have been associated with a failure of methanogenesis and the model indicates that this is due to insufficient pH buffering rather than nutritional deficiencies as has previously been supposed. The model also demonstrated that it may be useful to reduce the fraction of highly-degradable wastes present in a site, possibly by aerobic pre-composting.

The action of the bacteria within a site is a primary mechanism responsible for changes in its temperature, chemical composition and physical structure (ie. the saturation, permeability and density) and these factors in turn determine the viability of the many microbial species present. One of the primary goals of the project was therefore to develop a model to study the establishment of the landfill ecosystem, and in particular the methanogens since they seem to be more sensitive to adverse conditions than the other species.

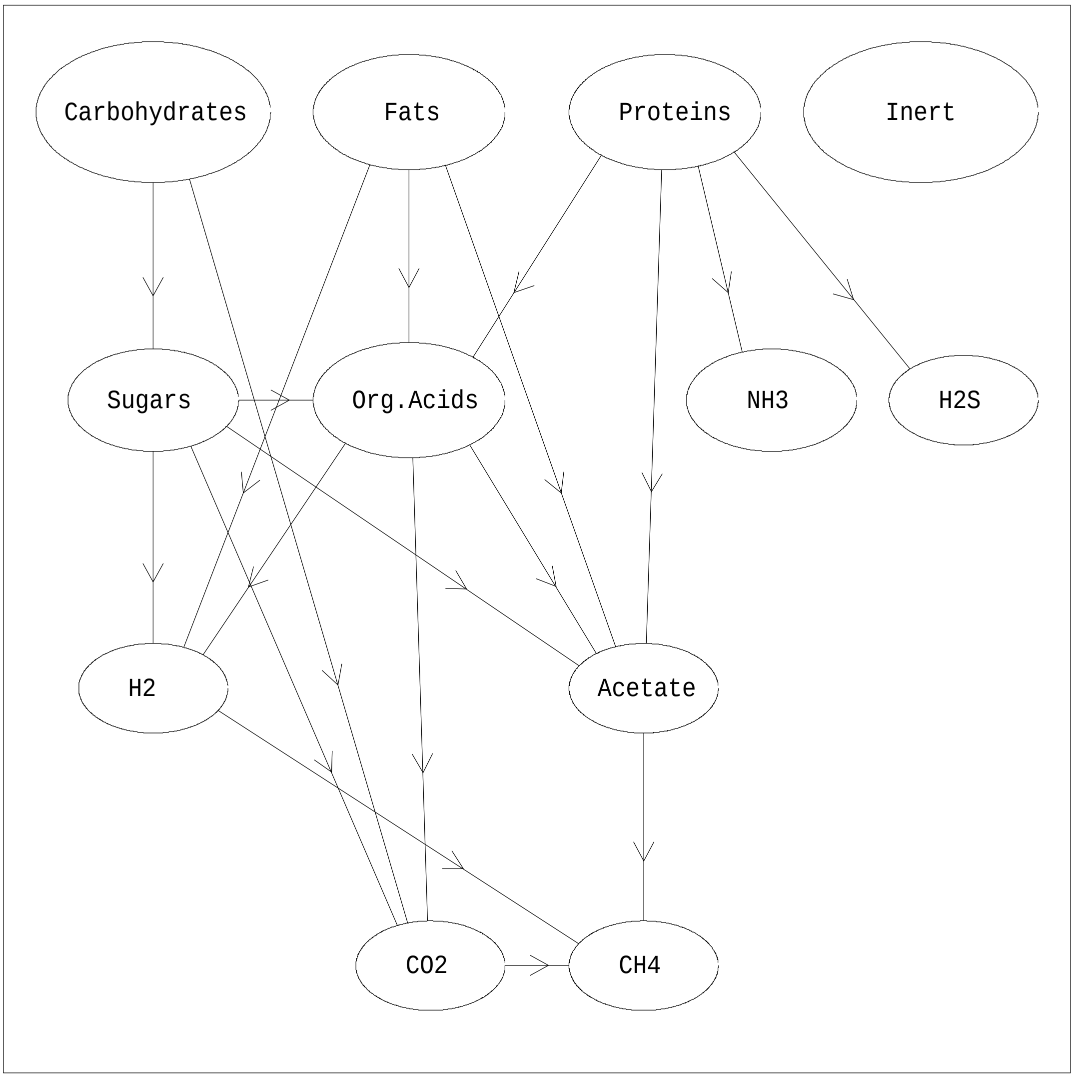


Figure 6.1 : Modelled biochemical processes.

The actual reactions taking place inside a landfill are too numerous to model precisely (even if sufficient data were available) and so the compounds involved must be grouped into a number of generic categories and the system phrased in terms of these. Figure 6.1 shows the main idealised processes used in the model (alternative groupings were tried and are also discussed in the main report).

When the model was subjected to a variety of initial conditions it responded in a sensible fashion and eventually settled down to some steady state, though without methanogenesis under the harsher starting regimes. Given the amount of variance between real landfill sites, the behaviour of this model falls well within the range of observed characteristics.

The lack of data which prevented fully incorporating feedback effects into the pH and temperature means that the model has little predictive power regarding acidogenesis. In particular, we were forced to incorporate the 'standard' division of waste into three different 'half-life' categories. However the simpler nature of methanogenesis allows much useful information to be extracted about it. The inclusion of spatial effects did not seem worth attempting until some of the biological and chemical problems highlighted by the model have been satisfactorily resolved by experimentation.

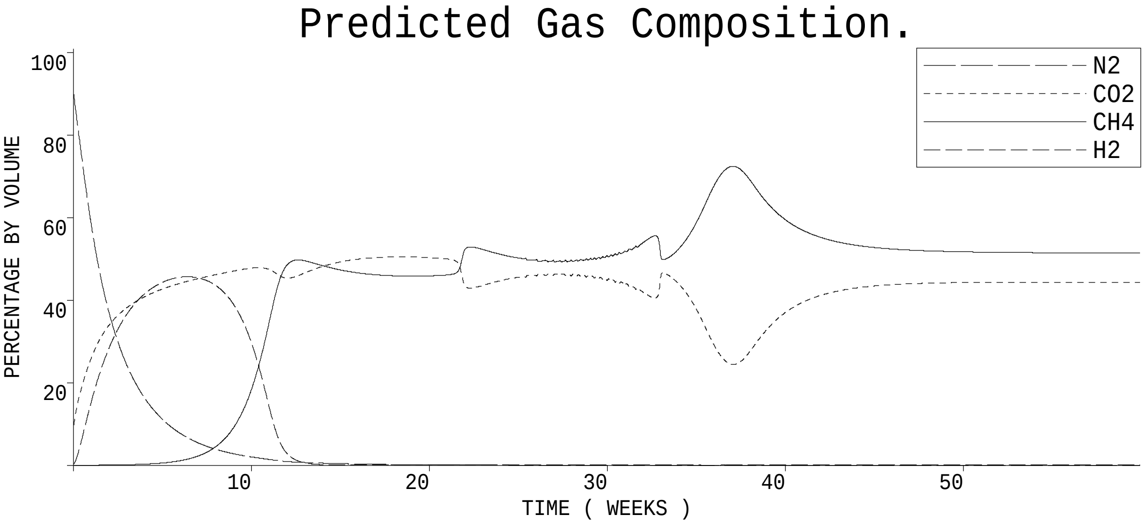


Figure 6.2 : Partial pressures of landfill gas during simulation.

Figure 6.2 illustrates the pattern of gas production observed during an example simulation, and it is possible to correlate each of the phases with specific changes in the leachate solutes and the biological ecosystem. This enables us to explain how some of the factors observed in sites are inter-related.

6.1 Laboratory Study.

A special study at Strathclyde University (Watson-Craik and Goldie, 1991) found that the temperature behaviour of methanogens agreed with the literature, but that the bacteria are significantly more tolerant of acidic pH conditions than is normally assumed. It was impossible to assess the relative importance of direct substrate inhibition versus indirect pH-inhibition effects in the acetoclastic reactions. It would be valuable to extend the scope of these experiments.

Also, it would be valuable to conduct experiments on the effects of moisture content within waste, especially as the newer containment landfills may have quite arid interiors while laboratory studies have generally confined themselves to very wet waste for reasons of speed and convenience.

Field observations generally do not distinguish whether methanogenesis from acetate cleavage or carbon dioxide reduction comes first. Knowledge of the links between these two processes would be useful — for instance it may be that monitoring hydrogen concentration can provide information about the establishment of acetate cleavage and hence give early warning of sites behaviour. This is especially important if both reactions are performed by the same species, in which case microbiological research on the switching mechanisms and critical concentrations should be carried out.

6.2 Aerobic Pre-digestion.

Increasing the amount of readily-degradable waste indefinitely does not increase the rate of the establishment of methanogenesis, and indeed if there is too much readily-degradable waste present then the initial acid production will kill the methanogens.

At some landfills taking pulverized waste which has gone through an initial aerobic phase, it has been observed that methanogenesis is established faster, and this may be due to the high rate of aerobic degradation removing much of the readily-degradable substrate and/or the higher initial temperature (and possibly also due to increased availability of alkali metals — see below). Some experimentation is required here, as it may be beneficial to adopt a policy of exposing some or all of landfill waste to oxygen before infilling.

6.3 The Influence of Metals.

Low alkali metal (ie. the elements in groups I and II of the periodic table) concentrations are frequently associated with a failure of methanogenesis to develop, and this has been attributed to some of these metals being essential nutrients for the bacteria. The model shows that low alkali metal concentrations mean the leachate is poorly buffered against the carboxylic acids so that the pH may fall too quickly for the methanogenic population to reach a self-regulating size, and furthermore that this effect is more important than nutritional aspects, since the levels required for adequate buffering are above those at which the bacterium's nutritional requirements are satisfied. Also, the model implies that the landfill system requires both 'permanent' buffering (cations which remain in solution at neutral pH levels) together with 'variable' buffering (cations whose solubility increases enormously as the leachate becomes more acid) if the methanogens are to prosper.

This pH dependent nature of the cation concentration greatly enhances the homeostatic influence of the bacteria, and allows them to maintain the leachate in a near-neutral state while still having adequately high levels of acid present to act as substrate. Some experimental work is required to assess the availability of metals within waste, and the rate at which they come into solution — which, if the metals are initially bound within the organic fraction of the waste, will be affected by the amount of degradation which has taken place, and perhaps also by any initial aerobic phase.

6.4 Diffusion.

Diffusion limitations within the liquid mean that the levels of dissolved gases present in the water held within the smaller waste pores (eg. soaked into paper) will be above the equilibrium values predicted from Henry's law, and could even be several times higher. The dissolved concentration is highly relevant to bacterial metabolism, and the present practise of inferring bacterial activity using gas samples from the void space is unsound. A laboratory experiment is essential to determine the rate at which gas molecules are evolved from the waste mass and pass across the liquid-gas interface — an initial step would be to isolate samples of waste in a vacuum chamber to determine the amount of dissolved gas actually held within them. This data is also required to improve our models of Chapters 4 and 7.

Chapter 7 : Temperature and Moisture.

The internal heat balance of landfills is one of the primary factors regulating their behaviour. A section of the model calculates the opposing effects of exothermic bacterial reactions and physical heat losses (including evaporation) and the way in which these are affected by such factors as emplacement temperature, site layout, and long-term site management practises.

One outcome of this is a study comparing the consequences of changes in capping regulations which would favour the creation of either wet or dry sites. The simulations indicate that although dry sites have fewer operational problems in the short-term, they represent a much greater long-term hazard and consequently wetter sites are recommended. The investigation also found that, for reasons of speed and convenience, microbial experiments have only been done with very wet wastes and the state of knowledge regarding dry wastes is inadequate.

7.1 Thermal Regulation.

The internal temperature of landfills has long been thought to be one of the primary factors affecting their behaviour. Chapter 7 explored the physical and biological processes controlling landfill temperature.

7.2 Natural Warming of Landfills.

First we considered the thermodynamics of the degradation reactions whilst ignoring spatial variability to give an estimate of the maximum possible rate of warming. It was assumed that all gas inside a landfill is saturated with water, so that for each mole of LFG produced the requisite amount of water must be evaporated to saturate it (this amount being highly dependent on the temperature). Under these assumptions, the theoretical maximum temperature that may be achieved in a fully anaerobic landfill is 73 °C.

This implies that any landfill approaching 70 °C cannot be completely anaerobic. The occurrence of such temperatures in sites (especially shallow ones) is an indicator that oxygen is reaching the interior, and operators should check for over-pumping and cracks in the cover material.

7.3 Rate of Temperature Rise.

The depth of a site greatly influences both the rate of warming of the site and the final temperature that it reaches. Numerous runs of the model show that the rate of warming is fairly slow, usually only a few degrees per year. We conclude that the early temperature of any particular site depends to a large degree on the temperature reached during the earlier stage of aerobic degradation, and that methods of raising this initial value should be investigated.

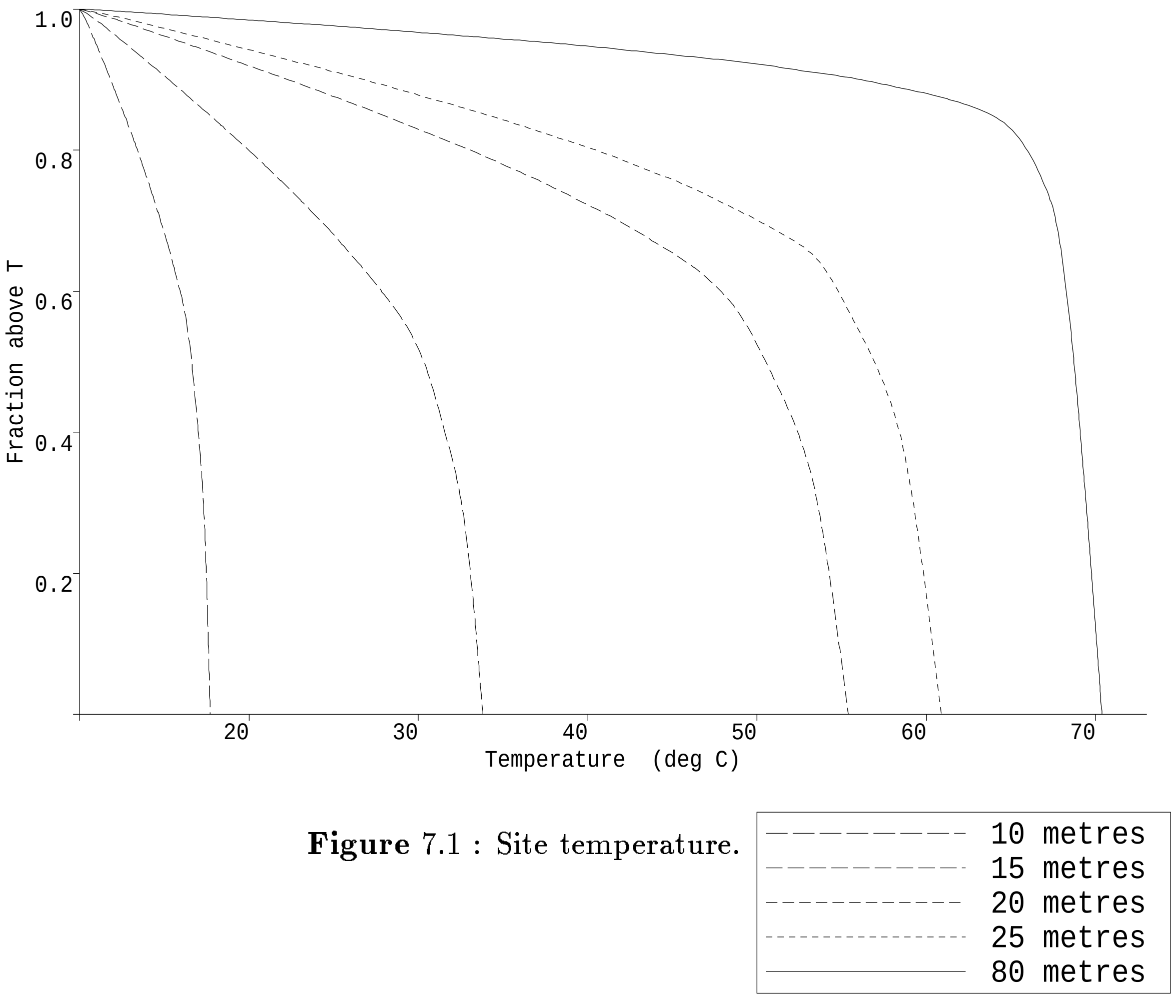


Figure 7.1 : Site temperature.

Figure 7.1 shows (for a particular set of parameters) the fraction of a site which can rise above a certain temperature versus the total depth of the site (assuming unlimited substrate and time). For instance, under the assumed gas production rate, under half of a 15 m deep site can get hotter than 30 °C, whereas 90% of an identical 25 m deep landfill will exceed this temperature (and the deeper site will approach it significantly faster).

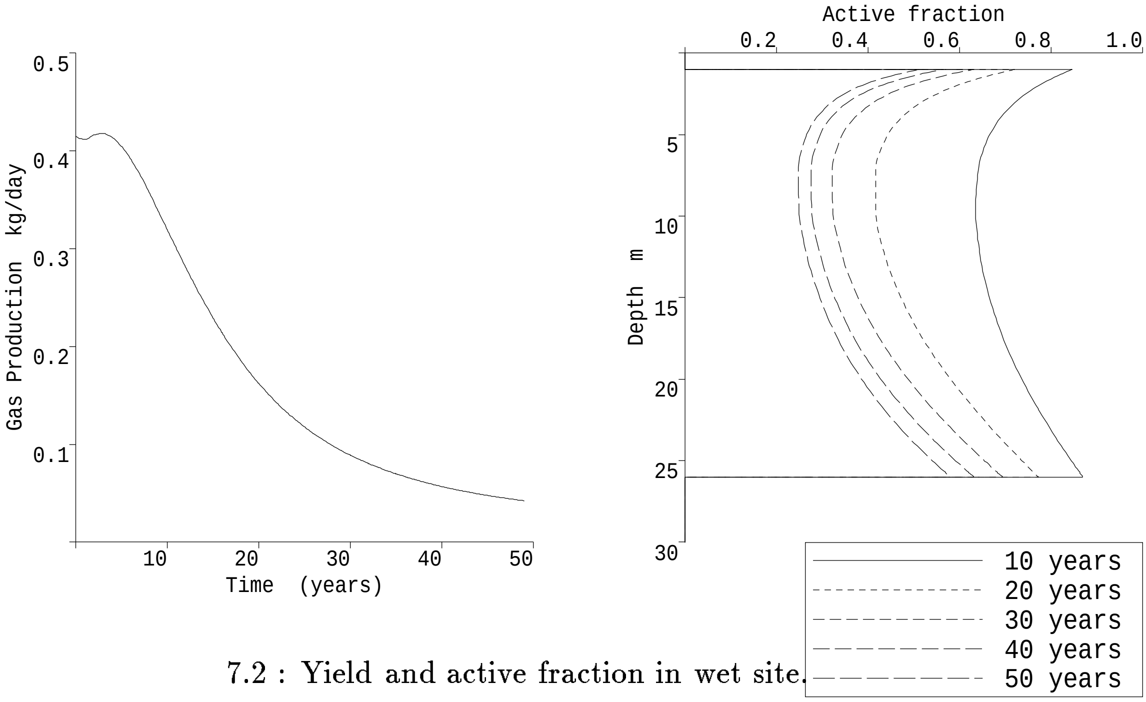
Consideration of these simulation results (together with others in the main report) leads us to recommend that sites should have a minimum depth of 15 m, and preferably be deeper than 20 m.

7.4 Long-term Comparison of Wet and Dry Sites.

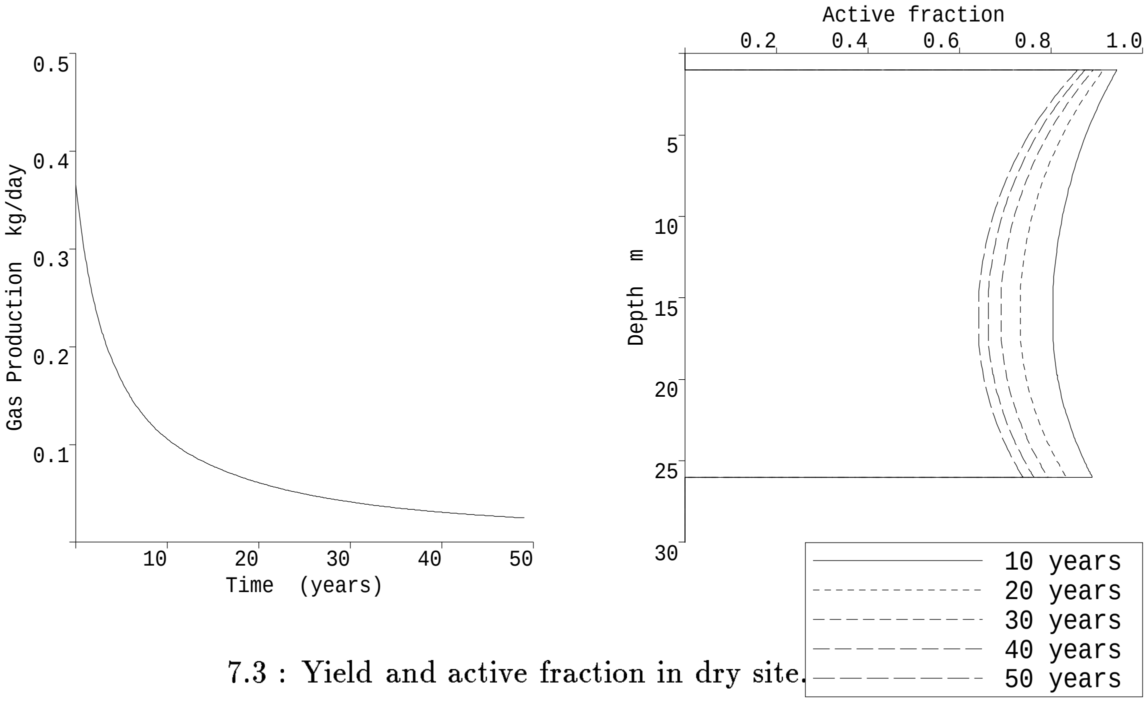
A key policy question in the management of landfills is whether (or to what degree) rainwater should be excluded from sites, and the model was used to investigate this. In order to investigate different strategies for controlling the moisture content of landfills we need to consider a combined model for the flows of heat, gas and moisture within the site. An age factor was incorporated to allow for the changes occurring in the waste due to decomposition.

The model predicts that wet sites undergo an initial rapid warming period, after which a high temperature is maintained until the degradation nears completion when the reaction rate and temperature fall. The model shows clearly that the cause of the drop in the activity of the site is the completion of the degradation. After 50 years the temperature and gas production in a dry site are similar to those in a wet site, but in this case the model indicates that it is the lack of water rather then the lack of degradable waste that halts the reaction, and adding water (which may happen accidentally if the cap cracks) restarts the processes once again.

Figures 7.2 and 7.3 illustrate this behaviour for two model sites which are identical in everything except initial moisture content and water management (the ‘dry’ site is assumed to be sufficiently well capped that there is no leakage through the surface). The active fraction quantifies the amount of the original waste which has not yet decomposed, and thus represents a reservoir of future gas production.



7.2 : Yield and active fraction in wet site.



7.3 : Yield and active fraction in dry site.

Dry landfills with their low levels of leachate and gas production pose fewer problems in their management than wet sites. However they offer little potential for power generation and remain active (even if only at a low level) for longer periods, thus requiring extra expenditure on monitoring. It is our opinion that it would be far easier, safer and (ultimately) less expensive to use wet landfills to process the waste now.

7.5 Enhancing Methane Production

It is usually economic factors that decide whether or not LFG is utilised or simply flared off.

A scheme is proposed for increasing gas production rates and accelerating site stabilization by partially re-circulating extracted gas. The simulations indicate that it should be possible to substantially raise the internal temperature, perhaps even to thermophilic levels. A field study is needed before this can be attempted at a real site.

This section proposed a scheme for exploiting the landfill gas at those sites where flows are below the current threshold for profitable electricity generation. The scheme involves using the heat produced by burning some of the gas to warm the landfill site itself, thus raising the internal temperature and thereby increasing the rate of gas production. By re-injecting unburnt heated LFG into the site, the anaerobic environment is not compromised and the quality of the gas yield is maintained.

In addition to controlling the temperature within the radius of influence of the injection well, the process allows the moisture level within a site to be regulated by introducing or excluding water vapour. The model predicts that the increased temperature and controlled moisture should enable the optimum environment for the methanogenic bacteria to be achieved and maintained. The faster reaction rates would give shorter completion times, and the large throughput of gas could be used to ‘scrub’ some of the pollutants out of the waste before they could reach the leachate.

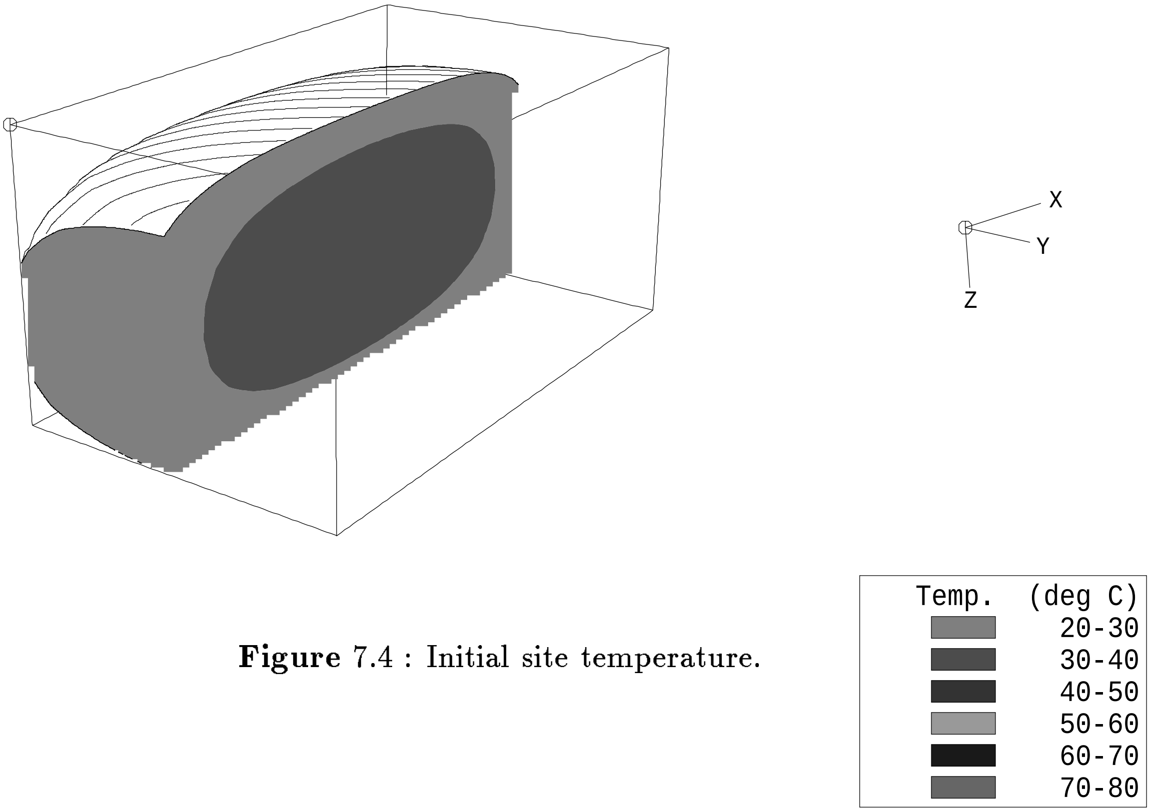


Figure 7.4 : Initial site temperature.

Figure 7.4 shows the initial steady temperature predicted for a hypothetical landfill cell (based on the site at Brogborough). Figure 7.5 demonstrates how the internal temperature is expected to change after the gas re-circulation scheme has been in operation for a year, raising the core temperature from 30–40 °C to about 60 °C.

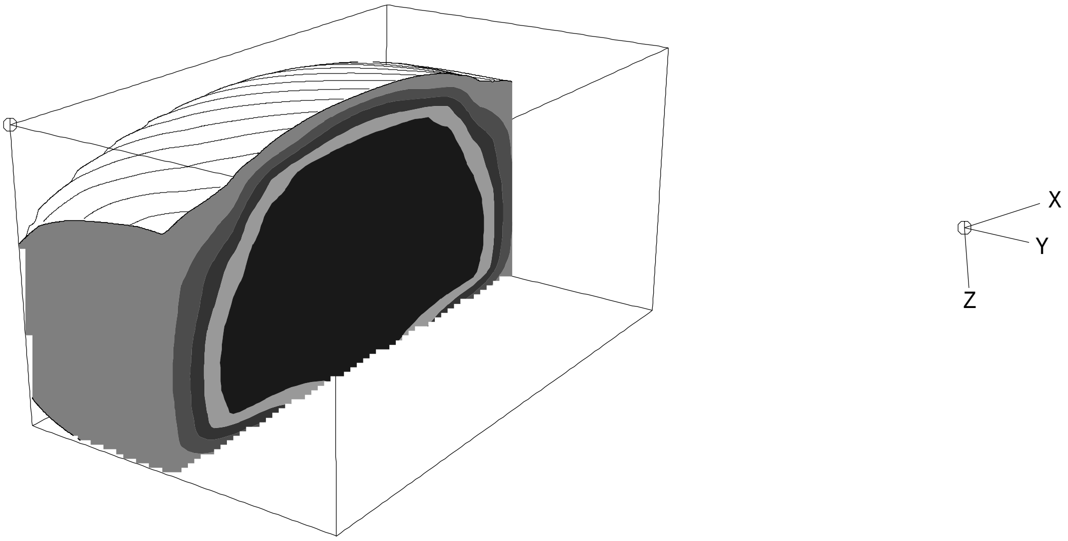


Figure 7.5 : Temperature after one year.

We feel that this scheme should be carried out on a trial basis after some smaller scale experiments. Firstly it is necessary to carry out pumping trials to investigate the forces required to re-inject gas into a landfill, and also some laboratory work is needed to assess the response of methanogens to rapidly rising temperatures and the possibility of establishing a thermophilic community.

Chapter 8 : Additional Topics.

8.1 Settlement.

Landfill settlement is an issue of growing importance to operators, and an initial aim of the project was to explain the major factors affecting its rate and magnitude and to produce a predictive model based on them. However despite the belief in the industry that good data exists, none of it is useful, since the only thing measured is the rate at which the surface height at a site decreases with time, and nothing is known of the extent to which interior layers have been compressed or displaced. This type of information on the internal deformation is required in order to understand how aging refuse responds to local applied loads, and is thus essential for predicting how a whole site will behave as time progresses.

As a preliminary step towards rectifying this dearth of information, an experimental determination of the bulk modulus of various types of fill is required. Ideally this should investigate several categories of waste and mixtures thereof, both fresh and decomposed, so that a table can be constructed relating the physical properties of waste to its composition. Such data could be used to develop a predictive model as originally envisaged, and a project has now been initiated by the DoE.

8.2 Doubly-Porous Media.

Several models for landfill moisture flow were compared, including a sophisticated approach based on a doubly-porous media formulation in which refuse is assumed to comprise two inter-connected systems of pores of greatly different sizes (the spaces between articles and the internal pores within them). It was concluded that, except during periods of sudden flooding, a basic single-media model represents the optimum balance between ease of parametrisation and accuracy.

Chapter 9 : Acknowledgements.

9.1 Official Disclaimer.

The opinions expressed in this summary are those of the author (Alan Young) and may not reflect those of the Department of the Environment. The results of this work may be used in the formulation of government policy, but at this stage they do not necessarily represent government policy.

9.2 Staff.

At the Mathematical Institute of Oxford University the staff involved with this project were Alan Young, Nigel J. Gay and Leslie C. Woods. At Aspinwall & Company the principal staff connected with this project have been David R. Davies, Philippa Towler, Brian Latham and Peter Young.

9.3 Acknowledgements.

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