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ESTIMATING THE POST-CLOSURE MANAGEMENT TIME FOR LANDFILLS CONTAINING TREATED MSW RESIDUES

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SUMMARY: The Landfill Directive will require the pre-treatment of MSW prior to landfilling. The removal of progressively increasing proportions of the biodegradable fractions from landfilled waste, and the UK Government's commitment to increase recycling of key waste fractions, will lead to an inevitable change, from the disposal of raw MSW, to the disposal of MSW treatment residues, to landfill. This will undoubtedly change the type and rate of emissions from landfills. The question that this research project has sought to answer is "how long will active management be required for different MSW treatment residues?" The term equilibrium status has been used to define the end point beyond which management of wastes is no longer necessary. Calculating the equilibrium status of waste involves an assessment of the landfill gas emissions, leachate quality and hydraulic status of the landfill. These key parameters change with time as the landfill evolves. Equally, the engineering performance of a site is also changing with the gradual degradation of the liner and capping systems. The question posed above is therefore not easily answered.

1 INTRODUCTION

One of the outcomes of adopting the Landfill Directive (Council of the European Union, 1999) for the UK will be a reduction in biodegradable municipal solid waste (MSW) being landfilled. In order to achieve the diversion targets and pre-treatment requirements there will need to be a major shift in the way MSW is managed. It is likely that, with regards to MSW, there will be a growth in landfills accepting the residual components or residues of various treatment systems.

This research contract has looked at the range of possible treatment processes that the waste management industry in the UK may adopt and the composition of those residues that need to be landfilled. The research has identified some knowledge gaps in relation to contaminant flows through some of the processes that have been identified.

The development of the waste treatment "option" list was based on a prediction of the likely processes that will be adopted to allow the UK to meet the various objectives. Using these options (listed in Section 2) we can then begin to consider the type and properties of the residues generated by these treatment options. Armed with this information we can begin to assess the length of time needed for landfills accepting these residues to achieve equilibrium status. Equilibrium status is that time in a landfill's life when no further management or intervention is required. It occurs when the emissions (gas or leachate) are at levels that natural processes can readily cope with, accepting that total containment and zero emission is unrealistic. That is not to say that, for example, the leachate meets some quality standard; rather the leachate will be at a concentration that allows the processes of natural attenuation to deal effectively with the residual pollutant load. A working definition, that additionally embodies the principles of sustainability, is:

"when emissions of contaminants are at a rate that allows full natural attenuation without further intervention or management beyond a post-closure period that is measured in decades rather than centuries."

This paper will therefore address the waste treatment options that are likely to be adopted, the likely changes in waste composition, and the properties for the residuals going to landfill, the future management options for landfills and the drivers to achieve equilibrium status. This must include leachate, gas and the overall hydraulic equilibrium of the landfill. Settlement has not been explicitly dealt with as it is likely that this process will be linked to the overall stabilisation of the landfill.

2 WASTE PROCESSES TO ACHIEVE BIODEGRADABLE DIVERSION TARGETS

As a precursor to understanding the likely changes in waste properties and composition, it is necessary to examine the likely process flows that could be adopted by the waste management industry and the possible range of residuals that would need to be committed for landfilling. This includes both material for which landfill is expected to provide the main solution and for out-of-specification material that will need to be landfilled. The identified processes include:

- Mechanical biological treatment (MBT) incorporating anaerobic digestion;
- MBT incorporating composting;
- MBT product - where MBT results in a product that should have been useable but is unable to be sold or used and must be disposed to landfill;
- Refuse derived fuel (RDF) dedicated incineration - produced by mechanical sorting only;
- RDF - Floc only - where floc cannot be sold for incineration and is destined to landfill;
- RDF/MBT - where RDF results from a more sophisticated MBT process;
- Energy from waste (mass burn and fluidised bed); and
- Advanced thermal treatment (pyrolysis/gasification).

There is an expectation that each of these processes will result in at least one residue that will need to be landfilled. The processing of waste, be it mechanical, thermal or biological, or perhaps simply the removal of recyclable materials from the waste stream will change the leaching characteristics of the waste, its physical properties (e.g. density) and its landfill gas generation potential.

3 MODELLING OF EMISSIONS

Leachates from landfills accepting raw MSW are reasonably well understood notwithstanding the fact that there are some regional and site-specific differences. Conventional (raw) MSW was taken as a starting point and bench mark within the assessment process. The main contaminants modelled are those that are included in the Waste Acceptance Criteria (WAC) (Council of the European Union, 2003) although the inclusion of ammoniacal nitrogen is necessary as for some waste streams it will continue to represent one of the key contaminants in relation to its concentration in leachate relative to its environmental standard in water.

Modelling has been undertaken using an implementation of the LandSim 2.5 algorithms (Drury *et al*. 2003) within GoldSim. It would have been technically feasible to use LandSim but it does not allow the management period of the landfill to be set as a stochastic variable. Furthermore, the post processing capabilities of GoldSim allow results mining (the ability to interrogate the time history of each variable and intermediately calculated value within an entire simulation) and multivariate analyses, essential in order to correlate the required length of managed aftercare with long-term groundwater quality variations.

The model allows a number of phases of the life-cycle of a landfill to be assessed. The first phase is the filling phase. During this period, the waste is likely to be exposed to high levels of infiltration. Engineered barrier systems and leachate management systems are expected to be working within design limits. Landfill gas will be managed, albeit that collection of gas from the operational phase has not been included as this is rarely undertaken in practice. The next phase is the managed post closure period. At the start of this period the site will have been capped. Leachate management will be continuing and most of the engineering systems will be working. Some degradation of the liner system may be occurring with decreased functionality becoming more severe with time. The landfill gas collection system will be working well and the capping will allow a high proportion of the landfill gas to be collected. The final phase of the landfill will cover the post managed closure period. During this period there is no management of leachate or landfill gas. Engineered systems (such as liners and caps) will continue to degrade but the cessation of leachate management may well result in a build-up of leachate and a corresponding increase in leakage.

Within the model the management period is defined as a stochastic variable and is allowed to vary between 3 years and 2050 years. During each iteration (each using a different management period) the maximum groundwater concentration for each of the contaminants modelled is recorded and then plotted against management time. In this way the management time period needed to achieve the water quality standard (typically taken to be the EC Drinking Water Directive, 1998) can be interpolated. Any result showing a contaminant requiring greater than a 2000 year management period was simply recorded as >2000 with no attempt at defining the value further.

In all cases the landfills were assumed to be composite lined landfills utilising an HDPE capping system. Infiltration into the open waste mass prior to capping is assumed to be 250 mm/y, reducing to 50 mm/y on capping and gradually increasing to 140 mm/y to simulate the degradation of the cap from 250 to 1000 years. Leachate levels are controlled to 1m throughout the management period but allowed to vary once management ceases based on the water balance model incorporated into LandSim 2.5.

The receptors for the various contaminants were selected as the down gradient boundary for retarded List II substances and 200 m down gradient for mobile List II and non-listed substances. The base of the unsaturated zone is the compliance point for List I substances as dictated by the Groundwater Directive.

Conservative retardation factors, identical to those used for the derivation of WAC, have been used (Hjelmar *et al*., 2001, Hall, 2002). Ammoniacal nitrogen was not included in the WAC. A typical value of 0.5 l/kg has therefore been used. Biodegradation of ammoniacal nitrogen in the unsaturated and aquifer pathways has not been assumed.

It should be noted that the leachate concentrations within the landfill at the end of the selected management period is not necessarily benign. However, the contamination that is left in the site at the end of the management period is at a level that would allow natural processes to attenuate and dilute to the required standards. The model has assumed that leachate pumping continued throughout the management period but ceased at the end of the period. Leachate levels are expected to increase as a result of increased cap infiltration due to deterioration of the cap even though the liner system may also be in the process of degrading. These processes will result in a marked increase in the rate of leakage and hence a step change in the flux of contamination entering the unsaturated zone. It should be noted that this should not result in an increase in the concentration of contaminants in the unsaturated zone, but will increase the rate of discharge and contaminant velocity in the unsaturated zone. This will also result in less dilution within the aquifer and a subsequent increase in aquifer concentrations.

Various management options have also been investigated including the simulation of flushing the landfill with the equivalent of an additional 200 to 500 mm/y (of fresh water or recirculated treated leachate). This recirculation ceases when management control ends.

4 WASTE PROPERTIES

4.1 Leachate Source Term

Data relating to initial leachate concentrations has come from a variety of sources. For the benchmarking studies (using current typical raw MSW landfills) data are largely based on LandSim default concentrations, which in turn are based on Robinson (1995). For the MBT and incinerator bottom ash, data have been derived from research by Robinson *et al*. (2004a+b).

The initial leachate concentrations used for the modelling MSW and treated MSW (or closely allied wastes) conducted to date are shown in Table 1, and incinerator bottom ash (both raw and treated) is shown in Table 2.

4.2 Notable Waste Properties

In addition to the collation of leachate source term data, this research contract has also examined other waste properties that may affect the determination of equilibrium status. Landfill gas potential is an important issue and is being dealt with during the research but is not reported here. Other properties of waste were noted where they may impact management of the waste.

Work by Kuehle-Weidemeier (2004) shows the relationship between MBT residue permeability and applied load. Results range from 3×10^{-5} m/s for waste under a load of 50 kN/m^2 to 6×10^{-9} m/s with an applied load of 550 kN/m^2. These values are comparable to those derived for raw MSW. Hydraulic conductivities in all but the very lowest end of this range would not preclude the ability to be able to flush the landfills at the rates noted above.

The increase in density needs to be taken into account in the leaching process as this is driven (within the model) on a liquid/solid ratio basis and clearly for the same volume of landfill, a larger mass of MBT waste and a subsequent higher mass of contaminants, can be deposited. The same applies for incinerator bottom ash which will also have a density greater than that of raw MSW.

Table 1: Initial leachate concentrations (mg/l) for MSW and allied waste streams

Waste Stream	MSW	MSOR	MBT	MBT
Treatment	Raw		Intensive	Medium
Arsenic (As)	0.013	0.06	0.006	0.055
Cadmium (Cd)	0.0101	0.0005	0.003	0.05
Chromium (Cr)	0.075	5	0.1	0.3
Copper (Cu)	0.03	0.5	0.2	0.35
Mercury (Hg)	8.91E-05	0.0001	0.0001	0.001
Lead (Pb)	0.17	0.05	0.04	0.24
Nickel (Ni)	0.012	0.3	0.05	0.4
Zinc (Zn)	0.25	0.3	0.1	1.5
Sulphate (SO_4)	263	400	500	2500
Chloride (Cl)	1466	3500	2000	4500
Ammoniacal Nitrogen (NH_4)	495	4000	200	550

Notes to Table

No reliable data from MSW Sites for Sb, Ba, Mo, Se or F
MSOR – Mechanically Sorted Organic Residues.

The implications of waste densities and (where available) differing leaching rates (kappa values) has been taken into account in the modelling undertaken as part of this study.

This will also affect landfill gas generation. While the amount of degradable carbon may well be reduced during various composting or anaerobic digestion processes, the increase in density of the residues will result in more mass of waste per m^3 of void space. The impact of the increased density has therefore be specifically addressed in the assessment.

5 MODEL RESULTS

Figure 1 shows the relationship between receptor concentration and management time for chloride for a non-flushed landfill that has accepted predominantly raw MSW. It is clear that the relationship between the length of management time and the reduction of receptor concentrations is not linear. Each point on the graph is the result of modelling a different management period (between 3 and 2050 years) using a logarithmic sampling scale. In this case the relevant water quality standard (WQS) for chloride is 250 mg/l and this is achieved with a management period of 40 years.

It must be stressed that the chloride concentration of leachate at this time would not meet the WQS, as at 40 years it was predicted to be 1275 mg/l. With the cessation of leachate management there is an expectation that leachate treatment (and removal) also cease, leachate levels will rise, and leakage will increase in line with the increased leachate head. In the example above, the groundwater concentration at the receptor did not reach 250 mg/l at 40 years. The maximum concentration was modelled to occur at 156 years, some 116 years after the management of the site ceased. Figure 2 shows a similar relationship for lead. In this case management period required to reach equilibrium status was 340 years. The same factors remain important. The leachate concentration at this time was 0.12 mg/l (some twelve times the WQS). The actual time take for the maximum groundwater concentration to be realised was 4000 years. There is therefore a large disjoint between the time when management of leachate ceases and the time when the maximum concentrations in groundwater could occur.

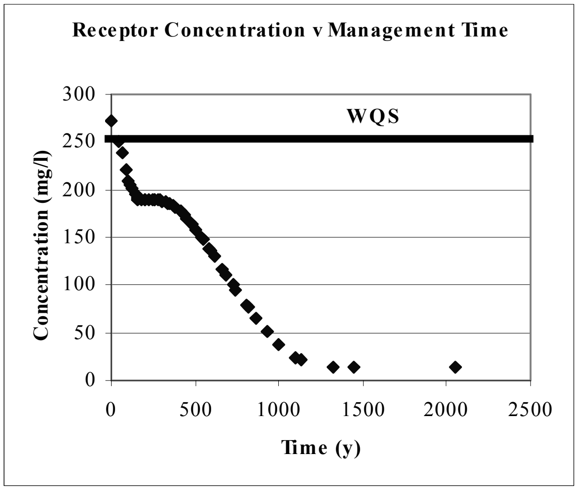

Figure 1 - Receptor concentration verses length of management time (Cl)

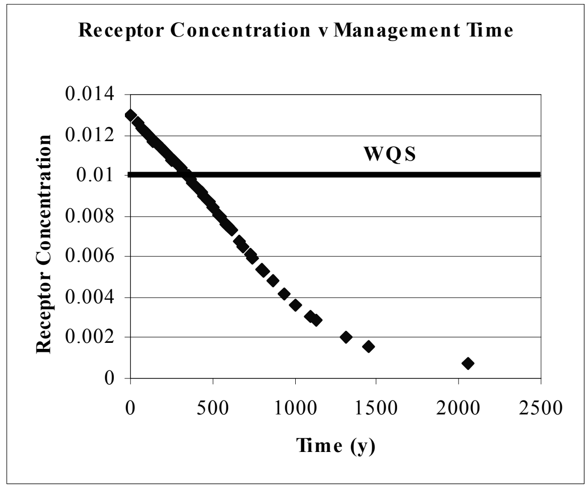

Figure 2 - Receptor concentration verses length of management time (Pb)

Tables 3 and 4 show a summary of the results of the modelling exercise simply indicating the number of years for each waste stream, each landfill management option and each species required to achieve equilibrium status. For each scenario the model has been run using what might be regarded as a standard management option (i.e. the waste remains uncapped during the filling sequence and is then capped). We have also modelled a scenario where infiltration is increased during the management period. Whether this is achieved by irrigation beneath the cap, not having a cap, removing the cap, or via treated leachate recirculation is, to an extent, not important from the modelling perspective, although we must not lose sight of the need to manage landfill gas for some of the waste streams.

Table 2: Initial leachate concentrations for MSW incinerator ash

Waste Stream	Incinerator Bottom Ash		
Treatment	Untreated	Carbonated	Acid Treated
Antimony (Sb)	0.025	0.05	0.16
Arsenic (As)	0.001	0.001	0.005
Barium (Ba)	1	0.1	0.3
Cadmium (Cd)	0.001	0.001	0.01
Chromium (Cr)	0.01	0.02	0.03
Copper (Cu)	10	1	4
Mercury (Hg)	0	0	0
Lead (Pb)	5	0.03	0.1
Molybdenum (Mo)	0.3	0.1	0.15
Nickel (Ni)	0.1	0.05	0.05
Zinc (Zn)	0.5	0.08	0.1
Selenium (Se)	0.001	0.05	0.015
Fluoride (F)	0	0	0
Sulphate (SO_4)	500	2250	3500
Chloride (Cl)	2200	3000	3000
Ammoniacal Nitrogen (NH_4)	15	3	15

True equilibrium status for the landfill is only achieved after each and every contaminant has reached equilibrium status. The final row in each table picks up the longest period defined by any species within the landfill and therefore the one that equilibrium status is dependant upon. Be aware that the list of species modelled is by no means all embracing and no organic species have, as yet, been modelled.

Table 3 examines raw MSW and residues from mechanical and biological treatments. Included within the results are the basic scenario and examples showing the effects of increased flushing with fresh water or treated leachate. Note that the analyses of leachate used within the source term model are less extensive than that used for incinerator bottom ash.

The option of disposing of raw MSW to landfill is unlikely to remain as the requirements of the Landfill Directive seek to reduce the volume of biodegradable MSW being disposed of to landfill. The flushed raw MSW meets the criteria of stabilisation at 40 years, subject to each of the leachate species being present at or below their average UK concentrations.

At this stage is it unlikely that landfill gas generation would have ceased, so the meeting of equilibrium status would need to be delayed until gas generation tailed off.

MSOR (mechanically separated organic residues) generates a waste that is high in contaminants and has a high ammonia loading. As such its stabilisation time (without flushing) is high and even with flushing, ammonia remains a problem as does arsenic and chromium. MBT waste may meet part of the MSW biodegradable waste targets and is a method of waste treatment that would appear to be gaining favour in the UK and other Member States.

Table 3: Modelling results (required number of years of site management)

Waste Type	**Raw MSW**	**Raw MSW**	**MSOR**	**MSOR**	**MBT**	**MBT**	**MBT**	**MBT**
Treatment	**None**	**None**	**None**	**None**	**Medium**	**Medium**	**Intense**	**Intense**
Flushing	**None**	**200 mm/y**	**none**	**500 mm/y**	**none**	**200 mm/y**	**none**	**200 mm/y**
Arsenic (As)	<3	<3	>2000	1000	>2000	1072	<3	<3
Cadmium (Cd)	<3	<3	<3	<3	700	183	<3	<3
Chromium (Cr)	<3	<3	1600	300	<3	<3	<3	<3
Copper (Cu)	<3	<3	50		<3	<3	<3	<3
Mercury (Hg)	<3	<3	<3	<3	<3	<3	<3	<3
Lead (Pb)	360	40	<3	<3	630	146	<3	<3
Nickel (Ni)	<3	<3	98	<3	410	76	<3	<3
Zinc (Zn)	<3	<3	<3	<3	550	125	<3	<3
Sulphate (SO_4)	<3	<3	<3	<3	980	135	<3	<3
Chloride (Cl)	40	4	700	40	790	125	367	40
Ammoniacal Nitrogen (NH_4)	<3	<3	1275	71	<3	<3	<3	<3
Maximum Management Period Required in Scenario	360	40	>2000	1000	>2000	1072	367	40

Two cases have been examined, one with medium intensity composting and one with highly intensive composting. Both have been subjected to the base scenario and a flushing scenario. The base case of both falls far short of the basic requirements of equilibrium status within decades. However, the intense composting option would appear to create a scenario where equilibrium status can be achieved.

The final set of results presented in this paper relate to incinerator bottom ash (raw and subjected to various treatments). Antimony, copper, chloride and sulphate appear to be the main controls in achieving equilibrium status of this waste stream irrespective of the treatment type. Flushing at higher flushing rates (500 mm/y) fails to make a significant reduction in the management period needed. It may be that the source term used has been selected with conservatism and that a greater familiarity with the material will generate lower mean values of the key contaminants. What is clear is that bottom ash on its own will remain a challenge. Adding fly ash to the bottom ash will make the situation worse.

As part of the study, the leachate concentrations at the end of the predicted management period were examined. No simple picture emerged to suggest what the leachate quality needed to be prior to the cessation of management. The reality is that where waste treatment or landfill management allows a shorter management period, higher acceptable residual concentration of leachate results. This is because the model includes the degradation of the engineering systems and the earlier the site reaches equilibrium, the better the liner system will be functioning. The flux of leachate that could migrate from the site increases with time as the liner and cap degrade. The more rapid the stabilisation process, the more intact the liner system is when completion is achieved. This will have implications for the timing of planned enhanced stabilisation of wastes – the earlier it is undertaken within the life cycle of the landfill, the better.

6 CONCLUSIONS

The key findings of this study are as follows:

- Waste pretreatment will not, on its own, deliver a sustainable landfill;
- Active flushing of landfilled residues will offer one means of achieving an early closure of modern landfills;
- Many waste treatment technologies increase the density of wastes thereby increasing the amount of flushing required to achieve the same liquid solid ratio;
- Landfilled incinerator residues appear to require the longest management time;
- Intensively treated MBT residues require the shortest management periods;
- Although not reported in this paper, leachate will generally require a longer period of management than landfill gas;
- Leachate quality in a completed landfill need not meet a specific water quality standard as dilution and attenuation will reduce the contaminant concentrations in groundwater; and
- Early stabilisation of wastes is advantageous as there is a higher probability that the engineering systems that must be relied upon are still functioning.

The waste industry needs to start to take on board the issues of sustainability and to plan the closure of their new landfills at the beginning of the permitting process. Regulators will need to encourage innovative approaches to waste stabilisation and insist that sites accepting residues of MSW treatment have a properly funded aftercare period through to completion.

Table 4: Incinerator bottom ash (required number of years of site management)

Waste Type	Bottom Ash	Bottom Ash	Bottom Ash	Bottom Ash	Bottom Ash	Bottom Ash
Treatment	**None**	**None**	**Carbonated**	**Carbonated**	**Acid Treated**	**Acid Treated**
Flushing	**None**	**500 mm/y**	**none**	**500 mm/y**	**none**	**500 mm/y**
Antimony Sb	1950	310	>2000	900	>2000	1150
Arsenic As	<3	<3	<3	<3	<3	<3
Barium Ba	<3	<3	<3	<3	<3	<3
Cadmium Cd	<3	<3	<3	<3	150	<3
Chromium Cr	<3	<3	<3	<3	<3	<3
Copper Cu	>2000	340	980	125	1500	215
Lead Pb	>2000	415	<3	<3	730	80
Molybdenum Mo	550	20	<3	<3	<3	<3
Nickel Ni	<3	<3	<3	<3	<3	<3
Zinc Zn	420	30	<3	<3	<3	<3
Selenium Se	<3	<3	<3	<3	<3	<3
Fluoride F	<3	<3	n/a	n/a	n/a	n/a
Sulphate SO_4	<3	<3	1344	116	1500	158
Chloride Cl	860	40	1020	71	1020	60
Ammoniacal Nitrogen NH_4	<3	<3	<3	<3	<3	<3
Maximum Management Period Required	**>2000**	**415**	**>2000**	**900**	**>2000**	**1150**

Research needs to be undertaken to see if the most problematic contaminants within MSW and its various treatment residues can be removed and alternate disposal routes or alternate treatment developed for these materials. Indications from the main report upon which this paper is based suggest that significant improvements could be made to the sustainability of landfills by the separate collection and disposal of hazardous household wastes.

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Estimating the post-closure management time for landfills containing treated MSW residues.

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