SUSTAINABLE LANDFILL IN THE UK:

A REVIEW OF CURRENT KNOWLEDGE AND

OUTSTANDING R & D NEEDS

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DEFINING SUSTAINABLE LANDFILL

1. To achieve sustainable landfill it must first be defined.

2. The definition requires two components, firstly a statement of broad environmental principles, defining what end point is to be achieved ('Final Storage Quality') and the timescale for achieving it. These qualitative objectives must then be expressed in the form of quantitative technical criteria that can be used for regulation. The former provide the driving force and represent the value judgements made by society. The technical criteria are then necessary as a practical tool for implementing the concept.

3. The following principles, from Switzerland, provide one of the earliest (1986) and clearest statements of the broad objectives and have formed the basis for much of the discussion in the UK in recent years:

   - Each generation should manage its wastes to a status of Final Storage Quality;

   - Final Storage Quality: any emissions to the environment to be acceptable without further treatment;

   - One generation = 30 years.

   Definitions in current UK official guidance are similar to these, but are stated rather more equivocally, particularly regarding the timescale.

4. Technical criteria for final storage quality (FSQ) may encompass one or all of:

   - solid waste characteristics;

   - gas quality and gas emission rates;

   - leachate quality.

5. In the UK, WMP26A sets out FSQ levels for solid waste characteristics, based on its potential to degrade. The criteria are restricted to non-hazardous wastes and do not address other characteristics such as leachable metals. WMP26A also sets levels for gas quality and emission rates. It does not set FSQ levels for leachate quality but instead advises a site-specific approach based on the characteristics of the local environment.

6. The solid waste and gas criteria in WMP26A require degradation of more than 99.9% of the gas potential in typical MSW, from ~$200m^3$LFG/t down to less than $0.1m^3CH_4$/dry tonne. No information is given on the derivation of this target or any associated risk assessment.

7. Other countries have not set FSQ criteria and appear not to have addressed the problem. Rather they have concentrated on developing landfill acceptance criteria for pre-treated wastes. These are not the same, conceptually, as FSQ criteria. In Germany for example, a gas potential of $20m^3$/t has been proposed as an acceptance criterion for composted wastes. This represents only 90% degradation of MSW and when landfilled in bulk, gas and leachate management may still be needed.

8. For leachate, it has been assumed in this report that FSQ levels will be similar to the limits set in discharge consents for leachate treatment plants discharging to surface waters. Comparison of these limits with typical concentrations and raw leachate indicates the likely dilution needed to reach FSQ. The dilution factors thus derived are:

chloride	6 - 12
NH_3-N	20 - 400
BOD	2 - 50

COD	10 - 50
Fe	1 - 20

This shows ammonia to be the controlling parameter, with typically two orders of magnitude dilution of the landfill required (i.e. 99% removal).

9. For other types of landfill the dilution factors and the controlling parameter may differ. For example, chloride may be the controlling parameter at landfills for incinerator ash. For treated hazardous wastes there is very little published information from which to infer probable controlling parameters and dilution (flushing) requirements.

ACHIEVING SUSTAINABLE LANDFILL

10. Achieving sustainable landfill (i.e. reaching FSQ in less than 30 years) requires:

either, waste pre-treatment to FSQ before landfilling;
or, degrading and flushing the wastes within the landfill, at a sufficiently high rate.

11. Pre-treatment technologies currently in common use do not produce FSQ residues:

- Incineration of MSW produces ash leachates with 10,000 - 20,000mg/l of chloride and air pollution control residues that leach high concentrations of toxic metals.

- Composting of MSW organics produces residues that leach similar concentrations of non-degradable COD to those found in methanogenic leachate, and that may have a gas potential up to $20m^3/t$.

- Conventional liquid waste treatment plants produce sludges that are physically unstable and that can leach high concentrations of TOC, including phenols.

12. There is no documented case, to date, of untreated wastes in landfills (other than inert wastes) being taken to FSQ, regardless of timescale.

13. The current status of knowledge on the promotion of decomposition of degradable wastes and the flushing of soluble pollutants is summarised in the table below. There seems every likelihood that a high proportion of waste degradation can be achieved in very much less than 30 years. An aerobic phase following active methane extraction appears to offer a promising route to accelerate the final stages of degradation.

The current state of knowledge on the flushing of soluble pollutants from landfills is summarised in the table below. It remains unclear whether it will be practicable to flush MSW landfills to the necessary dilution, once degradation and settlement have occurred. Heterogeneity and the low permeability of the wastes are the main concerns. It is, however, clear that depth will be an important factor and that the chances of success appear best for landfills less than ~20m deep.

14. A significant volume of research has been directed at promoting faster degradation and flushing, and is reviewed in the report. This research effort is continuing, with funding coming mainly from the Environment Agency, EPSRC and from Landfill Tax.

A summary listing of current and recent research projects in the UK is shown in Table 1 of the report (pages 2/3).

15. Additional research needs identified in the report are shown in Table 10 of the report (page 22), with the most urgent shown in bold type. The majority are not being addressed by any of the projects known to be underway or planned.

Promotion of decomposition [Target 99%]

What we know

- Key factors are: moisture content, temperature, inoculation and recirculation
- Brogborough and LF2000 showed acceleration to 20-60m^3/t.a easily achievable
- Yolo (USA) and VAM (Holland) test cells show we can reach ~140m^3/t in ~2 years, even with crude MSW
- Point at which gas rate slows to uneconomic level = f (temperature)
- At T>30^{o}C we may get 90% of gas at >10m^3/t.a
- Every likelihood that we can reach BMP <20m^3/t in 5 years (i.e. >90% degradation)
- No evidence of salts or NH_3-N reaching inhibitory levels as a result of recirculation
- In situ aeration can lead to huge reduction in NH_3-N
- In situ aeration has negligible effect on soluble hard COD

What we don't know

- Last third of gas curve is very poorly characterised at large scale
- Characteristics of solid residues when gas, leachate and BMP targets are met
- Nature and concentration of non-degradable COD from a flushing bioreactor landfill
- Aerobic post-treatment:
  - optimum point to begin aeration
  - efficiency at full scale
  - quality/odour of off-gas
  - how low we can get TKN
  - what effects on other leachate parameters (COD, BOD, SO_4, pH, metals)
  - any temperature problems

Flushing of pollutants

What we know

- MSW lysimeters and landfills appear to behave like completely mixed reactors
- Explained by 2-domain or 3-domain models: rapid flow in channels and rapid equilibration between mobile and non-mobile water
- Positive implications for flushing
- 7 BV (3-5m^3/tonne) needed for NH_3-N; 2-4 BV (1-2m^3/tonne) needed for COD
- Re-injection systems susceptible to chemical and biological clogging
- Waste K may be too low for required flushing rates, at depths >20m

What we don't know

- Hydraulic behaviour of highly degraded wastes under high compaction
- Hydraulic behaviour of treated hazardous wastes
- Effects of other hydraulic barriers (e.g. cover layers)
- Optimum design of liquid re-injection systems
- Effects of settlement on leachate re-injection systems
- Actual flushing efficiency achievable at large scale
- Extent of flushing required for hazardous waste landfills

1. INTRODUCTION

This study has been funded jointly by two Environmental Bodies, the Norlands Foundation and ESART. It takes as a backdrop the comprehensive examination of the flushing bioreactor concept undertaken by a working group of the Institute of Wastes Management. Their report was published recently (IWM, 1999), following three years of activity. The purpose of the present study is not to replicate the IWM study. Its specific objectives are to provide:

- An updated summary of R & D and of current knowledge related to sustainable landfill (much of the work in the IWM study dates from ~1996-7);

- An interpretation of the issues involved in sustainable landfilling, taking a broader view than simply the flushing bioreactor, which is aimed primarily at degradable wastes;

- Identification of gaps in our knowledge;

- Recommendations for the direction of future research.

2. RECENT, CURRENT AND PLANNED R & D IN THE UK

A similar format has been used to that used by the IWM Working Group, which, in 1996, published a summary of R & D into sustainable landfill. Up-dated information has been obtained from discussions with EA and EPSRC project officers; with research contractors directly; with ENTRUST and with some Environmental Bodies; and by analysis of ENTRUST's database of active projects. A listing of relevant projects is given in Table 1. More detailed information on each project is given in a matrix format in Appendix 1 under the following headings:

title
description
funding
participants
dates
techniques investigated
results to date
references

Most of the listed projects are funded by the Environment Agency or EPSRC but an increasing proportion are now funded wholly or partly by Environmental Bodies.

Table 1 reveals a steady progression of new projects, with at least eleven currently under way, ranging from theoretical studies to full-scale experiments at landfills. It identifies a further eleven landfill-related studies, funded by Environmental Bodies, some of which may be relevant to sustainable landfilling. No further information has been obtained about them yet, so they are not included in the matrix in Appendix 1.

In addition to the above, it is known that several landfill operators have begun in-house research projects, particularly on leachate recirculation. There is currently no way of collating and summarising these projects because they are not in the public domain and many are not formally structured. It may be possible via a future ESA or ESART initiative to attempt a survey of the extent and scope of these projects.

Table 1. SUMMARY OF UK RESEARCH RELEVANT TO SUSTAINABLE LANDFILL

[completed prior to 1996 IWM review;
completed since 1996;
started since 1996;]

1. LANDFILL STUDIES

1.1 Warm gas re-injection, Belfast: increase gas generation [Aspinwall]
1.2 Mucking, Essex: leachate recirculation: Phase 1: raise moisture to stimulate gas [WRc]
1.3 Mucking, Essex: leachate recirculation: Phase 2: [WRc]
1.4 Walpole, Somerset: leachate re-injection, wells vs stone pits; effect on gas flow [Chris Harries]
1.5 Trials of alternative daily covers [ADAS]
1.6 Effect of recirculation and new waste composition on settlement [BRE]

2. LARGE-SCALE TEST CELL STUDIES

2.1 Landfill 2000 test cells: accelerated stabilisation [WRc]
2.2 Brogborough test cells, Phase 1: degradation enhancement [AEA; Mouchel]
2.3 Brogborough test cells, Phase 2: recirculation hydraulics [Mouchel et al.]
2.4 Auchencarroch test cells, Strathclyde: recirculation [Glasgow Caledonian U]
2.5 Auchencarroch test cells, Strathclyde: recirculating nitrified leachate[Strathclyde U]

3. LABORATORY AND PILOT-SCALE STUDIES

3.1 Laboratory and field studies of drainage systems [Paksy, Powrie et al]
3.2 Total pollution load from domestic refuse [Beaven]
3.3 Denitrification and contaminant flushing in refuse [Knox]
3.4 Hydrogeological properties of waste, Phase 1 [Beaven]: K_v
3.5 Hydrogeological properties of waste, Phase 2 [Beaven]: K_h; degraded wastes.
3.6 Nitrogen balances in landfills [Watson Craik]
3.7 Biochemical Methane Potential test [MTD]
3.8 Long term fate of heavy metals [Atkins]
3.9 Gene probe for methanogenic DNA [CAMR+U of Liverpool]
3.10 Application of methane oxidation [MTD]

4. MODELLING, THEORETICAL AND REVIEW STUDIES

4.1 Sustainable landfill study [AERC]
4.2 Behaviour of fluids in landfills [Aspinwall]
4.3 Gas yield enhancement techniques [BJWManley]
4.4 Connon Bridge feasibility study [Aspinwall]
4.5 Review of landfill microbiology research [WRc/Archer]
4.6 Application of tracer studies for monitoring leachate recirculation [WRc]
4.7 Design and costing of a HRFB demonstration cell [Knox/Beaven]
4.8 Modelling use of vertical wells for landfill flushing [Beaven]
4.9 Use of pre-composting layer to accelerate methanogenesis [AEAT]
4.10 Linking degradation and flow models [U of Southampton: J White]
4.11 Stochastic modelling of landfill processes [Imperial College]
4.12 Deterministic modelling of biodegradation [Napier University, Edinburgh]

5. OTHER ACTIVE ENTRUST REGISTERED PROJECTS

5.1 Measure methane fluxes at 24 landfills [CMTC Environmental]
5.2 Review characteristics of bottom ash at UK landfills [Energy from Waste Foundation]
5.3 Distington odour study [Groundwork West Cumbria]
5.4 Odour control systems for landfill [North West Environmental Trust]
5.5 Identification of landfill impacts on surface water systems [Landtrust]
5.6 Computer simulation of methane production processes in landfill sites [EB Nationwide]
5.7 Horizontal wells for leachate control [SUnRISE]
5.8 Leachate attenuation in natural geological formations [SUnRISE] **cont'd…**
5.9 Computer model to estimate leachate production and site contamination history [Canford Environmental]

5.10 Research at Thackwood landfill: towards sustainable landfill practices [Environmental Waste and Policy Research Group]
5.11 Methane oxidation enhancement [Aspinwall; funding from SITA Trust; starts late 1999]
5.12 Modellling of leachate production [Imperial College; funding from SITA Trust; start 2000]

6. ENVIRONMENT AGENCY PLANNED PROJECTS

6.1 P1B(99)03 Waste sampling and acceptance criteria [compliance with Landfill Directive]
6.2 P1C(00)04 Landfilling incinerator residues and hazardous wastes [generic title, no detail]
6.3 P1B(00)02 Impact of hydraulic conductivity of waste on accelerated stabilization [generic]
6.4 P1B(00)03 Maintenance, review and recommendations for the future of the Brogborough test cells: possible support for ESART initiative [generic]

3. CURRENT UNDERSTANDING OF THE ISSUES AND STATE OF KNOWLEDGE ON SUSTAINABLE LANDFILLING

The issues can be divided conveniently into two groups as follows:

DEFINING SUSTAINABLE LANDFILL
- Environmental principles/objectives
- Translation into technical criteria
  - solid waste characteristics
  - gas quality and emission rates
  - leachate quality

ACHIEVING SUSTAINABLE LANDFILL
- Achieving FSQ by pre-treatment before landfilling
- Promoting in situ decomposition of biowaste
- Flushing of pollutants from landfills
  - degraded biowaste
  - inorganic and hazardous wastes

These issues are discussed below.

3.1 Overall environmental principles and objectives

These have been most clearly and forcefully expressed outside the UK, but current UK guidance and policy statements are consistent with principles developed elsewhere. This is illustrated with examples shown in Table 2. The Brundtland definition of sustainable development has been widely accepted and embodies the concept of a ‘generation’ as the reference time frame. This concept was accepted by signatories at the Earth Summit in 1992, including the UK and other EU Member States. The Brundtland definition has subsequently been quoted as a guiding principle in successive UK Government policy documents on waste management (e.g. Cm3040, 1995). For principles and objectives specifically directed at landfill, those from Switzerland and Denmark, in Table 2, stand out for their simplicity and clarity. The Swiss definition was developed in 1986 Government Guidelines on Waste Management (Belevi and Baccini, 1989). The Austrian government adopted objectives identical to the Swiss in 1987. The Danish definition was contained in a Government Plan of Action for waste and recycling in 1992(Johanessen et al, 1993). In all three countries, a clear impact of these principles on the subsequent development of their waste management practices can be seen.

Table 2. Environmental principles/objectives: defining sustainable landfill

Brundtland (1987), on development in general
“...meets the needs of the present without compromising the ability of future generations to meet their own needs.”
Switzerland (1986)
• Each generation should manage its wastes to a status of Final Storage Quality
• Final Storage Quality: any emissions to the environment to be acceptable without further treatment
• One generation = 30 years
Denmark (1992)
• Each generation must take care of its own wastes
• No active management or monitoring should be needed after 30 years
UK, WMP26A & 26B (1993 & 1995)
• “...stabilised physically, chemically and biologically to such a degree that...post-closure controls, leachate management and gas removal systems are no longer required.”
• “...in equilibrium with its environment 30-50 years after cessation of filling

In the UK, similar principles can be found in current landfill guidance documents, namely Waste Management Papers 26A and 26B published in 1993 and 1995 respectively. The 'completion condition' that forms the central theme of WMP26A, is identical with the concept of Final Storage Quality (FSQ) i.e. the point when no further active management or monitoring is needed. However, WMP26B is, overall, ambivalent on the subject of the timescale for achieving completion, or FSQ. It states at paragraph 1.22:

"...the present generation should deal with the wastes it produces and not leave problems to be dealt with by future generations.......a generation is regarded as 30-50 years after the completion of the landfill operation."

Paragraph 1.26 of WMP26B also refers to minimising pollution control burdens for future generations, and the WMP discusses the flushing bioreactor concept for achieving this. However, neither WMP26B, nor any other UK Government policy document, makes it an overriding principle that completion criteria should be met within a generation. WMP26B recognises the practical uncertainties involved in flushing bioreactor landfills and effectively makes the principles of paragraph 1.22 optional (see schematic decision tree forming Figure 1.1 of WMP26B). As a result of this ambivalence in the UK guidance, the principle of a one generation timescale has had no impact so far on the selection of waste disposal methods, the design/operation of landfill, or on waste management planning or licensing. Achieving sustainable landfill in the UK is therefore hampered by the lack of sufficiently unequivocal guiding principles.

3.2 Technical criteria for completion, or Final Storage Quality

3.2.1 *Residual characteristics of solid wastes*

WMP26A suggests that leachate and gas monitoring could form the main basis for judging whether bioreactive wastes in landfills have reached completion, and that characterisation of solid samples may only be needed in a few cases. In practice it is very unlikely that a completion certificate would ever be issued without the confirmatory evidence from solid samples. WMP26A gives guidance on the parameters and levels that should be met, for biodegradable non-hazardous wastes. They are focused entirely on the potential to form gas, and fall into three categories:

(i) Direct measurement of degradable materials;
cellulose; hemicellulose [= acid digestible fibre ADF]

(ii) Measure surrogate parameters;
Loss on ignition, COD, TOC. These tests will include non-degradable materials such as plastics and lignin.

(iii) Measure gas emission under optimised conditions in the laboratory
Biochemical Methane Potential test (BMP)

Other parameters are not considered (e.g. leachable metals, releasable TKN, etc) and no completion criteria are considered for inorganic or hazardous wastes.

The levels suggested in WMP26A for indicators of degradation potential are summarised in Table 3. No derivation is given in WMP26A for the values proposed. The values for cellulose and surrogate parameters were in fact derived from data accumulated over many years by Prof. Bob Ham, in the USA. There is currently no basis for comparing them with FSQ criteria from other countries because most have concentrated their efforts to date on developing ***landfill acceptance criteria***. The latter have a different purpose and are considerably more relaxed than would be appropriate for FSQ criteria. This can be seen by reference to the BMP value in Table 3: compared with a typical expected BMP of ~200m^3 gas per wet tonne for fresh MSW, the completion criterion of 0.1m^3 CH_4/t represents >99.8% degradation. In contrast, landfill acceptance criteria for composted waste, currently under development in Germany and Austria, for example, are being set at 20m^{3}gas/t (e.g. Soyez et al., 1999; Binner et al., 1999). This is only ~90% degradation. Neither the UK values nor the German/Austrian values have been subjected to a validated risk assessment process, although Soyez et al.

(1999) refer to 'ecologically tolerable' levels. It therefore remains unclear whether the current UK value is either achievable or necessary. It may be that site-specific values, based on risk assessment, would be a more sensible approach.

The present UK position on residual waste characteristics is defined by WMP26A and it is clearly very limited in its scope, even for MSW. It does not address other wastes at all (e.g. MSW incinerator ash, biologically pre-treated wastes, hazardous wastes). These will become increasingly prevalent and therefore represent a gap in our knowledge.

Table 3. Completion criteria for solid biodegradable wastes, taken from WMP26A

VS <10% dry weight
unlikely to have the potential to generate significant amounts of methane
VS >25% dry weight
likely to have the potential to generate significant amounts of methane
VS 10-25% dry weight
likely to have significant methane potential if:
ADF >2.5% dry weight, or
ADF:VS ratio >0.25, or
BMP >0.1m^3CH_4 per dry tonne

3.2.2 *Gas criteria*

Landfill gas criteria in WMP26A are summarised in Table 4. As with the solid criteria, the stipulated gas emission rate is extremely low: assuming a waste depth of only 10m and a radius of influence of only 10m, the emission rate limits in Table 4 equate to a landfill gas generation rate of ~0.1m^3LFG/t.a. For more realistic depths and well spacings, the generation rate per tonne would be even lower. This may be compared with typical generation rates of 5-10m^3/t.a in UK landfills with active gas extraction. Thus, the completion criterion represents not more than 2% of a typical rate, at most. As with the solid waste criteria, no derivation or reference to a risk assessment is given in WMP26A. It remains unclear whether the guidance levels are overly cautious or could still represent a significant risk in some circumstances.

Table 4. Gas criteria for landfill completion, given in WMP26A

EITHER concentration based:
Less than specified trigger levels for at least 2 years (at least 4 sets of data)
CH_4 < 1%
CO_2 <1.5%
OR emission based:
Less than specified rate from any borehole, for at least 2 years
CH_4 < 15 litres/hour
CO_2 < 22 litres/hour
[NB this is roughly equivalent to <0.1m^3 LFG/t.]

3.2.3 *Leachate characteristics*

For leachate characteristics, WMP26A gives no fixed values but instead advises a risk assessment process for deriving site-specific values for completion: paragraph 4.4 states: "....completion criteria for leachate should be based on....the expected attenuation of leachate and its dilution on entering [controlled] waters." This is, in effect, the same basis on which discharge criteria for leachate treatment plants are derived. A knowledge of discharge criteria for current plants discharging to surface waters may therefore be used to derive an indicative range of completion criteria for the main leachate components and hence estimate the extent of flushing needed. Table 5 shows typical ranges of leachate concentrations for five parameters in MSW leachate, and typical discharge limits for them. The dilution required to meet the discharge limit is shown in the final column of Table 5, which thus indicates the extent of flushing needed for each parameter. The Table shows clearly that under most circumstances, ammoniacal nitrogen will require the greatest dilution and will therefore dictate the volume of flushing water required for a landfill receiving predominantly bioreactive wastes. Dilution by between 2 and 3 orders of magnitude will typically be necessary.

Table 5. Leachate dilution requirements for MSW landfills

component	typical MSW leachate [methanogenic] mg/l	typical discharge limit (inland) mg/l	dilution/reduction required
chloride	1500 - 3,000	250	6 - 12
NH_3-N	500 - 2,000	5 – 25	20 - 400
BOD	50 - 1,000	20	2 - 50
COD	1,000 - 5,000	125	10 - 50
Fe	10 - 50	3 – 10	1 - 20

NB Often no COD limit is specified. Value shown is from the Urban Wastewater Directive

For other types of landfill, other parameters may control the flushing requirement:

- In landfills receiving MSW incinerator bottom ash, chloride concentration in leachate may be in the range 10,000-20,000mg/l. Dilution by 40-80x may therefore be necessary in some inland locations. NH_3-N and COD are typically at far lower concentrations than in MSW leachates, and so chloride may be the controlling parameter.

- Composted MSW and composted MRF residuals may have much lower NH_3-N concentrations than landfills, but have similar concentrations of non-degradable COD. When landfilled in dedicated cells, COD may therefore become the controlling parameter, and the extent of flushing necessary would be less than for a conventional landfill.

- For hazardous waste landfills, we have very little information on leachate characteristics expected when the UK implements the Landfill Directive. From the published work that is known from sites elsewhere in Europe, (e.g. Hjelmar et al, 1995), high concentrations of chloride, sulphate and List I and List II organics may be present, any of which could be the controlling parameter. More comprehensive search and collation of leachate monitoring data from existing hazardous waste landfills is needed in order to identify the main parameters of concern and the likely magnitude of flushing that will be necessary.

3.3 Sustainable landfill by pre-treating to FSQ

Although the previous section concludes that FSQ criteria are not adequately defined for most wastes, it is still instructive to examine what is achieved by the forms of pre-treatment currently dominant as alternatives to direct landfilling.

3.3.1 *Incineration of MSW*

This is the most commonly advocated technical solution to the problems of managing the pollution potential caused by landfilling of crude MSW. The main residues from incineration are bottom ash and air pollution control (APC) residues. The organic and nitrogen pollution potential of the waste is dramatically reduced: leachate COD in the range 100-300mg/l and NH_3-N in the range 1 - 50mg/l are reported for bottom ash landfills (Hjelmar et al., 1989 and 1993). However, inorganic pollution potential is concentrated: chloride concentrations are typically in the range 10,000-20,000mg/l in leachate from bottom ash, while sulphate concentrations may be several thousand mg/l. In many locations, uncontrolled release of such a leachate would not be acceptable. Only in locations adjacent to saline waters could bottom ash be said to be at final storage quality. Elsewhere a considerable degree of flushing would be required to reach FSQ.

APC residues leach similarly high concentrations of chloride and, more importantly, they can leach high concentrations of heavy metals (Hjelmar et al, 1995). These include lead (up to 50mg/l), as well as Cd, Zn, Cr, Hg and As. High concentrations of lead may continue to be leached, up to high liquid:solid ratios. APC residues cannot be regarded as FSQ materials, under any circumstances. Processes to treat these residues, to reduce the solubility of the heavy metals, are only currently being developed (Hjelmar et al., 1999; Lundtorp et at., 1999). Although the results from pilot-scale trials are promising, the processes involve flushing the APC residues, generating ~3m^3 of brine wastewater per tonne of APC residue. This has implications for the locations that could be used for treating APC residues.

In summary, incineration of MSW, as currently practised does not produce FSQ materials.

3.3.2 *Composting of MSW fractions*

Composting of residual organic fractions is a central feature of Mechanical-Biological Treatment (MBT) processes being established in many parts of the EU. These are widely seen as an alternative to incineration that will allow Member States to meet the organic reduction targets of the Landfill Directive. The UK Government has also advocated composting or recovery of up to 30% of household and other biodegradable wastes. The planned scale of composting in the UK and other parts of the EU is such that much of the composted materials will have to be landfilled rather than utilised. Research during the last few years has begun to generate a large body of data on the characteristics of composted materials destined for landfill. Table 6 summarises characteristics reported in papers at the 1999 Sardinia Symposium.

Table 6. Characteristics of composted MSW, reported at Sardinia ’99

reference	composting) period (weeks)	90-day gas potential m^3/dry tonne	eluate concentration (mg/l) COD	TOC	TKN
Raninger et al. Vol I: 479-486	14 - 22	35	8,000-11,400		2,200-2,800
Bidlingmaier et al. Vol I: 401-408	16 - 26			150-642	
Höring et al. Vol I: 409-418		20 – 35		800	
Ziemann and Meier Vol I: 435-442		4.4 - 21.4		169 – 485	
Scheelhasse & Bidlingmaier Vol I: 487-494			1,000-1,500	~500	~300
Leikam et al. Vol I: 495-502	13	19	800-1,800	480-740	180-260
Raninger et al. Vol I: 387-394	10 - 16	10 - 24			
Piehler & Kögel-Knabner Vol I: 395-400	14 - 55	2 - 19			
Von Felde & Doedens Vol I: 533-540	16	10	700-2,500	300-950	10-37

Composting, even for extended periods, may only remove ~90% of the gas potential. There is currently no justification, in the form of validated risk assessments, for regarding a BMP of ~20m^3/t as being Final Storage Quality. Table 6 also shows that eluates from compost contain similar concentrations of poorly degradable carbon compounds to methanogenic leachates. The nitrogen cycle during composting is not well characterised: the juxtaposition of aerobic and anoxic conditions during composting might be expected to encourage nitrogen losses by nitrification/denitrification processes. However, some authors report uptake into humic acids as an important sink for nitrogen. Most eluates appear (Table 6) to contain lower soluble TKN concentrations than in methanogenic leachates, but in many cases the TKN and NH_3-N remain many times higher than dischargeable levels.

3.3.3 *Liquid waste treatment plants*

A high proportion of the UK's ~1Mt/a liquid industrial wastes are now sent to centralised treatment facilities rather than being co-disposed and this proportion will increase upon implementation of the Landfill Directive. Typically, the treatment processes in current use comprise blending, neutralisation, addition of lime, settling and dewatering. The clarified effluent is usually discharged to sewer and the dewatered solids are landfilled as a sludge or filter cake. Characterisation of these sludges has generally been rudimentary at best.

An Environment Agency research study [Anon.,1995] was conducted to develop a leaching test, so that the suitability of solid wastes for co-disposal could be assessed more rigorously. During the course of this study, data on the leaching of TOC and phenols were generated for sludges from 10 merchant waste treatment centres in the UK. These data are reproduced in Figures 1 and 2. They show that filter cakes may leach high concentrations of TOC and phenols. Both parameters would have to be greatly diluted or degraded in order to reach dischargeable concentrations. The sludges therefore fall a long way short of reaching Final Storage Quality.

Figure 1. Eluate TOC concentrations during sequential leaching of 10 UK filter cakes

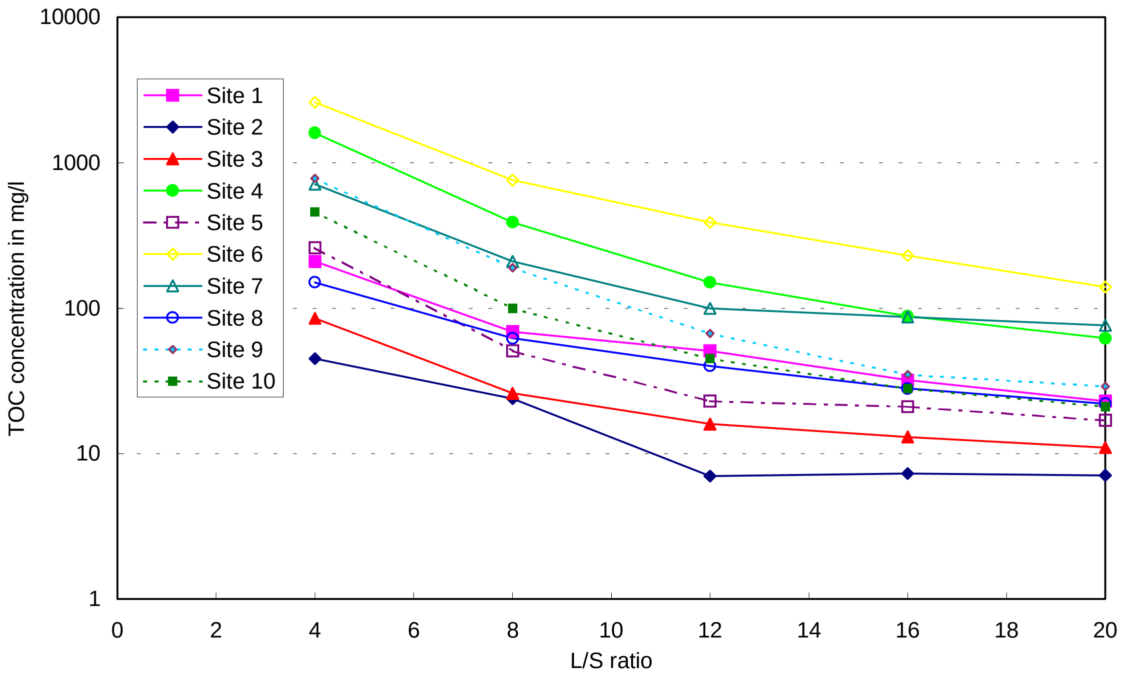
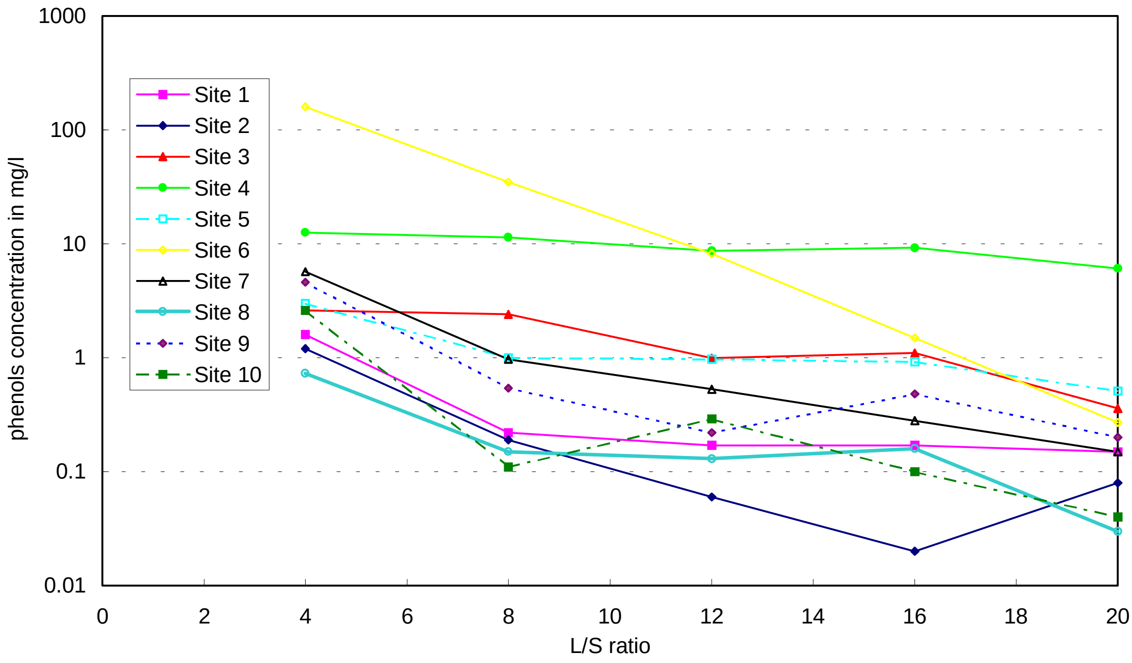


Figure 2. Eluate phenols concentrations during sequential leaching of 10 UK filter cakes



3.3.4 *Comment on pre-treatment to FSQ*

The preceding sub-sections consider three treatment routes that are in common and increasing use, and which are typically perceived as ***alternatives*** to landfill. In fact, they are not alternatives but ***pre-cursors***, that remove ***some*** of the polluting components of the crude wastes. The residues still have to be landfilled, and in future this is likely to be in segregated cells. It is clear from the considerations above that in all three cases the polluting potential of the residues remains high, and none can be considered as being Final Storage Quality materials. The consequence of this is that landfills receiving these wastes should be designed and operated so the FSQ is reached within the landfill. In all three cases this will involve flushing with large volumes of water. In the case of MBT residues it will also mean managing the final part of the degradable organic content.

Overall, it is clear that the most important mainstream treatment methods currently in use do not produce FSQ materials. Considerable improvements would be needed in order to produce residues that required no active management after placement in a landfill.

3.4 Achievement of FSQ in landfills

This involves two activities:

- promotion of decomposition
- flushing of soluble pollutants

The current state of knowledge on each of these is considered separately below:

3.4.1 *Promotion of decomposition*

The current state of knowledge and areas of remaining uncertainty are summarised in Table 7 and discussed below.

Table 7. State of knowledge and outstanding uncertainties concerning accelerated decomposition of bio-degradable

Promotion of decomposition [Target 99%]

What we know

- Key factors are: moisture content, temperature, inoculation and recirculation
- Brogborough and LF2000 showed acceleration to 20-60m^3/t.a easily achievable
- Yolo (USA) and VAM (Holland) test cells show we can reach ~140m^3/t in 2 years, even with crude MSW
- Point at which gas rate slows to uneconomic level = f (temperature)
- At T>30^{o}C we may get 90% of gas at >10m^3/t.a
- Every likelihood that we can reach BMP <20m^3/t in 5 years (i.e. >90% degradation)
- No evidence of salts or NH_3-N reaching inhibitory levels as a result of recirculation
- In situ aeration can lead to huge reduction in NH_3-N
- In situ aeration has negligible effect on soluble hard COD

What we don't know

- Last third of gas curve is very poorly characterised at large scale
- Characteristics of solid residues when gas, leachate and BMP targets are met
- Nature and concentration of non-degradable COD from a flushing bioreactor landfill
- Aerobic post-treatment:
  - optimum point to begin aeration
  - efficiency at full scale
  - quality/odour of off-gas
  - how low we can get TKN
  - what effects on other leachate parameters (COD, BOD, SO_4, pH, metals)
  - any temperature problems

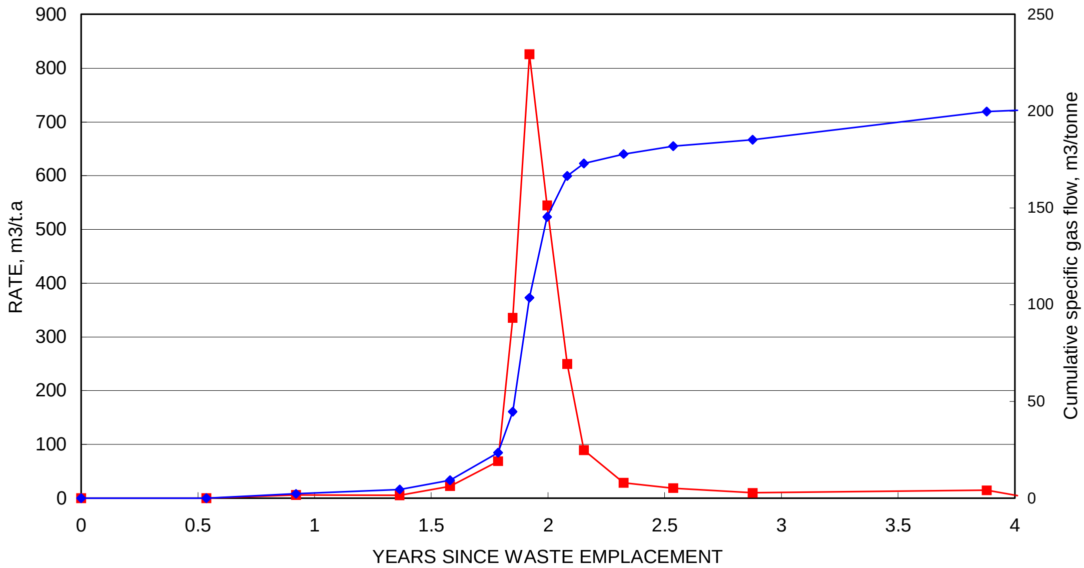
Numerous research studies over the last 20 years have investigated and reviewed the factors affecting decomposition and their relative importance. The weight of evidence shows that the four most important are (in decreasing order):

moisture content
temperature
inoculation
recirculation

In laboratory studies, with all these factors optimised, very high rates of degradation have been achieved in many different studies, peaking as high as 800m^3/t.a (e.g. Beaven, 1996; Beaven & Walker, 1997) and releasing the full gas potential (~200m^3/t) in little more than 2 years. An example is shown in Figure 3 (Beaven, 1996).

Several large test cells have also been constructed, in attempts to optimise these factors, with varying degrees of success. The Brogborough and Landfill 2000 test cells in the UK both achieved considerably higher gas generation rates than conventional landfills (Knox, 1999). Cumulative gas curves from these two studies are shown in Figures 4 and 5. At Brogborough, gas flow rates of ~20m^3/t.a were achieved in cells that had either air or water injection. This is approximately double the expectation from a conventional landfill. At Landfill 2000, gas flow rates peaked even higher at the equivalent of ~60m^3/t.a in a cell with high rate leachate recirculation. In practice, neither the Landfill 2000 test cells nor any of the Brogborough test cells were optimised: the Brogborough cells were, overall, too dry, while the Landfill 2000 cells, while wet enough, were too cold (<15ºC), because of their shallow depth. Two more recent sets of large scale test cells have come closer to optimising conditions and have led to correspondingly higher rates of degradation. They are at Yolo County, in California, USA, (Augenstein et al., 1999) and at VAM landfill in Holland (Woelders and Oonk, 1999).

Figure 3. Gas generation in an optimised small scale reactor (Beaven, 1996)



At Yolo County, an ~11,000m^3 cell containing ~8,000t of mixed municipal wastes was accelerated by the addition of water to field capacity, followed by leachate recirculation. In a 27 month period it generated 70m^3 CH_4/dry tonne. At 50% methane this would be equivalent to 140m^3 gas per dry tonne.

At the VAM landfill in Holland, a ~50,000 tonne cell has been constructed containing mechanically separated organic residue (MSOR) from a MSW separation plant. Construction was complete by the end of 1997. Leachate addition, recirculation and active gas extraction were started at the beginning of 1998. In 16 months a gas volume of 1.85 x 10^{6}m^3, at 56% CH_4, has been extracted. This is equivalent to 37m^{3}gas/t MSOR, or 64m^{3}gas/t dry matter (the MSOR has a relatively high initial moisture content at ~42%). Woelders and Oonk, 1999 estimate that this is ~30% of the total gas potential of the waste, released in less than a year and half. Massive acceleration of gas generation rates is therefore readily achievable.

It is equally important to know how long gas generation will continue at rates that can be used for energy recovery, and conversely what proportion of the gas yield requires active management but with no prospect of recovering energy. It is also important to know whether these proportions can be influenced by landfill operational techniques.

The manner in which gas generation rates decline, as the waste becomes depleted of degradable matter, is only poorly characterised, as are the factors that influence it. There are virtually no published data for the end of the gas curve, from full-scale landfills, while most large-scale test cells have either been discontinued at too early a stage or are still too young to have exhibited a significant decline. Some information is available from small-scale studies and useful observations can be made from some of the large-scale test cells. The results from a 400 litre lysimeter (Beaven, 1996) are shown in Figure 3. In this study, conditions were optimised: the waste was finely shredded, brought to a high moisture content, leachate was recirculated and the temperature was maintained at 30-40ºC. This lysimeter exhibited a period of intense activity following a lag period, followed by a gradual decline (Figure 3). The peak rate of gas production was reached when cumulative gas production was ~100m^3/t (i.e. ~50% of the ultimate value). Rates then declined exponentially, implying a first order, substrate-limited system. However, they still exceeded 10m^3/t.a even when cumulative gas production was ~180m^3/t, or ~90% of the ultimate yield. This would imply that a high proportion of the gas would be generated at economically attractive rates.

Some recent research has suggested that the point at which rates fall to very low levels is temperature dependent. This may be because temperature effectively determines the size of the substrate pool: Grischeck et al. (1999) presented results from 100 litre landfill simulation reactors operated at 10ºC and 35ºC. Gas curves initially followed very similar courses at both temperatures. Gas generation rates then fell to virtually zero in the 10ºC reactors much earlier than in the 35ºC reactor, and at approximately half the total gas yield. This behaviour suggests that certain components are readily degradable at both cool and warm temperatures, while others are only very slowly degradable at lower temperatures. Results from the Landfill 2000 and Brogborough test cells are consistent with this possibility. In Figure 4, gas generation in Brogborough Cell 4 (mean temperature ~34ºC) is seen to be continuing at an elevated rate (~18m^3/t.a) with no evidence of slowing down, when cumulative gas volume is ~130m^3/t. Figure 5, in contrast, shows that the gas flow rate in Landfill 2000 Cell 1 (average temperature ~12ºC) declined sharply from its peak at an early stage: only ~61m^3/t had been generated by the end of the study. At Yolo County (temperature ~40°C) although a slight decline in rate occurred after ~60m^3 **methane** per dry tonne had been produced, the rate still continues at a consistent high level.

Yolo County and Brogborough Cell 4 represent the furthest progress along the gas curve of any large scale test cells to date. Their continued operation and monitoring are therefore of great importance. It is also possible that some landfills where full-scale gas utilisation schemes were installed in the early 1980s, are now reaching the end of their gas curves. Records at some of these landfills might allow derivation of a gas generation curve that is almost complete. It would be a worthwhile exercise to seek out and collate any such data sets.

The range of characteristics of solid wastes from landfills that meet gas emission, gas potential and leachate targets have not been investigated to any significant extent. Opportunities to do so at full-scale landfills are limited because few, if any, landfills of recent age are likely to have reached completion. Those that have are predominantly ‘inert’ waste landfills. Nevertheless, a large quantity of useful data could be generated by examining appropriate samples. These would allow the range and variability of the characteristics of Final Storage Quality wastes to be described. Sources of suitable waste for characterisation would be:

- Small-scale reactors that have been taken to completion, or close to it, and which have not yet been destroyed, for example the lysimeters of Beaven (1996). It may be that several other sets of ‘completed’ lysimeters still exist. An important feature of these sources is that often the entire gas curve has been accurately recorded, and often the characteristics of the initial waste were determined.

- Large-scale test cells at the end of their experimental life. For example, the Brogborough test cells will in due course be a suitable source of waste for characterisation.

- Old landfills: the most suitable are those with a known history that have been subject to detailed site investigation (e.g. for development purposes) and shown to have low gas emissions and low gas potential. Shallow sites with little or no final cover, in high rainfall locations, are the most likely to have been flushed of pollutants to a sufficient extent.

The range of parameters to be determined in such an investigation should be broader than the range in WMP26A. The choice may be informed by the large number of papers published in recent years on the characterisation of residues from pre-treatment processes for MSW, such as composting and anaerobic digestion. Many such papers were presented at the 1999 Sardinia symposium. Parameters found in these papers are collated in Table 8, along with a suggested additional parameter: Biochemical Nitrogen Potential (BNP).

Figure 4. Cumulative gas abstraction at the Brogborough test cells

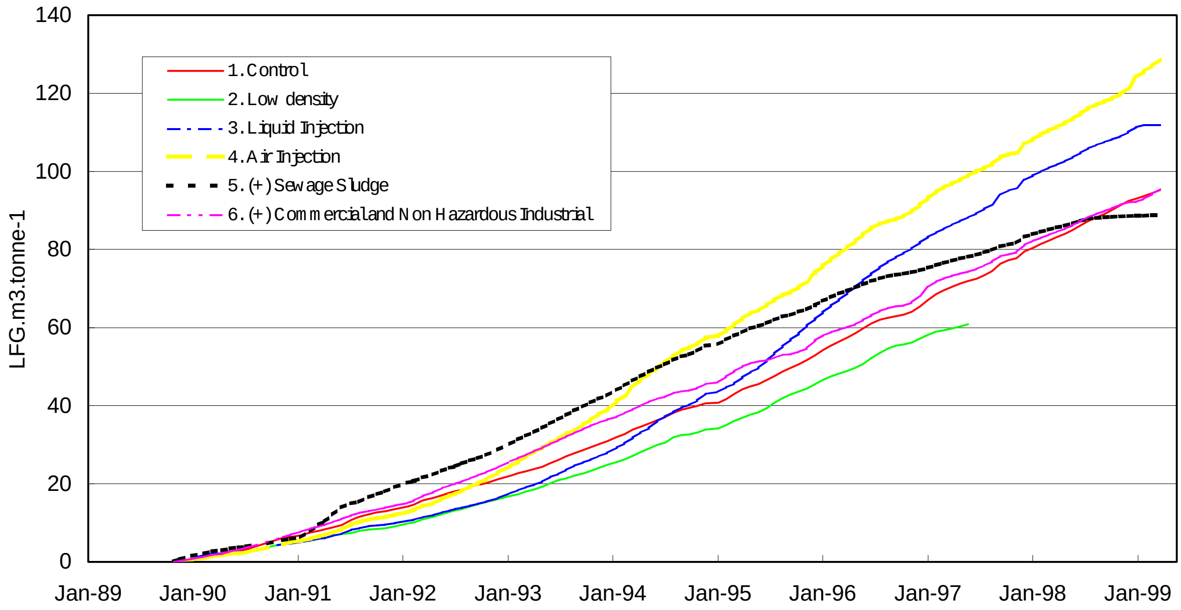


Figure 5. Cumulative gas flow at the Landfill 2000 test cells

Table 8. Candidate parameters for characterisation of stabilised MSW (primary source: papers at Sardinia '99 Landfill Symposium)

General
Loss on ignition, LoI
Total organic carbon, TOC
Calorific value, CV
Cation exchange capacity, CEC
Redox potential
Hydraulic conductivity
Acid/base neutralising capacity, ANC/BNC
Biological stability
Biochemical methane potential, BMP (UK 90day, inoculum)
GB_{12}, GB_{28}, GB_{90} (German/Austrian tests, with or without inoculum)
Respiration coefficient, AT_4, AT_7 (a.k.a. specific oxygen uptake rate, S.O.U.R.)
Quantity and nature of humic material
Cellulose and hemi-cellulose (acid-digestible fibre, ADF)
Lignin
Protein
Lipid
Humic acids, fulvic acids
Nitrogen content
Total N
Leachable N
Heterocyclically bound N
Biochemical nitrogen potential, BNP* [=nitrogen released into leachate during BMP test]
Leaching tests
Metals
SO_4
Chloride
TOC, COD
Toxicity
Trace organics (e.g. AOX, BTEX, PAH)

*Author's suggestion to be based on BMP, not yet developed as a practical test.

Two areas of concern in flushing bioreactor landfills are the nature and concentration of non-degradable COD that remains to be flushed out, and the possible build up of inorganic salts and NH_3-N to inhibitory levels, due to prolonged recirculation. Data on leachable COD and TOC from composted MSW, summarised in Table 6, appear similar to expectations for methanogenic MSW leachates. This leads to the expectation that MSW stabilised fully in a high rate flushing bioreactor (HRFB) landfill may also have similar concentrations and COD characteristics. However, this remains to be investigated in practical research studies.

There is no evidence that salts or NH_3-N would build up to inhibitory levels as a result of recirculation: the releasable nitrogen content of MSW is on the order of 2kgN/tonne (IWM, 1999). If this were all released into one bed volume of moisture (assume bed volume 40%v/v; density 1 t/m^3) the resulting concentration would be:

$$\frac{2\text{kg/t} \times 1\text{t}}{0.4\text{m}^3} = 5 \text{ kg/m}^3$$

$$= 5{,}000 \text{ mgN/l}$$

In recent Hong Kong Landfills, NH_3-N concentrations have reached ~6,000mg/l due to a higher putrescible content than in UK MSW. Chloride has reached ~4,000mg/l. Their leachates have become methanogenic within two years (e.g. Chen et al., 1997) and gas rates show no evidence of inhibition. Similarly, in the VAM test cell in Holland (Woelders and Oonk, 1999) the high gas rates referred to earlier have been reached at leachate concentrations of

~5,000mg/l (TKN) and ~6,000mg/l (chloride). These chloride concentrations are consistent with the results of Beaven's (1996) small-scale studies, which indicated releasable chloride to be ~2.5kg per dry tonne, when the waste was fully degraded.

The benefits of completing the degradation with an aerobic phase have begun to attract considerable attention in recent years. The essence of the concept is to begin with an accelerated anaerobic phase to minimise external energy usage and maximise energy recovery from gas. This would continue until the degradable organic content of the wastes fell to the point where energy recovery was no longer practicable. Completing the remainder of the degradation with an aerobic phase has several potential advantages:

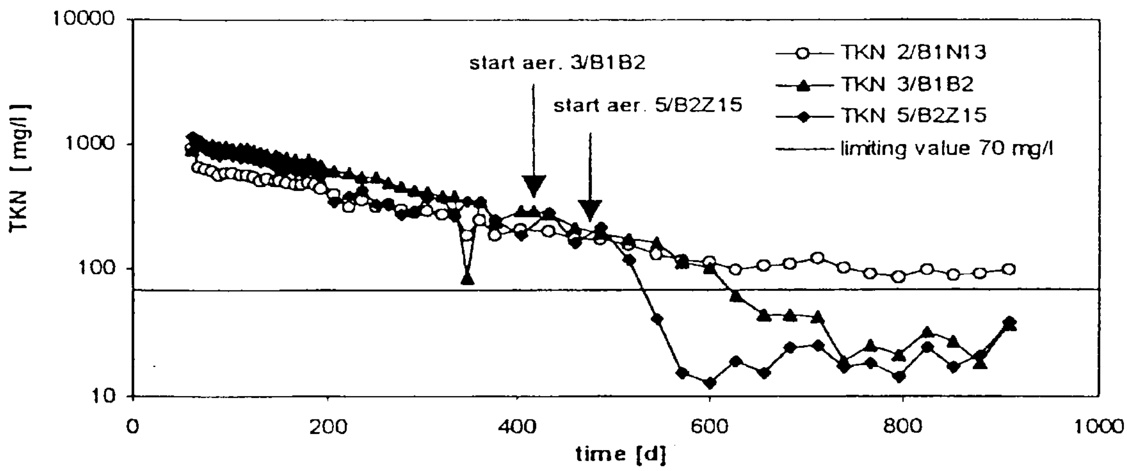
- It may offer a route for nitrogen removal via simultaneous nitrification/denitrification, utilising the remaining degradable components within the wastes as a carbon source for denitrification; flushing requirements would then depend on COD and chloride and would be greatly reduced.

- Aerobic processes are often regarded as more efficient than anaerobic processes. The final stage of stabilisation could therefore be quicker and lead to a more stable final residue;

- The need for support fuel to flare gas with a low methane concentration is avoided.

In Japan, the concept of aerobic and semi-aerobic landfills has been known and practised for many years (e.g. Hanashima, 1999). There has, however, been little appreciation of the relevance of these techniques to sustainable landfill, partly because of language and translation barriers. More recently, projects in Europe have illustrated the potential benefits of aerobic post-treatment, sometimes coincidentally during other projects. Leikam et al. (1997) investigated air injection as a remedial technique for old landfills. In pilot-scale trials (~200 litres) prior to aeration, TKN was being flushed out exponentially from three identical lysimeters, consistent with the lysimeters behaving as a completely mixed reactor. This is illustrated in Figure 6, which reproduces the graph of Leikam et al. (1997). TKN had been diluted from ~1,000mg/l to ~200mg/l before air was introduced. Shortly after aeration was introduced in two of them, their TKN concentrations dropped dramatically to ~20mg/l. This took as little as 50 days in one reactor (Figure 6). No oxidised nitrogen was found in the leachate from either of the two aerated lysimeters but the nitrogen removal mechanism was not investigated further. In contrast to the nitrogen, aeration had no discernible effect on the leachate COD concentration which continued to follow the exponential flushing curve in all three lysimeters. Aeration resulted in acceleration of carbon release via the gas pathway, by a factor of 3 to 5 times the rate prior to aeration.

Figure 6. Loss of nitrogen following air injection into waste (after Leikam et al., 1997)



Loss of nitrogen, following deliberate air ingress, was also observed in MSW columns during a small-scale study of the long term fate of heavy metals in landfill (Revans et al. 1999).

While the potential benefits of aerobic post-treatment appear achievable, many important questions remain unanswered. These need purpose-designed studies before the technique can be exploited, and include:

- Confirmation of the nitrogen removal mechanism. Research on composting has indicated the concentration present in a non acid-hydrolysable form (i.e. organically bound) increases with composting duration, up to ~40% of the total after 24 weeks (Heiss-Ziegler and Lechner, 1999). Research needs to quantify the importance of this route compared with the nitrification/denitrification route, and the stability and water solubility of the organic nitrogen.

- Optimum point to begin aeration.

- Quality/odour of off-gases, and the possible need for treatment (e.g. biofilter).

- How low can the leachate TKN and organic nitrogen fall as a result of aeration.

- Effects on waste temperature. (Elevated temperatures caused by aerobic activity could damage engineered landfill components.)

- Effects on other leachate parameters. (pH, metals, SO_4, COD, BOD)

- Efficiency at full scale or large scale test cell.

3.4.2 *Flushing of pollutants*

The current state of knowledge is summarised in Table 9 and discussed below.

Table 9. State of knowledge on the flushing of pollutants from landfills

Flushing of pollutants
What we know • MSW lysimeters and landfills appear to behave like completely mixed reactors • Explained by 2-domain or 3-domain models: rapid flow in channels and rapid equilibration between mobile and non-mobile water • Positive implications for flushing • 7 BV (3-5m^3/tonne) needed for NH_3-N; 2-4 BV (1-2m^3/tonne) needed for COD • Re-injection systems susceptible to chemical and biological clogging • Waste K may be too low for required flushing rates, at depths >20m
What we don't know • Hydraulic behaviour of highly degraded wastes under high compaction • Hydraulic behaviour of treated hazardous wastes • Effects of other hydraulic barriers (e.g. cover layers) • Optimum design of liquid re-injection systems • Effects of settlement on leachate re-injection systems • Actual flushing efficiency achievable at large scale • Extent of flushing required for hazardous waste landfills

No landfill or large-scale test cell has yet been flushed to FSQ, so we have no definite proof of how difficult it may be or how much water it will take. Nevertheless, there is a lot of evidence that MSW lysimeters and landfills behave like completely mixed reactors exhibiting exponential dilution curves rather than plug flow. This knowledge can be used to estimate probable flushing requirements for different leachate components: in a completely mixed reactor, dilution, by a factor of 10 requires flushing by ~2.3 bed volumes (BV). Numerous examples of exponential dilution curves have been produced from lysimeters of various sizes operated in a downward flow, unsaturated condition, for example:

- Knox (1999) presented NH_3-N and TOC dilution curves from a 1.6m^3 MSW lysimeter leached over 16 bed volumes, in unsaturated downflow mode.

- Exponential flushing of TKN was observed from a ~200 litre lysimeter in Germany, reproduced in Figure 6 (Leikam et al. 1997).

- In 400 litre lysimeters containing shredded MSW (Beaven, 1996; Beaven and Walker, 1997), exponential dilution of TOC and chloride was clearly observed.

Further evidence for quasi complete mixing behaviour in MSW is found in breakthrough times and breakthrough curves for tracers added as a slug to test cells or lysimeters. In a small-scale (3.5m^3) lysimeter and pilot (410m^3) landfill (Rosqvist, 1999) breakthrough of added lithium tracer occurred rapidly and peaked at 0.04 and 0.11 bed volumes respectively. Thereafter, its concentration declined exponentially. The lysimeter and landfill were operated in a downward flow unsaturated mode. On a much larger scale, a lithium bromide tracer was added as a slug to one of the 15,000m^3 Brogborough test cells, during a study of recirculation hydraulics (Mouchel, 1999). The tracer was added at the top of one end of the cell, via a brick-filled trench beneath the clay cap. Breakthrough was detected at an abstraction well near the base of the far end of the cell, after recirculation of only 6% of the estimated bed volume. The concentrations of lithium and bromide were consistent with equilibration with a high proportion of the moisture content of the cell. The cell had a ~10m saturated zone and the flow regime is assumed to have included both vertical and horizontal components within the saturated zone.

That a stationary solid phase medium such as MSW should behave like a completely mixed reactor can be explained by multi-domain flow models. These have been derived from theoretical and experimental studies (e.g. Rosqvist, 1999; Bendz and Singh, 1999) and are supported by observations from the Brogborough recirculation study. In the simplest of these models, the water is taken to be present in two domains:

(i) a rapid mobile domain consisting of channels and preferential flow paths between waste components;

(ii) a non-mobile domain (e.g. absorbed water) which can equilibrate with the rapid mobile water.

Typically, the rapid mobile domain is a small proportion of the total moisture content, accounting for the rapid short-circuiting of tracer observed in many studies. In the lysimeter and experimental landfill studied by Rosqvist (1999) only 6% and 12%, respectively, of the total moisture content participated in solute transport. This is consistent with the rapid breakthrough of tracer at Brogborough. It is also consistent with hydraulic analysis of drawdown and well yields during the Brogborough study, which indicated effective yields of only ~3% (Mouchel, 1999). An important additional observation from Brogborough was that the ***concentrations*** of the added tracer were consistent with its having equilibrated with a high percentage of the cell's total moisture content. This implies that the equilibration between the non-mobile and mobile water is rapid.

These features of landfilled wastes have encouraging implications for flushing:

- They give some confidence that efficient flushing of large masses of waste may be possible, and,
- they allow us to estimate the volumes of water necessary.

The flushing volumes required for MSW landfills have been estimated (e.g. Knox, 1990; Beaven, 1996) at ~7BV (3-5m^3/tonne) where ammoniacal nitrogen is the controlling parameter. This calculation is based on the assumption that NH_3-N concentrations would have to be diluted one-thousand-fold. In some situations a lesser degree of dilution would be needed and this would be the case if in situ aerobic post-treatment proved successful. Then, COD may become the determining factor and the flushing volume would fall to 2-4BV (1-2m^3/tonne). All of these volumes estimates remain untested at a scale larger than a 1.6m^3 litre lysimeter. There is a need for larger scale demonstration of flushing, whether in a test cell (e.g. Brogborough) or a full-scale landfill cell.

Few estimates of flushing volumes or hydraulic characteristics have been generated for landfills containing wastes other than MSW or similarly bioreactive materials. Such landfills are not yet common in the UK and there is little knowledge of the defining characteristics of their leachates. Pre-treatment processes under development for air pollution control residues from MSW incinerators (Hjelmar et al., 1999; Lundtorp et al., 1999) require flushing with a volume of 3-5m^3/t to remove soluble salts (mainly Na, K and Cl). This is similar to the estimates above for flushing NH_3-N from MSW landfills. More data of this type are needed for major waste types, to assess the requirements for landfills that will be developed after the implementation of the Landfill Directive.

The quasi complete mixing behaviour of MSW landfills depends on two features:

- Rapid flow to all parts of the cell via pathways that comprise a small proportion of the total moisture content;

- Rapid equilibration between mobile and non-mobile water.

All of the work on this hydraulic aspect, to date, has been based on MSW and most of it has used small scale reactors or relatively shallow test cells. The deepest cell has been the Brogborough cell, which is ~20m deep. It is therefore not known whether these key features will persist in:

(i) Deep, highly compact MSW;
(ii) Other types of waste and mixed waste landfills.

These factors could be studied in lysimeters or test cells.

It is known that some of the hydraulic properties of wastes change dramatically as the depth, and hence applied stress on the waste, increases: Beaven and Powrie (1995) showed that the hydraulic conductivity of fresh MSW can fall by several orders of magnitude from greater than 10^{-5}m/s at shallow depths to less than 10^{-7}m/s at 60m depth. Even lower values are expected when the waste has degraded: several authors have reported hydraulic conductivities of 10^{-8}m/s or lower, for composted MSW after compaction (e.g. Bidlingmaier et al., 1999; Van der Sloot et al., 1999; Soyez et al., 1999; Horing et al., 1999). For a 30m deep landfill, flushing rates on the order of ~3,000mm/a ($\cong 10^{-7}$m/s) would be necessary to pass 7 Bed Volumes in 30 years (IWM, 1999). For landfills greater than 20-30m, the hydraulic conductivity may therefore be too low for the required volumes to be flushed in 30 years. If the aerobic post-treatment concept proves successful, the required flushing volume and flushing rates would be lower, so that it may become practicable to flush deeper landfills inside a 30 year period.

While the hydraulic conductivity decreases with depth, Beaven and Powrie (1995) also showed that the effective porosity fell from 9-23% v/v at shallow depths, to ~2% v/v or less at 60m depth, in fresh MSW. It is uncertain whether quasi complete mixing behaviour will persist under these conditions. The critical factor will be the rate of equilibration between mobile and non-mobile water. Tracer studies under high compaction are therefore needed.

Also unknown is the impact of macro features such as layers of daily cover, bunds, site roads, boreholes, areas of low permeability material, on the efficiency of flushing. These factors would require investigations in full-scale landfill cells. A common view is that traditional low permeability daily cover will constitute a major barrier to efficient flushing. Many operators have begun informal trials of alternative types of daily cover and a small number of formal research studies have also been undertaken. There is however, no consensus on their suitability in achieving the aim of daily cover (e.g. control of vectors, litter and odour). There is a need to collate as much information as possible from trials to date. It may then be possible to draw objective conclusions on the efficiency of various alternatives. That would allow their wider adoption and acceptance by regulators.

Many treated hazardous wastes have a much smaller particle size and are far more homogeneous than MSW. Their hydraulic conductivity is expected to be low, particularly when compacted, and their flushing behaviour when landfilled in bulk is unknown. Studies are therefore needed on the hydraulic properties and flushing of such materials.

The large volumes of water necessary for flushing will have to be introduced over a prolonged period after waste deposition has finished. The most likely arrangement will be via discrete zones of drainage material placed beneath restoration layers. In addition to water, it is likely that at MSW landfills, leachate will be recirculated to a significant extent via these re-injection layers, to encourage even and rapid degradation of the wastes. Re-injection of leachate may also be part of the flushing strategy, by including a nitrification plant in the recirculation loop. The waste mass would then provide a carbon source for denitrification. Prolonged recirculation at high rates has not yet been demonstrated on a large scale and several problems are known, or suspected, that need further practical investigation to resolve:

- Liquid injection layers, like basal drainage layers, may be susceptible to clogging, due to the combined effects of particle ingress, chemical precipitation and biological growth. The extent to which this will occur, and its dependence on leachate quality and on simple leachate pre-treatment (e.g. filtration) are not known.

- The conversion within a landfill, of leachate from acetogenic to methanogenic characteristics, can occur preferentially within zones of drainage stone. This can result in the localised precipitation of calcium carbonate and has sometimes resulted in clogging of drainage layers, re-injection layers (e.g. Mouchel, 1999) and borehole gravel packs. Techniques have been proposed to ensure that methanogenesis is established within the landfill before significant volumes of acetogenic leachate flow through these engineered materials. They include placement of a layer of pre-composted biowaste above leachate drainage layers, and inoculation of leachate drainage layers with methanogenic leachate. There has been very little documented study of these methods and evidence of their effectiveness remains largely circumstantial or anecdotal.

- The range of optimum designs and specification for re-injection systems (e.g. type and depth of drainage media; size of discrete zones, dual design for gas extraction, etc.) has not been established. Designs would be expected to evolve based on theoretical calculations combined with practical experience and there has so far been insufficient of either.

- Differential settlement could cause disruption and malfunction of liquid injection systems. High rates of settlement may be expected during accelerated stabilisation. Development and trials are needed to establish designs that are able to accommodate these movements with minimum loss of function.

4. COLLATION OF RESEARCH NEEDS

The foregoing sections have highlighted many areas where current knowledge is lacking. These have been compiled into a list of outstanding research needs shown in Table 10. The background to most of these is given in the preceding sections. The topics listed are sub-divided into three groups:

- establishing FSQ criteria and pollutant removal requirements;
- promotion of decomposition of bioreactive wastes;
- hydraulic aspects of recirculation and flushing.

For each topic, an indication is given in Table 10 of the probable scale at which the research needs to be directed. Those regarded as being of highest priority are shown in bold italics. In some cases this priority arises because of opportunities that may be lost if there is a delay (for example, studies that could make use of the Brogborough test cells).

Notes on the objectives and suggested scope of each topic shown in the table are given below, together with an approximate estimate of the probable cost and timescale to carry out the work.

The outline scope represents the author's initial suggestions. In practice, refinement of the objectives and more detailed development of the scope, costs and timescales would be needed in order to use these outlines to initiate new R&D projects.

The costs indicated in these notes add up to ~£4.8M, in projects whose duration would range from 6 months to 5 years. A total of 18 topics is listed in Table 10. Some of these might conveniently be split into separate projects (e.g. characterising the last third of the gas curve). Others could feasibly be lumped together under a single contract (e.g. 1.7 and 3.7: geotechnical and hydraulic properties of hazardous wastes).

Table 10. Sustainable landfill research needs in the UK

Scales: 1 = landfill studies
2 = large scale test cells
3 = laboratory and pilot studies
4 = modelling, theoretical and review studies

TOPIC		SCALE 1	2	3	4
1. Establishing final storage quality and pollutant removal requirements					
1.1	Compare characteristics of 'stabilised' organic wastes: composts, digestates, lysimeters, test cells, old landfills etc. [BMP, SOUR, LoI, C:L ratio, eluate COD, TKN, Cl^- etc.]			3	
1.2	More detailed risk assessment evaluation of 'safe' FSQ level of BMP				4
1.3	Nature of non-degradable soluble COD and how it is affected by HRFB practices/composting/anaerobic digestion etc.	1	2	3	
1.4	Develop TKN/NH_3-N version of BMP test			3	
1.5	***Hazwaste and inorganic waste landfills: survey leachate quality/ determine controlling parameters, gas and leachate control needs***	***1***			***4***
1.6	***Determine pre-treatment and eluate criteria for wastes/landfills where degradation/flushing is excluded by design/legislation***			***3***	
1.7	***Geotechnical properties of hazardous wastes and degraded biowastes***	***1***	***2***	***3***	***4***
2. Promotion of decomposition of bioreactive wastes					
2.1	***Full scale HRFB demonstration cell***	***1***	***2***		
2.2	Characterise the last third of the landfill gas generation curve ***(i) continue running the Brogborough cells to the end*** (ii) collate data from long-established LFG schemes (iii) collate data from lysimeters and pilot studies	1	2	3	4
2.3	Field-scale trial of basal seeding techniques: compost layer	1	2		
	inoculate LCS	1	2		
2.4	***Anaerobic/aerobic landfill concept***	***1***	***2***	***3***	
3. Hydraulic aspects of recirculation/flushing					
3.1	***Large-scale flushing trial***	***1***	***2***		
3.2	***Clogging of re-injection media after various leachate pre-treatments***	***1***	***2***		
3.3	***Vertical flow tracer studies via unsaturated wastes (i) conventional landfills (ii) ideal: no cover etc (iii) under pressure***	***1***	***2***	***3***	
3.4	Measure hydraulic response at site base to infiltration events (i) conventional daily cover (ii) no cover	1			
3.5	Comparison of Li and Br as tracers, using tritium as marker [effect of waste type and age]		2	3	
3.6	Alternatives to daily cover: review and further trials				4
3.7	***Hydraulic properties of hazardous wastes and degraded biowastes***			***3***	***4***

BREAKDOWN OF TOPICS IN TABLE 10.

1. ESTABLISHING FINAL STORAGE QUALITY AND POLLUTANT REMOVAL REQUIREMENTS

1.1 Compare characteristics of stabilised wastes

Objective
Provide background data on which to base FSQ criteria for processed bioreactive wastes.

Scope
(i) Collate literature data (e.g. many values for MBT wastes at Sardinia '99)
(ii) New measurements, to fill in gaps in literature

Cost
£75K

Timescale
1 year

1.2 Risk assessment of FSQ levels of gas potential

Objective
Place FSQ criteria for processed biowaste at the right level, or establish protocol to determine site-specific levels.

Scope
Use HELGA model at range of selected sites.

Cost
£50K

Timescale
1 year

1.3 Nature of non-degradable COD

Objective
Allow comparison of environmental consequences of different options for processing biowaste. [COD could become the controlling parameter if aerobic post-treatment is used to reduce NH_3-N concentrations.]

Scope
Analysis of samples from existing plants/experimental studies, including humics, fulvics, functional group, MW distribution etc.

Cost
£150K

Timescale
3 year study

1.4 Develop nitrogen version of BMP test

Objective
Assess processed waste for potential to release further nitrogen into leachate.

Scope
Modify existing BMP protocol to measure organic and NH_3-N release into the aqueous phase; apply to a range of processed biowastes at varying stages of stabilisation.

Cost
£50k

Timescale
1 year

1.5 Leachate and gas quality at inorganic and hazardous landfills

Objective
Provide background data to identify flushing volumes required and controlling parameters for flushing to FSQ for new landfill types following implementation of Landfill Directive.

Scope
(i) Collate literature and unpublished data
(ii) Visit hazwaste and inorganic waste landfills and sample where possible

Cost
£75k

Timescale
1 year

1.6 Pre-treatment and eluate criteria

Objective
To support derivation of FSQ criteria for inorganic and treated hazardous wastes going into dry tomb landfills, and establish protocol to determine site-specific criteria.

Scope
(i) Establish appropriate suites of determinands, initially for selected major classes of inorganic and treated hazardous wastes.
(ii) Derive FSQ leachate criteria for the chosen determinands using site-specific risk assessment, for a representative range of landfill locations.
(iii) Cary out leaching tests and compare eluates with FSQ leachate criteria.
(iv) Evaluate relationship between eluate characteristics and leachate characteristics from landfills receiving the same waste types.

Cost
£200K

Timescale
2 years initially, then on-going.

1.7 Geotechnical properties of hazardous and degraded wastes

Objective
Determine whether stable landfills can be constructed using monofilled hazardous wastes or processed biowastes.

Scope
(i) Collate literature data
(ii) Testing of samples of treated waste;
(iii) Trials in test cells and landfills

Cost
£250K

Timescale
3 years +

2. PROMOTION OF DECOMPOSITION OF BIOREACTIVE WASTES

2.1 Full scale HRFB demonstration

Objective
To prove the practicality, or otherwise, of the high rate flushing bioreactor concept at full scale.

Scope
Construct purpose-built fully-contained cell, with high rate leachate recirculation, active gas extraction, intensive instrumentation/monitoring.

Cost
£1.5M – 2M

Timescale
5 years+

2.2 Characterise the end of the gas curve

Objective
Determine how long the uneconomic ‘tail’ of the gas curve is and its dependence on factors such as temperature.

Scope
(i) Continue running the Brogborough cells as long as possible.
(ii) Collate data from long established LFG schemes.
(iii) Collate data from lysimeters and pilot studies.

Cost
(i) £50K/a
(ii) & (iii) £50K

Timescale
(i) Indefinite
(ii) & (iii) 1 year

2.3 Seeding techniques for basal landfill in layers

Objective
Prove whether it is feasible to avoid any acetogenic leachate phase or to reduce its duration of a very short period.

Scope
Fill three identical cells simultaneously with the same waste: inoculate drainage layer of one with methanogenic leachate; cover layer of second with composted MSW; leave third as control.

Cost
£100K

Timescale
1 year

2.4 Aerobic post-treatment

Objective
Determine limitations and optimum conditions for aerobic post-treatment phase in landfill of bioreactive wastes.

Scope
(i) Bench–scale trials
(ii) Pilot–scale trials
(iii) Test-cell scale trials (e.g. using one of the Brogborough test cells).

Cost
(i) £50-100K
(ii) £250K
(iii) £250K

Timescale
(i) 1 year
(ii) 3 years
(iii) 3 years

3. HYDRAULIC ASPECTS OF RECIRCULATION/FLUSHING

3.1 Large scale flushing trial

Objective
Determine whether efficient flushing of conventionally landfilled MSW is practical at large scale and whether it follows the predicted ‘complete mixing’ behaviour.

Scope
Flush one of the Brogborough test cells (or equivalent), incorporating either on-site nitrification or leachate disposal via operators leachate treatment plant and replacement with ‘grey water’.

Cost
£400K

Timescale
4 years

3.2 Clogging of liquid injection layers

Objective
Determine degree of pre-treatment necessary to ensure that re-injection media retain their function for the required duration.

Scope
Pass leachate at an accelerated rate through beds of drainage stone, after various pre-treatments e.g. no treatment; settling; aeration and settling; aeration and settling and filtration; biotreatment and filtration.

Cost
£300K

Timescale
3 years

3.3 Tracer studies in unsaturated wastes

Objective
Determine whether the multi-domain quasi complete mixing behaviour observed in various trials occurs under realistic flushing scenarios (macro scale, unsaturated vertical flow).

Scope
Lithium bromide tracer additions at real landfill, test cells and lysimeters, including a test under a high applied stress.

Cost
£100K

Timescale
1 year

3.4 Hydraulic response to infiltration events

Objective
Determine the extent to which discontinuous infiltration events at a landfill surface are smoothed and attenuated during passage through a waste mass.

Scope
Install grid of pressure transducers in site base, within drainage layer and install recording rain gauge at surface.

Cost
£100K

Timescale
3 years

3.5 Evaluation of lithium and bromide as tracers

Objective
Determine the extent of non-conservative behaviour for the two most commonly used tracers in landfill research. Determine dependence in waste age.

Scope
Add slug of mixed tracer (Li, Br, tritium) to columns of waste: fresh MSW, aged MSW, MSW incinerator ash. Compare breakthrough times and equilibrium concentrations.

Cost
£50K

Timescale
1 year

3.6 Review of alternative daily cover options

Objectives
(i) To draw objective conclusions from the many trials of alternatives to daily cover that have been conducted around the UK.
(ii) To recommend and undertake any additional trials that are needed.

Scope
(i) Identify as many trials as possible, both formal and informal. Visit, and discuss with local operators and regulators.
(ii) Undertake additional trials.

Cost
(i) £50K
(ii) £100K

timescale
(i) 1 year
(ii) 2 years

3.7 Hydraulic properties of hazardous and stabilised wastes

Objectives
Determine hydraulic conductivity and complete mixing/multi-domain behaviour for new waste types that will be landfilled in bulk when the EU Landfill Directive is implemented.

Scope
Hydraulic conductivity measurements and lysimeter tracer studies on a range of wastes including: composted MSW; anaerobically digested MSW; MSI bottom ash; sludges from liquid wastes treatment plants; solidified liquid wastes

Cost
£50K

Timescale
1 year

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