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ACHIEVING EQUILIBRIUM STATUS AND SUSTAINABLE LANDFILL - THE HOLY GRAIL?

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SUMMARY: This paper presents the results of a research contract jointly funded by the Environment Agency and ESART examining the residues of likely post-Landfill Directive waste streams that will need to go to landfill and the time taken to achieve sufficient stabilisation such that management controls can be removed. The first part of the project has identified a number of processes that are likely to be adopted by the waste management industry in order to meet the biodegradable waste diversion targets. Both leachate quality and landfill gas generation data has been assessed for each residue stream. Forward modelling has been undertaken on these data using LandSim2.5 within GoldSim to assess the likely period of management needed in order to achieve equilibrium status.

1. INTRODUCTION

One of the outcomes of adopting the Landfill Directive (Council of the European Union 1999) will be a reduction in biodegradable municipal solid waste (MSW) being landfilled. In order to achieve the diversion targets there will need to be a major change in the way MSW is treated prior to the residual components being landfilled. This research contract has looked at the range of possible waste treatment processes that the waste management industry may adopt and the likely composition of the landfilled residues. Views expressed are those of the authors.

The prime purpose of looking at these options is to determine the likely timescales to achieve something called "equilibrium status". Equilibrium status relates to the 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 emissions is unrealistic. That is not to say that, for example, the leachate meets drinking water quality; rather the leachate will be at a quality 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 or properties for the residuals going to landfill, the future management options for landfills and the drivers to achieve equilibrium status.

2. WASTE PROCESSES TO ACHIEVE BIODEGRADABLE DIVERSION TARGETS

As a precursor to understanding the likely changes in waste composition and properties, it is necessary to examine the likely process flows that could be adopted by waste management companies 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).

Each of these processes will generate residues that have differing properties that will affect either their landfill gas generation and profile, or will generate a waste with markedly different properties to raw MSW that (until now) has represented the main route for the disposal of MSW in the UK. The change in properties will include both differing leaching potential and different physical characteristics such as density and waste hydraulic conductivity.

3. MODELLING OF EMISSIONS

Leachates from conventional MSW landfills are reasonably well understood notwithstanding the fact that there are some regional and site-specific differences. In order to benchmark typical aftercare periods of the various residues that each of the processes listed might require, a conventional raw MSW landfill site has been modelled as a starting point. 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 and its various water quality standards. The inclusion of ammoniacal nitrogen within the list of contaminants modelled required the derivation of a nominal (and certainly non-statutory) waste acceptance criterion for ammonia.

Modelling has been undertaken using an implementation of LandSim2.5 (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 variable. Furthermore, the post processing capabilities of GoldSim allow multivariate analyses of the results, essential in order to correlate the required length of managed aftercare with long-term groundwater impacts.

Essentially the management period is defined as a variable and the model is run allowing this period to vary between 2 years and 2000 years. During each iteration (each using a different management period) the maximum groundwater concentration for each of the contaminants modelled is recorded and them plotted against management time. In this way the management time period needed to achieve the water quality standard (typically taken to be the Drinking Water Standard) can be recorded. Any model run that results in 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 from 250 to 1000 years to 140 mm/y to simulate the degradation of the cap. Leachate control is assumed to maintain leachate levels at 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 List II or non-listed substances and the base of the unsaturated zone for List I substances. Note that in all cases the water quality standard and not the Minimum Reporting Values contained in Environment Agency (2003) have been used to determine compliance.

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 has not been assumed.

It should be noted that the leachate quality 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 attenuation and or 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. As such leachate levels where expected to increase as a result of cap infiltration and cap deterioration even though the liner system may still be in a process of degrading and as such the leakage rate is likely to increase markedly.

Albeit that the Landfill Directive seeks to minimise leachate production via limiting rainfall infiltration and groundwater inflow, simulations were also run as flushing systems with 200 or 500 mm of treated leachate recirculation in addition to infiltration. This recirculation ceases when time 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 research by Robinson (1995). For the MBT and incinerator bottom ash, data have been derived from research by Bone *et al*. (2003a+b). Those model runs relating to WAC values use the initial flush from a column test equating to a liquid solid ratio of approximately 0.05 l/kg back calculated from the published waste acceptance criteria. Additional data has been drawn from personal knowledge and judgement.

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. The column in Table 1 entitled stable non-reactive relates solely to the Co values derived from the Waste Acceptance Criteria for that waste that could be placed in a non-hazardous landfill in a separate cell. The implied assumption is that the entire waste is deposited at the maximum concentration of each species.

The likelihood of this occurring is very low, but given that we are looking at each of the individual species it does provide an insight into which species are likely to result in the need to extend aftercare periods.

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.

Table 1: Initial leachate concentrations for MSW and allied waste streams

Waste Stream	MSOR	MBT	MBT	MSW	Stable Non-Reactive
Treatment		Intensive	Medium	Raw	None
Derivation	Bone *et al*.	Bone *et al*.	Bone *et al*.	LandSim	WAC
Species					
Sb					0.15
As	0.1	0.006	0.05	0.013	0.3
Ba					20
Cd	0.0005	0.003	0.02	0.0101	0.3
Cr	5	0.1	0.3	0.075	2.5
Cu	0.5	0.2	0.35	0.03	30
Hg	0.0001	0.0001	0.0001	8.91E-05	0.03
Pb	0.05	0.04	0.3	0.17	3
Mo					3.5
Ni	0.5	0.1	0.4	0.012	3
Zn	0.5	0.2	1.5	0.25	15
Se					0.2
F					40
SO_4	400	500	3000	263	7000
Cl	6000	2000	6000	1466	8500
NH_4	4000	200	550	495	2000

Notes to Table

No reliable data from UK MSW Sites or literature

MSOR – Mechanically Sorted Organic Residues.

MBT - Mechanical Biological Treatment.

MSW - Raw Municipal Solid Waste.

WAC - Waste Acceptance Criteria C_O values.

A number of literature sources (Scheelhaase *et al.* 1997; Leikam *et al.* 1997) have highlighted the low hydraulic conductivity of MBT waste residues. Typical values range from $1e^{-8}$ to $1e^{-9}$ m/s or less. Hydraulic conductivities in this range may make flushing and recirculation of leachate physically difficult although at the higher end of the scale fully saturated waste should be able to transmit 300 mm/y of effective infiltration. However, there may remain a barrier to these wastes readily achieving a high liquid-solid ratio. The reality remains that raw MSW probably exhibits similar hydraulic conductivities in large deep landfills.

5. MODEL RESULTS

Figure 1 shows the relationship between receptor concentration and management time for chloride for a non-flushing 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 (near) 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 leachate chloride concentration at this time would not meet the WQS, as at 41 years it was predicted to be 1275 mg/l. However, the processes of natural attenuation and dilution result in this concentration (at this specific site) to allow compliance with this standard if the management of leachate ceased at this time. It must also be stressed that on the cessation of leachate management there is an expectation that leachate treatment (or removal) ceases, leachate levels will rise, and leakage will increase in line with the increased leachate head.

Furthermore, it should be noted that the 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.

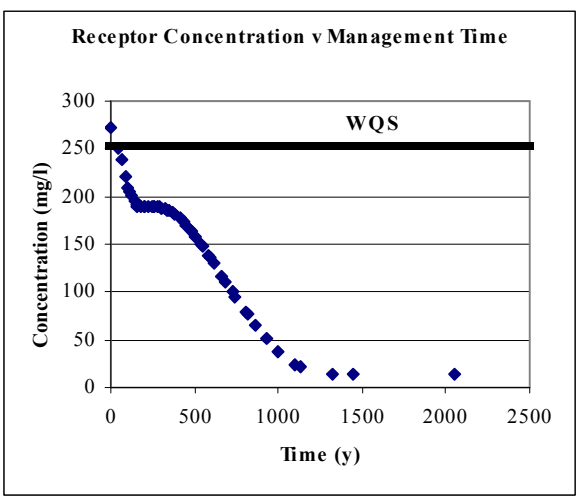

Figure 1 - Receptor concentration verses length of management time (Cl)

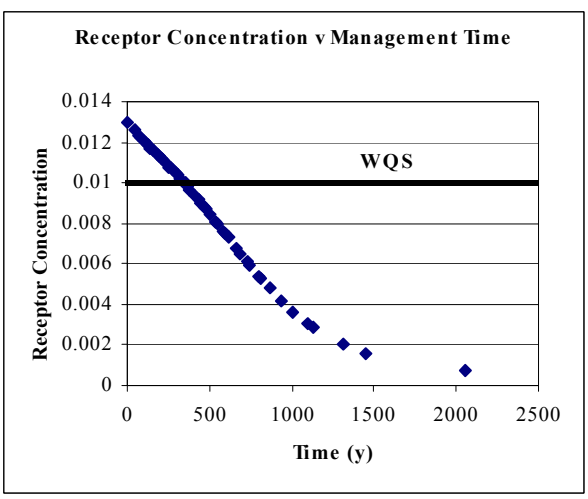

Figure 2 - Receptor concentration verses length of management time (Pb)

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 could cease and the time when the maximum concentrations in groundwater will be realised.

Tables 3, 4 and 5 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). In addition, 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.

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 2: Initial leachate concentrations for MSW incinerator ash

Waste Stream	**Incinerator Bottom Ash**		
Treatment	**Raw**	**Carbonated**	**Acid Treated**
Derivation	Bone *et al (2003a)*.	Bone *et al (2003a)*.	Bone *et al (2003a)*.
Species			
Sb	0.025	0.1	0.2
As	0.001	0.001	0.001
Ba	1	0.1	0.25
Cd	0.01	0.01	0.01
Cr	0.01	0.2	0.03
Cu	5	5	10
Hg	0	0	0
Pb	5	0.005	0.015
Mo	0.3	0.4	0.5
Ni	0.075	0.05	0.05
Zn	0.001	0.001	0.002
Se	1	0.05	0.02
F	0	0	0
SO_4	500	2000	2000
Cl	1700	1700	1700
NH_4	10	10	15

Table 3 examines raw MSW and a synthetic leachate derived to meet a site filled with waste at its maximum WAC for stabile non-reactive waste. This is a slightly fictitious scenario as it is unlikely (in the extreme) that wastes infilling a site would all equal the relevant WAC. However, it is conceivable that a process waste might be consistently close to the limit for one species. The raw MSW waste in the basic scenario (i.e. one where the waste is placed, capped and leachate generation minimised) forms the base case. Somewhat surprisingly this scenario contains only one contaminant that fails the general criteria of equilibrium status. It must me noted however that the compliance concentration for cadmium is taken as the drinking water standard and not the MRV albeit that the compliance point has been taken as the base of the unsaturated zone.

If the compliance water quality standard is the MRV, the time for cadmium to reach equilibrium status increases to slightly over 2000 years. 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.

Table 3: Modelling results to date

Waste Type	**Raw MSW**	**Raw MSW**	**Stable Non-Reactive**	**Stable Non-Reactive**	**Stable Non-Reactive**
Treatment	**None**	**None**	**None**	**None**	**None**
Scenario	**Basic**	**Additional 200 mm/y infiltration**	**Basic**	**Additional 200 mm/y infiltration**	**Additional 500 mm/y infiltration**
Contaminant	**Years to achieve Equilibrium Status**				
Antimony (Sb)			>2000	1350	700
Arsenic (As)	<3	<3	>2000	>2000	>2000
Barium (Ba)			>2000	1050	490
Cadmium (Cd)	<3	<3	>2000	533	240
Chromium (Cr)	<3	<3	1200	1200	185
Copper (Cu)	<3	<3	>2000	500	219
Mercury (Hg)	<3	<3	>2000	>2000	1300
Lead (Pb)	360	40	>2000	750	350
Molybdenum (Mo)			1375	440	200
Nickel (Ni)	<3	<3	1750	533	240
Zinc (Zn)	<3	<3	>2000	670	300
Selenium (Se)			965	275	115
Fluoride (F)			1700	665	250
Sulphate (SO_4)	<3	<3	1375	390	150
Chloride (Cl)	40	4	965	200	75
Ammoniacal Nitrogen (NH_4)	<3	<3	1100	130	50
Maximum Management Period Required in	**360**	**40**	**>2000**	**>2000**	**>2000**

Scenario					

Table 4: Mechanically and biologically treated wastes

Waste Type	**MSOR**	**MSOR**	**MBT**	**MBT**	**MBT**	**MBT**
Treatment	**None**	**None**	**Medium**	**Medium**	**Intense**	**Intense**
Scenario	**Basic**	**Additional 500 mm/y infiltration**	**Basic**	**Additional 200 mm/y infiltration**	**Basic**	**Additional 200 mm/y infiltration**
Contaminant	**Years to achieve Equilibrium Status**					
Antimony (Sb)						
Arsenic (As)	>2000	1100	<3	<3	<3	<3
Barium (Ba)						
Cadmium (Cd)	<3	<3	41	<3	<3	<3
Chromium (Cr)	1600	300	<3	<3	<3	<3
Copper (Cu)	50	<3	<3	<3	<3	<3
Mercury (Hg)	<3	<3	<3	<3	<3	<3
Lead (Pb)	<3	<3	780	206	<3	<3
Molybdenum (Mo)						
Nickel (Ni)	580	50	410	76	<3	<3
Zinc (Zn)	<3	<3	550	125	<3	<3
Selenium (Se)						
Fluoride (F)						
Sulphate (SO_4)	<3	<3	1050	184	<3	<3
Chloride (Cl)	900	70	900	157	367	40
Ammoniacal Nitrogen (NH_4)	1275	85	<3	<3	<3	<3
Maximum Management Period Required in scenario	**>2000**	**1100**	**1050**	**206**	**367**	**40**

MSOR – Mechanically sorted organic residues (generally the fines)

MBT - Mechanical and Biological Treatment (Separation and composting)

Treatment – in this table it relates to the amount or intensity of the composting process.

At this age 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.

Stable non-reactive wastes meeting the WAC fair badly in the base scenario with only two species stabilising within 1000 years and the majority taking in excess of 2000 years. The flushing scenarios show only a marginal improvement with arsenic still persisting beyond 2000 years with an additional 500 mm/y of infiltration.

MSOR 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 arsenic and chromium remain a problem. In this case cadmium does not appear to be an issue at either of its WQSs.

Table 5: Incinerator bottom ash

Waste Type	**Raw Bottom Ash**	**Raw Bottom Ash**	**Bottom Ash**	**Bottom Ash**	**Bottom Ash**	**Bottom Ash**
Treatment	**None**	**None**	**Carbonated**	**Carbonated**	**Acid Treated**	**Acid Treated**
Scenario	**Basic**	**Additional 500 mm/y infiltration**	**Basic**	**Additional 500 mm/y infiltration**	**Basic**	**Additional 500 mm/y infiltration**
Contaminant	**Years to achieve Equilibrium Status**					
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)	140	<3	150	<3	150	<3
Chromium (Cr)	<3	<3	<3	<3	<3	<3
Copper (Cu)	600	240	1750	240	2050	870
Mercury (Hg)	N/a	N/a	N/a	N/a	N/a	N/a
Lead (Pb)	2000	750	<3	<3	<3	<3
Molybdenum (Mo)	410	20	710	55	860	85
Nickel (Ni)	<3	<3	<3	<3	<3	<3
Zinc (Zn)	950	130	<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	1190	75	1180	75
Chloride (Cl)	580	90	570	75	570	20
Ammoniacal Nitrogen (NH_4)	<3	<3	<3	<3	<3	<3
Maximum Management Period Required in scenario	**2000**	**750**	**>2000**	**900**	**>2000**	**1150**

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 State. 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. Note again that for cadmium the DWS and not the MRV has been used in the table. Cadmium meets the MRV at around 400 years.

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.

6.0 CONCLUSIONS

The Holy Grail remains as illusive as ever. While raw wastes managed within a site allowing a moderate amount of leachate generation may be close to achieving equilibrium status the requirements of the Landfill Directive will make this option unavailable for the majority of sites. Combusting waste in incinerators will meet the waste diversion targets, but the effect of combustion and the concentrating of non-combustible fractions would appear to make equilibrium status more difficult to achieve. Treatment technologies such as MBT (providing the composting is intensive) may provide a means of getting close to the objectives. However, the hydraulic conductivity of MBT residues may make it difficult to recirculate the fluids or introduce irrigation within the landfill meaning that they will remain at low liquid-solid ratios for extended periods. The time disjoint between achieving what is modelled as equilibrium status and the timing of the maximum groundwater impacts probably remains as one of the major hurdles. It will be a brave Regulator that signs a closure certificate for a landfill that still contains contaminants at 10 times the WQS (albeit that the surrender criteria in Waste Management Paper 26A are not too dissimilar to the leachate concentrations at the time of management cessation generated as part of this research). It remains a fact that certain waste streams should be diverted from landfill. Those containing List I substances, high concentrations of chloride or sulphate and appreciable quantities of metals are not well suited to landfill.

References

Bone B.D., Knox K., Picken A. and Robinson H. (2003a) The effect of carbonation on leachate quality from landfilled municipal solid waste (MSW) incinerator residues. *Proc. Sardinia 2003*, Paper No. 453.

Bone B.D., Knox K., Picken A. and Robinson H. (2003b) The effect of mechanical and biological pretreatment on landfill leachate quality. *Proc. Sardinia 2003*, Paper No. 454.

Council of the European Union (1999) Directive 1999/31/EC on the landfilling of wastes. Official Journal of the European Communities, L182, 1-19.

Council of the European Union (2003) Council decision of 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC. Official Journal of the European Communities, L11, 27-49.

Drury D., Hall D.H. and Dowle, J. (2003) The development of LandSim 2.5. NGCLC Report GW/03/09. Environment Agency, Solihull.

Environment Agency (2003) Hydrogeological risk assessments for landfills and the derivation of groundwater control and trigger levels. Report LFTGN01, Bristol.

Hall D.H. (2002) Landfill directive waste acceptance criteria: a perspective of the UK's contribution to the Technical Adaptation Committee's Modelling Subgroup. *Proc. Waste 2002 Conf. Integrated Waste Management and Pollution Control*, 72-81.

Hjelmar O., Van Der Sloot H.A., Guyonnet D., Rietta R.P.J.J., Brun A. and Hall D.H. (2001) Development of acceptance criteria for landfilling waste: an approach based on impact modelling and scenario calculations. *Proc. Sardinia 2001*, Vol.III, 711-721.

Leikam K. and Stegmann R. (1997) Mechanical, biological pretreatment of residual municipal solid waste and the landfill behaviour of pretreated waste. *Proc. Sardinia 1997*, Vol.I, 463-474.

Robinson H. (1995) A review of the composition of leachates from domestic wastes in landfill sites. Department of the Environment Research report CWM 072/95. Environment Agency, Bristol.

Scheelhaase T. and Bidlingmaier W. (1997) Effects of mechanical-biological pre-treatment on residual waste and landfilling, Proc. *Sardinia 1997*, Vol.I.

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