General enquiries on this form should be made to:
Defra, Science Directorate, Management Support and Finance Team,
Telephone No. 020 7238 1612
E-mail: research.competitions@defra.gsi.gov.uk

SID 5 Research Project Final Report

- **Note**
  In line with the Freedom of Information Act 2000, Defra aims to place the results of its completed research projects in the public domain wherever possible. The SID 5 (Research Project Final Report) is designed to capture the information on the results and outputs of Defra-funded research in a format that is easily publishable through the Defra website. A SID 5 must be completed for all projects.
- This form is in Word format and the boxes may be expanded or reduced, as appropriate.
- **ACCESS TO INFORMATION**
  The information collected on this form will be stored electronically and may be sent to any part of Defra, or to individual researchers or organisations outside Defra for the purposes of reviewing the project. Defra may also disclose the information to any outside organisation acting as an agent authorised by Defra to process final research reports on its behalf. Defra intends to publish this form on its website, unless there are strong reasons not to, which fully comply with exemptions under the Environmental Information Regulations or the Freedom of Information Act 2000.
  Defra may be required to release information, including personal data and commercial information, on request under the Environmental Information Regulations or the Freedom of Information Act 2000. However, Defra will not permit any unwarranted breach of confidentiality or act in contravention of its obligations under the Data Protection Act 1998. Defra or its appointed agents may use the name, address or other details on your form to contact you in connection with occasional customer research aimed at improving the processes through which Defra works with its contractors.

Project identification

1. Defra Project code: WR0110 (formerly WRT220)
2. Project title: Characterisation of residues from industrial processes and waste treatment
3. Contractor organisation(s):
   WRc plc
   Open University
   Cranfield University
   Golder Associates (UK) Ltd
   Energy research Centre Netherlands (ECN)
   DHI
   Knox Associates (UK) Ltd
   SINTEF (Norway)
   Severn Trent Laboratories Ltd (STL)
4. Total Defra project costs (agreed fixed price): £ £441,956
5. Project: start date .... 01 September 2005
   end date .... 20 March 2009

6. It is Defra's intention to publish this form.
Please confirm your agreement to do so...**YES** ☒ **NO** ☐

(a) When preparing SID 5s contractors should bear in mind that Defra intends that they be made public. They should be written in a clear and concise manner and represent a full account of the research project which someone not closely associated with the project can follow.
Defra recognises that in a small minority of cases there may be information, such as intellectual property or commercially confidential data, used in or generated by the research project, which should not be disclosed. In these cases, such information should be detailed in a separate annex (not to be published) so that the SID 5 can be placed in the public domain. Where it is impossible to complete the Final Report without including references to any sensitive or confidential data, the information should be included and section (b) completed. NB: only in exceptional circumstances will Defra expect contractors to give a "No" answer.
In all cases, reasons for withholding information must be fully in line with exemptions under the Environmental Information Regulations or the Freedom of Information Act 2000.

(b) If you have answered NO, please explain why the Final report should not be released into public domain

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

SUMMARY

Good quality waste characterisation data are fundamental to Defra's policies and strategies to manage environmental challenges, yet the UK dataset for the new generation of treated wastes was poor. This project aimed to fill some of the gaps in understanding the characteristics of residues from the treatment of municipal solid waste and industrial process wastes.

Objectives and research methods in outline

The overall objectives were to:

a) provide "state of the art" data and information on the characteristics of pre/post-treatment wastes;
b) provide a UK-wide data resource focusing on composition and leachability (through UK support to leachXS©);
c) review the UK landfill waste acceptance criteria for monolithic wastes.

In outline, the sampling and testing programme included the following stages:

1. identify and select candidate waste streams for testing;
2. design sampling plans to generate appropriate samples of UK waste streams;
3. collect organic and inorganic residues from waste processes;
4. characterize the residues including: chemical composition, biodegradability and/or leaching behaviour;
5. export data to the UK satellite database of LeachXS©, the leaching expert system developed by ECN (Energy Research Centre, Netherlands), DHI (Denmark) and Vanderbilt University (US); and
6. review UK waste acceptance criteria for monolithic wastes based on the assessment of stabilized waste data and comment from European experts.

Key questions addressed in the Research

- Can laboratory tests predict process performance or behaviour of treated wastes if landfilled or recycled to land?
- How successfully can leaching tests be applied to organic wastes?
- Does the correlation between current biodegradability tests hold for a wider range of wastes?
- Is the non-biological cellulase test more cost-effective & reliable than the 4-day and 100-day DR4 and BM100 tests for assessing biodegradability?
- Can the lack of comprehensive characterisation information to support landfill acceptance and modelling emissions to land, water air be satisfactorily addressed?

Key Findings

Application of sampling and testing toolbox

A consistent approach to the sampling and testing of the residues has been used as advocated in the Environment Agency's sampling and testing guidance (2005). This includes the use of scenario-specific sampling plans to enable future replication of testing and the full characterisation toolbox (e.g. composition, leachability, biodegradability testing). The datasets have been imported into leachXS© and the benefits of this data management and expert tool to technical specialists and policy developers can be seen, for example the rapid comparison of the characteristics of the new generation of treatment residues with more traditional waste streams.

A valuable public domain dataset is now available for secondary research on inputs and outputs from the treatment of a range of mixed and single-stream organic wastes as well as waste treatment filter cakes, municipal solid waste (MSW) gasification residues and cement-stabilized incineration residues from an operational European stabilization plant. In addition to the significant body of information on composition, leachability and biodegradability, kappa values have also been generated for future fate and behaviour modelling of major and trace determinands for five organic and three inorganic waste streams.

The upflow percolation leaching test was successfully applied to organic wastes although the standard method presented technical challenges. Further method development on sample preparation, especially related to moisture content and column packing methods, is recommended.

Calculations for landfill diversion of biodegradable municipal waste (BMW) require reliable data on dry matter content and loss on ignition as well as consistent sample preparation methods. Between-laboratory comparisons show that the base datasets are robust. Sample preparation procedures for large mixed municipal waste samples should be agreed before testing commences.

The two biodegradability tests used to assess biodegradable municipal waste diversion were as per the 2005 version of the Environment Agency's MBT guidance i.e. the 4-day and 100-day DR4 and BM100 biodegradability tests. All BM100 tests conducted during this project were taken to completion, and not limited to 100 days, therefore 'BM100' as used throughout this report is equivalent to the term 'BMc' used in the revised MBT monitoring guidance (Environment Agency, 2009). A statistically valid correlation between the DR4 and BM100 tests has been achieved for BMW derived from mixed inputs but not for specific waste streams such as feathers and food waste. This correlation should therefore only be applied for mixed-source BMW associated with monitoring mechanical-biological treatment plant.

Data from the BM100 test represent anaerobic biodegradation in the short term (c. 100 days). This may not indicate ultimate biodegradability over an extended time-scale of several decades, but may represent the inherent risk of potential biogas production when landfilled.

Data from the 24-hour non-biological enzyme hydrolysis test (EHT) correlate well with the more time consuming and costly 100 day BM100 test. However, further research is in progress to improve its versatility and validity.

Potential impact from treatment process or management of treatment residues

The nitrogen fertilizer value of most organic wastes is much lower than that of sewage sludge. More organic waste would therefore be needed to be applied to soils to provide the same fertiliser value as sewage sludge. The partially stabilized organic wastes have a high requirement for oxygen. There is a risk that the soil system would be unable to sustain the oxygen needed for respiration by the *in situ* microbial population and so adverse anoxic conditions are likely to exist in the soil.

As with sewage sludge, most of the organic wastes derived from municipal waste contained levels of metals that exceeded PAS100 limits for metals in quality compost. Where the material is to be applied to land rather than used as quality compost, it may be more appropriate to use limit values for sewage sludge application to land (Department of the Environment, 1996) where sludge application is considered acceptable.

Mechanical biological treatment (MBT) treatment of biodegradable municipal waste (BMW) results in the concentration of metals in the treated residues. There is tentative evidence that MBT also brings about short-term stabilization although this requires verification. There may be a benefit in landfilling MBT residues if the stabilization is permanent. This would be in line with the aims of operating sustainable landfills.

Fully stabilized composted organic wastes contain sufficient amounts of leachable non-biodegradable dissolved organic carbon to risk contaminating groundwater with organic pollutants of unknown biological activity when applied to soils.

Pilot study monitoring of an MBT plant showed the importance of optimising processing conditions during the composting of fresh biodegradable waste. Matching the waste characteristics to emissions may indicate potential risks for enhanced greenhouse gas emissions from biological treatments. This approach may also provide the necessary data to model process conditions with the aim of maximising waste biodegradation while minimising environmental impact. At the same time there is a need to close the extensive knowledge gaps on the most efficient use of biofilters for MBT and there is scope for improved regulation such as the adoption of a standard suite of analysis.

Monolithic waste acceptance criteria for landfill

New characterisation data for stabilized wastes have been used to reassess the waste acceptance criteria for monolithic wastes. The leaching data showed that generally the contaminant release was not controlled by diffusion i.e. that the materials did not therefore perform as monolithic materials but as granular materials. Assessment of cement-stabilized air pollution control residues as granular wastes rather than as monolithic wastes, as permitted in the Landfill (Amendment) Regulations (2005) may be more appropriate.

Key Recommendations

When interpreting waste characterisation data it is important to understand the source, scale, timescales and operational factors of relevance to the sample. The use of sampling plans according to EN 14899 is therefore recommended to ensure replication of the sampling approach. Waste producers need to be encouraged to use the full characterisation toolbox relevant to their waste stream rather than relying only upon tests required for compliance monitoring. A wider uptake of upflow percolation leach testing will provide further data to verify the kappa values reported here and to extend the range of waste streams for which they are available.

The most appropriate criteria for assessing the performance of the cement-stabilized wastes collected for this report were the landfill waste acceptance criteria for granular wastes, not for monolithic wastes.

The characterisation of organic wastes has highlighted some intriguing issues related to the landfilling and land application of the treated residues. We therefore recommend further research in the following areas.

- *Long-term leaching of metals from landfilled MBT residues*: assessing the leachability of carefully linked inputs and outputs to residues from a number of MBT plants will demonstrate whether or not MBT affects the short-term stabilization of metals.

- *Impact of soil application of partially treated wastes on the biological oxygen demand in soils*: investigation is needed to determine whether detrimental effects are observed and whether organic waste applications to soil should be limited by biological oxygen demand.

- *Leachable organic compounds from partially stabilized or stabilized organic waste applied to soil:* information on dissolved organic carbon, an indicator of the total load to surface and groundwater, needs to be extended through assessments of specific organic contaminants, including potentially hazardous compounds derived from anthropogenic activities.

- *Longer-term monitoring of emissions and waste characteristics from MBT treatment plant:* mass – balance calculations require rigorous linked monitoring of inputs and output wastes and gaseous and liquid emissions. This should incorporate seasonal and operational variations at a number of plants representing different treatment operations.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

- the scientific objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
- details of methods used and the results obtained, including statistical analysis (if appropriate);

- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

1. INTRODUCTION

1.1 Background

The waste hierarchy, landfill pre-treatment requirements and landfill diversion targets are among the drivers for reducing the amount of waste that is landfilled. The EU Thematic Strategy on the Prevention and Recycling of Waste recognizes that different waste treatment methods have different environmental impacts and that there will always be residual materials for landfilling. However, where landfilling is required, it needs to be carried out in a sustainable way, for example by limiting the input of materials that prolong the aftercare of landfills and minimizing the generation of environmentally challenging emissions.

Defra is committed to evidence-based policy making. The gaps in appropriate data present a serious barrier to the successful implementation of these policies as there is a lack of technical information about the new generation of treated residue streams, for example, their gross composition, leaching behaviour and biodegradability. It is therefore difficult to predict their behaviour when landfilled or recycled to land with respect to release of metals, nutrients and greenhouse gases. As the proportion of these new treated wastes in landfill increases, modelling the changing source term will become critical. There are also gaps in technical and operational knowledge, for example how efficient are organic waste treatment methods at removing biodegradability and how should biodegradability be defined?

The UK landfill waste acceptance criteria (WAC) for monolithic wastes (monWAC) were published in the Landfill (England and Wales) (Amendment) Regulations 2005. Under this project, testing of cement-stabilized wastes from European production plant has provided comprehensive data for reassessing the monWAC.

1.2 Approach

Project WR0110 (formerly WRT220) was commissioned under Defra's Waste and Resources Evidence Programme to improve understanding of the characteristics of treated wastes by applying the waste characterisation toolbox developed by the Waste Characterisation Technical Committee (TC292) of the European Committee for Standardization (CEN). The overall objectives were to:

- provide "state of the art" data and information on the characteristics of pre/post-treatment industrial and organic wastes;
- provide a UK-wide data resource focusing on composition and leachability (through UK support to leachXS©) and to demonstrate whether the characteristics of the materials render them acceptable for re-use or disposal;
- review the UK waste acceptance criteria for monolithic wastes.

In outline, the main steps of the sampling and testing programme included the following steps.

- Identify and select candidate waste streams for testing.
- Design sampling plans to generate appropriate samples of UK waste streams.
- Collect residues from waste treatment.
- Undertake comprehensive characterisation of the residues including composition, the use of a toolbox of leaching behaviour tests for inorganic residues and/or biodegradability tests.
- Export data to the UK satellite database of the leachXS©, the leaching expert system developed by ECN (Energy Research Centre, Netherlands), DHI (Denmark) and Vanderbilt University (US) (van der Sloot *et al.*, 2003).
- Review UK waste acceptance criteria for monolithic wastes based on the assessment of stabilized waste data and comment from European experts.

1.3 Report structure

The wide-range of wastes and treatment processes sampled lends itself to reporting in discrete packages. Broadly the project can be sub-divided into the assessment of organic wastes and inorganic waste streams with each sub-divided further to highlight those subject areas that may be of relevance to Defra in terms of current and future research and policy development.

This reporting in discrete themes has been adopted here with further details available in annexes and referenced published papers.

Annex A – waste sampling,

Annex B – waste testing,

Annex C – gasification residue characterisation (SINTEF),

Annex D – stabilized residue characterisation (ECN),

Annexes E1, E2, E3.1 and E3.2 - characterisation datasets (spreadsheets),

Annex F – waste stream summaries,

Annex G – reassessment of monolithic waste acceptance criteria for England & Wales (Golder Associates (UK) Ltd),

Annex F – enzymatic hydrolysis test (Cranfield University).

2. SAMPLING AND TESTING

2.1 Overview

The design of the sampling plans follows the guidance provided by the Framework Standard EN 14899:2005 and five supporting Technical Reports produced by CEN Technical Committee 292, Working Group 1. Preparation of a sampling plan ensures that the key objectives of a test programme are considered at an early stage, as well as how those objectives can be practically achieved for the situation and material under investigation, and ultimately provides an audit trail of the sampling exercise.

Two basic approaches have been used in sampling plan design.

The **organic waste programme** required collection of a wide range of organic residues to provide a calibration line for the new BM100 and DR4 biodegradability tests. For the initial test programme single snapshots were needed from a comprehensive set of processes, as opposed to repeat sampling for a small number of residues. To ensure compatibility between sample types and sampling events a generic sampling plan was produced that could be used anywhere, for any process, at any time, and by anyone for this project or for future sampling events. The sampling plan was supported by site-specific sampling records which are provided in Annex A.

In contrast the **inorganic waste programme** was focused on collecting more comprehensive data for a smaller number of waste streams. This objective was achieved by selection of a discrete number of processes or plants, each of which handled a complex cocktail of input wastes and operated a suite of basic treatment recipes. A second objective of this testing programme was to obtain samples that represented the extremes and middle ground of waste inputs and outputs and encompassed the range of processes being undertaken at the selected plants. Process complexity and variability dictated in this instance that sampling would need to take place over a much longer period of time than the single point in time snapshot approach used in the organic waste programme. A discrete number of site-specific sampling plans were produced that targeted each individual operating regime. Paired input/output samples were collected from a suitable fixed operating period determined after analysis of background testing data and discussions with plant personnel. Sampling plans are provided in Annex A.

Details of the laboratory preparation, test methods and analytical procedures are provided in Annex B, including full references to relevant standards (for example leaching tests), which are not repeated here. A number of laboratories undertook the analyses. Variations in approach are also outlined in Annex B with links to other annexes as required.

A large number of generic waste streams were proposed as potential candidates for the testing programme. The project consortium, steering committee and project peer reviewers all contributed to the selection process, both of waste streams and constituents to be quantified, to ensure that the resultant dataset and findings were relevant and fit-for-purpose.

2.2 Organic wastes

Organic waste samples were selected to cover a diverse range of biochemical composition and degree of biological or physical/chemical treatment to challenge the selected waste characterisation methods. For example, this includes waste materials with high carbon/nitrogen (C/N) ratios (such as wood and cardboard packaging wastes), low C/N ratios (such as feathers and fish wastes), partially and fully composted municipal solid waste, partially anaerobically digested wastes, selected wastes treated by autoclaving, samples of compost-like outputs derived from mechanical biological treatment (MBT) and fully composted greenwastes being used in plant growth trials as part of a Grantscape funded project at Reading University (Bardos *et al.,* 2007).

The management of organic wastes entails measuring the biodegradability of waste for process monitoring, landfill diversion of biodegradable municipal waste (BMW) for the Landfill Allowance Trading Scheme (LATS) and product quality. Such measurements are currently carried out using biological test methods (either the anaerobic 100-day BM100 test or aerobic 4-day DR4 test) that involve the use of microbial cultures to decompose the waste during the test. It is envisaged that comparison of the methods in relation to each other and the type of organic waste will help to derive an understanding of how useful each test is with regard to waste characterisation and prediction of how the waste might behave if composted, anaerobically digested, autoclaved, landfilled and recycled to land.

This has been achieved by collecting a wide variety of organic and inorganic wastes and subjecting the wastes to a range of characterisation tests. The 38 organic wastes tested include 18 mixed MSW-derived BMW samples with the rest being specific organic wastes (e.g. feathers, pizza and fish wastes) many of which had undergone treatment by composting, anaerobic digestion or autoclaving.

Each waste was characterised by several analytical tests (Annex B) that included:

- general composition - %BMW (where waste sample is MSW), dry matter at 105ºC (DM), loss on ignition at 550ºC (LOI), total organic carbon (TOC), total nitrogen (TN);
- biodegradability - aerobic DR4 test, anaerobic BM100 test taken to completion and enzyme hydrolysis test (EHT);
- elemental composition - S, Al, Fe, Mn, Cd, Cr, Cu, Ni, Pb, Zn, Hg, As, Ba, Mo, Sb, Se, Ag, Co, Sr, and V;
- biochemical composition - fat, soluble cell contents, hemicellulose, cellulose, lignin and ash;
- one-step L/S10 compliance leaching test BS EN 12457-2.

The term ‘BM100’, as used throughout this report, is equivalent to the term ‘BMc’ as used in the revised MBT monitoring guidance (Environment Agency, 2009), published after completion of this project.

In addition the upflow percolation test BS DD CEN/TS 14405 was carried out on five selected organic wastes representing different stages of decomposition and/or the end-points of different treatment processes. These were: fully composted greenwaste, anaerobic digestion (AD) treated BMW from MBT, fully composted BMW from MBT and partially composted BMW from MBT. Anaerobically digested sewage sludge was also included as there is an existing regulatory framework for its disposal to land and land application is a potential route for many of these other treatment residues.

2.3 Inorganic wastes

The following treatment residues were tested:

- filter cakes from a 100,000 tonne per annum (tpa) continuous batch physico-chemical treatment process handling hazardous and non-hazardous liquid industrial effluents;
- residues from a 100,000 tpa continuous batch physico-chemical process treating air pollution control (APC) residues from MSW energy-from-waste plants;
- bottom ash and APC residues from a 35,000 tpa continuous batch full scale European MSW gasification plant, to provide data to assess comparability with traditional incineration residues; and
- cores from a European cement stabilization plant for hazardous wastes including APC residues from MSW energy-from-waste plants and metal filter cakes.

The selected treatment plants handled high volume wastes from a wide range of sources and were representative of their type. The samples are considered to be comparable with other plants operating similar processes across the UK as the variability observed within one plant is as large, or greater than, the likely variability between plants. Collection of samples from single plants allowed investigation of the variability in waste outputs over time. Detailed discussions were held with the plant operators before sampling. Routine compliance monitoring data for input and output wastes were analysed using spreadsheet plotting and regression tools. This enabled changes in input and output quality to be evaluated and a suitable sampling period that encompassed the main variability expected to be identified. The three physico-chemical processes were operated to minimise process extremes, so while there were significant batch to batch effects, no obvious time or quality trends were observed in the short or longer term. A period of one month was chosen as being of sufficient length to reduce vulnerability to day to day or week to week bias. Samples at the gasification plant were taken over a two week period. This was considered to be sufficient as inputs were single source MSW, pre-shredded to reduce variability in the feedstock. A random start date was chosen and samples were then collected at fixed intervals within the sampling period, i.e. a stratified random sampling approach was selected that covered all the potential components of variability. The sampling plans provide an audit trail of any given sampling exercise and ensure that repeat sampling can be undertaken in a comparable manner. These plans provide worked examples of the approach advocated in BS EN 14899 and the UK Landfill Regulations but importantly these examples could form the basis of a generic industry-wide approach.

A number of representative spot samples of the output wastes were taken within the identified period from a representative mix of process input wastes. Each spot sample was made up of 20 increments to ensure that the sample was representative of the chosen scale of sampling, which in this case, was the size of the load of treated waste being taken off site for disposal. The samples were not designed to be linked. Instead the random sampling approach provides information on the wider population of waste that is not directly sampled.

A comprehensive dataset was required to avoid limiting secondary research (Lewin *et al.*, 2008). Therefore in addition to compositional analysis, the full toolbox of leaching behaviour tests was used as appropriate (compliance - BS EN 12457, upflow percolation - BS DD CEN/TS 14405: 2004, pH dependence - DD CEN/TS 14429:2005 and maximum availability for leaching - EA NEN 7371: 2004. Additional diffusion testing was undertaken on the monolithic wastes. The tank test methodology of EA NEN 7375: 2004 was modified slightly to bring it in line with the Dynamic Monolithic Leaching Test with Periodic Leachant Renewal, which is currently in development within CEN TC292 (WI 292055/prEN 15863)). References to these standard methods and other analytical methods undertaken on the samples analysed in the UK are provided in Annex B. The MSW gasification residues and cement-stabilized ‘monolithic’ wastes were obtained from European plant and characterised by SINTEF and ECN respectively. The data for these residues are reported separately by SINTEF in Annex C and ECN in Annex D. Annex C presents best practice with respect to analytical laboratory reporting. Annex D presents an example of the detailed interpretation that can be undertaken with full characterisation data and a suitable modelling tool.

2.4 Data management

The test data have been exported to the national satellite database of the leachXS© system (van der Sloot, *et al.*, 2003 and http://www.leachxs.org/LeachXSFlyer.pdf). The database can be interrogated at several levels by a range of users allowing the leaching behaviour and composition of specific plant outputs to be compared and the characteristics of generic waste streams to be evaluated on a national and, ultimately, European basis. Operationally, such powerful contextual information may reduce future requirements for plant-specific testing. LeachXS© is backed up by a powerful geochemical modelling framework, ORCHESTRA, which offers the potential for predicting long-term emissions as undertaken for the Sustainable Landfill project (van Zomeren *et al.*, 2005).

Examples of plots of the data that have been exported from leachXS© are included in Annex E3. A more extensive set of leachXS© outputs are appended to the research report for project WR0108 (Defra, 2009 (*in prep*)).

The results from the characterisation tests were then used to assess the potential application of the tests for discerning the environmental implications for the treatment, re-use and disposal of the waste, principally by either landfilling or spreading on land. Whilst the number of samples has been limited, the broad range of sample types and their characteristics allows for a wide-ranging consideration of potential implications as a prelude to more focused prioritised studies to support the Waste Strategy for England (Defra, 2007). The data generated itself becomes the base data which can then be added to from further studies or investigated in secondary research projects.

High level summaries of key characteristics are provided for the key waste streams in Annex F, to allow rapid assessment of major differences between the waste streams e.g. composition, biodegradability and landfill WAC performance, as appropriate.

3. ORGANIC WASTE CHARACTERISATION

3.1 Overview

For this project 38 organic waste samples were collected. Of these 18 samples were MSW-derived BMW composed of a mixture of biodegradable materials whilst the remaining 20 samples were of specific wastes such as feathers, pizza, wood, greenwaste, fish and digested sewage sludge. Samples of several of the organic wastes were taken before and after treatment in different composting, anaerobic digestion and autoclave processes, some of which were themselves part of more complex MBT facilities. Whilst every effort was made to collect representative samples, the study was limited to only a single sample per source in most cases. Therefore the results should not be taken as definitive characteristics of the wastes in question, but seen as an evaluation of the value of the characterisation methods and its potential for assisting future Defra research and policy development. Sampling and testing details are provided in Annexes A and B, summaries of the five key organic wastes are presented in Annex F.

3.2 Robustness of key component determinations: dry matter and loss on ignition

The dry matter (DM) and loss on ignition (LOI) content of organic wastes are key general parameters for normalising waste characterisation data and crucial for some applications such as determining the BMW diversion from landfill achieved by MBT treatment (Environment Agency, 2009). In this study the majority of the organic wastes were analysed by both WRc and the Open University (OU) for their DM and LOI contents. A comparison between the two laboratories (Annex E1.13) shows that a close correlation between results from the two laboratories is possible for these important parameters, i.e.

$DM_{OU} = 0.9918 \times DM_{WRc}$ (correlation coefficient 0.96, $P < 0.0001$)

$LOI_{OU} = 1.0123 \times LOI_{WRc}$ (correlation coefficient 0.98, $P < 0.0001$)

However, an important factor is that most MSW-derived organic wastes require significant preparation in order to provide a sample suitable for DM and LOI analysis. This may mean, for example, preparation of a small, highly shredded and homogenised BMW sample from as much as 100 kg of untreated MSW. The ability of different laboratories to prepare good sub-samples for testing by such methods as DM and LOI from large mixed waste samples has not been evaluated. It is recommended that the waste preparation procedures are evaluated and approved in any waste characterisation study, particularly if this involves the preparation of small sub-samples from large mixed MSW type samples.

3.3 Biodegradability testing of organic wastes

a) Correlation between DR4 and BM100

The rationale behind the Landfill Directive requirement to reduce the amounts of BMW landfilled is to reduce the amount and risk of fugitive emissions from landfills of methane which is a potent greenhouse gas. The methodology for measuring BMW for Landfill Allowance Trading Scheme (LATS) purposes is based on the total wet weight of the BMW, i.e. one LATS unit is equal to one tonne of wet weight of BMW. This assessment takes little account of the actual environmental impact of the BMW. Different BMW materials may differ considerably in their moisture and ash contents which constitute no risk of producing fugitive methane emissions if landfilled. The potential methane emissions are only derived from the biodegradable fraction of the organic matter content of the BMW and this proportion of biodegradable organic matter may also vary between different BMW materials. The aerobic DR4 and anaerobic BM100 biodegradability methods were developed in order to measure the reduction in the biodegradable fraction of the organic matter that occurs during MBT treatment. A correlation between the tests was established so that the quicker and less costly 4-day aerobic DR4 test could be used to give an estimate of the potential biogas production from the BM100 tests.

As the biodegradability dataset has increased with time, the correlation between the DR4 and BM100 tests has been extended to cover a wider range of matrices, including the MSW-derived BMW samples and other commercial BMW samples collected and tested for this project. This information has been used in the revised Environment Agency MBT monitoring guidance (Environment Agency, 2009).

However, while a good between-test correlation was exhibited by the MSW-derived BMW samples, no correlation was observed between DR4 and BM100 tests when applied to the samples from specific waste streams (e.g. feathers, card, food and greenwaste, (Godley *et al.,* 2007)). Therefore it is important that the use of the correlation between the two tests should only be applied within its original design application for MSW-derived mixed BMW associated with MBT monitoring. It is interesting to note that, if the BM100 test results for specific organic waste components of BMW are compared on a wet weight basis, that the biogas production values do not match the biodegradability values currently applied to BMW components within LATS (Table 1).

Table 1. Comparison of measured anaerobic biodegradability of BMW components with LATS values

Sample	BM100 l/kg LOI	% LOI	% DM	Biogas l/kg wet wt	LATS assumed biodegradability factor (%)
Feathers	375	97.9	56.6	208	100
Cardboard	210	90.0	92.3	174	100
BMW (1)*	385	67.4	50.0	130	100
BMW (2)**	312	71.6	53.6	120	100
Mixed food waste	489	91.8	26.8	120	100
Newspaper	130	94.0	90.1	110	100
Greenwaste	182	73.8	41.0	55	100
Mixed wood waste	27	99.1	94.4	25	100

* Input to MBT process (BMW fraction) 1

**Input to MBT process (BMW fraction) 2

Whilst the BM100 data represent anaerobic biodegradation in the short term (c. 100 days) they may not indicate ultimate biodegradability over an extended time-scale of several decades, but may represent the inherent biogas production potential risk when landfilled.

b) Enzymatic hydrolysis test (EHT)

The BM100 test is a good indicator of biodegradability and is arguably the most appropriate test for ascertaining the residual biodegradability of organic wastes for LATS. However, it is a relatively time consuming and costly test. Treatment plant operators require timely and robust information on plant performance with respect to delivering reductions in waste biodegradability for LATS during plant commissioning, optimisation and routine monitoring. The DR4 test provides a result after just 4 days of testing which shows a reasonable correlation with the BM100 test results for mixed BMW. However it measures the readily biodegradable components and this study (Section 3.3.1) has confirmed that the DR4 test is not appropriate for use without the BM100 test for some single-source waste streams.

A novel non-microbial enzyme hydrolysis test (EHT) has been developed as a potential substitute for the DR4 test (Godley *et al.,* 2004; Wagland *et al.,* 2008). The EHT is based on the principle that the majority of the biogas yield (90%) is derived from the cellulose and hemicellulose content of the organic materials (Rodriguez *et al.*, 2005). As described in greater detail in Annex H, the EHT is a short (24 hour) test which is conducted in three phases, the chemical oxygen demand (COD) is determined during each phase and the result converted to dissolved organic carbon (DOC). The cumulative DOC released during the three phases is indicative of the biodegradability of the material. The DOC released during Phase 1 of the test is likely to represent the readily soluble low molecular weight organic matter in the waste. Phase 2 DOC may include carbon mobilised during heat treatment by hydrolysis of polymer desorption of soluble materials. Phase 3 uses enzymes to hydrolyse the cellulose and hemicellulose present in the waste and the DOC released by enzymatic hydrolysis may be indicative of biodegradability.

As part of this research the EHT test was used to measure the amount of DOC released for a range of treatment process wastes including partially treated and fully stabilized MSW samples and other specific non-MSW samples such as pizza and fish waste. A correlation between the quantities of DOC released during enzymatic hydrolysis and the BM100 tests was established for the same waste samples (Annex H, Godley *et al.*, 2007 and Wagland *et al.*, 2009) and this was compared with the correlation between the DR4 and the BM100 test. It was shown that the EHT provided a better correlation with the BM100 than the DR4, and provided biodegradability data in much shorter time scales (24 hours) than other tests. However, further development of the EHT method is required to ensure its robustness and versatility.

c) Comment

The application of actual biodegradability (biogas) production characteristics of organic wastes in a waste management strategy might better reflect the environmental risks associated with landfilling the waste and redefine the cost/benefit for prioritising particular wastes for treatment within a waste strategy. Such an approach would provide a better scientific base from which to take policy decisions that would reflect real risks from environmental emissions of methane. We therefore recommend that Defra considers the implications of applying actual biodegradability data rather than assumed biodegradability data within its waste strategy.

3.4 Landfilling of MBT outputs and sustainable landfills

a) Concentration of inorganic constituents

A key objective of making landfills sustainable is to minimise the period of emissions monitoring and treatment for completed landfills so that no legacy from landfills is passed to future generations. The Landfill Directive requires treatment of waste prior to landfilling and this may include MBT treatment when considered with respect to reducing the amount of BMW landfilled. The characterisation of MBT outputs landfilled is currently based on determination of organic matter content (LOI) and its anaerobic biodegradability, i.e. the extent of biostabilization achieved by MBT treatment. During MBT with a biological composting stage the BMW may lose moisture and some organic matter through microbial decomposition, decreasing the mass of waste if landfilled. This may therefore be beneficial in terms of maximising usage of limited landfill space and Landfill Tax liability as this tax is based on whole waste mass. There is also some current lobbying of government for lower Landfill Tax for MBT wastes to reflect the treated status of the waste.

As the biodegradable organic content of the wastes is removed through treatment the proportion of inorganic components increases. If the composting process does not generate any leachate, there will also be pre-concentration of metals. The implications might be increased levels of metals per m^3 of landfill void and the consequences may need to be considered in terms of moving towards sustainable landfills. In this study we have analysed the total metals and leachable metals (one-step leaching tests) of several BMW samples before and after MBT. Limited evidence suggests that the metal content in the treated wastes is higher than the input wastes. The leachability of some metals also appears to be lower in the output wastes when compared with the inputs. However the observation from the snapshot linked samples must be considered to be tentative. Careful matched input and output sampling, with a greater level of replicate testing is required to demonstrate whether partial metal stabilization is occurring.

The stabilization of metals during biological treatment might be beneficial when considering landfilling of MBT outputs. However it is not known whether this stabilization is a short-term effect or is time-dependent. Treated organic wastes may still decompose under landfill situations and the extent of decomposition would depend on the extent of biostabilization achieved prior to landfill. If the metal loading is higher with MBT residues (due to concentration of metals) then the time-scale for leaching metals may increase. This might be a step away from operating sustainable landfill.

b) Declining leachate source term

One measure for defining the decreasing source term of a non-volatile contaminant is to use kappa values. The Environment Agency's LandSim software tool for groundwater risk assessment for landfill design (Environment Agency, 2004) uses kappa values to describe the decline of the leachate source term with time for different contaminants. While default values can be set, Wahlström, et al. (2006), recommend the use of kappa values generated from column leaching tests.

The upflow percolation test (BS DD CEN/TS 14405) is conducted in a vertical column packed with granular waste, through which the leachant is pumped continuously in upflow mode. Eluate is removed at cumulative liquid to solid ratios of 0.1 to 10 l/kg. The upflow percolation test was applied in duplicate to 5 selected organic wastes. To our knowledge only limited upflow percolation tests have been carried out on organic wastes to date in the UK and there is a demand for an understanding the leaching behaviour and hence kappa values for MBT organic wastes that might be landfilled in the future.

The upflow leaching test can take up to one month to complete under anoxic/low redox conditions which allows the potential for further biodegradation of the waste to occur during the test. Samples were run in standardised anoxic/low redox conditions as far as possible. The application of the upflow percolation test proved feasible experimentally although some adaptations were required as the standard method does not cover some issues, in particular:

- the standard packing method is not applicable to sludges - the sewage sludge sample used an adapted procedure that would need further testing to be generally applicable;
- the standard column size and timing produces a low volume of eluate for the early fractions, limiting the number of analyses possible;
- the high dissolved organic content of the eluates makes filtration difficult and complicates analysis.

Sample preparation especially moisture content and column packing methods are critical to replicability, and further method development research is recommended.

The project peer reviewers and steering committee were consulted to ensure that contaminants for which upflow leaching test data (and kappa values) were missing or poor were prioritised. Calculation of cumulative release and kappa values for a specific contaminant requires its determination in all eight eluates. However this objective can be compromised by the very low eluate volumes released in the initial low solid-to-liquid ratio fractions, particularly for absorbent organic wastes. Key determinands must therefore be prioritised before analytical testing of the eluates commences. Kappa values derived from duplicate upflow percolation testing of the organic waste samples are presented in Annex E3.

The total amount of eluate generated during the upflow percolation test corresponds approximately to that generated during a one-step LS/10 leaching test. Table 2 shows the kappa values and total amount of leached DOC, NH_4^+ and Cl^- for the five selected wastes. As expected, highly leachable NH_4^+ is present in the AD treated materials and poorly leachable NH_4^+ is present in the two fully composted samples. In general the higher the kappa value the more rapid the leaching of any particular parameter. The full significance of these results needs further evaluation and although there is some variation, the values do provide a starting point for further LandSim modelling of landfills with MBT outputs.

In most cases there was an increase in concentration for the first few fractions followed by a decline (Figure 1). This included the conservative "tracer" Cl^- which might be expected to leach out readily giving highest concentration in the first eluate fractions. This suggests most of the leachable material may be held within the solid matrix and that it takes time for this to leach out of the solid matrix into the eluate. The first eluate fractions are then the immediately available leachable material at the surface of the organic material. The tests have shown replicable results comparable to inorganic samples despite the widely varying physical properties, porous and colloidal nature of the organic materials used.

Table 2. Comparison of kappa values and material leached during upflow percolation and one-step L/S10 leaching tests on five selected organic wastes

Parameter	Fully composted greenwaste	AD treated BMW (ex-MBT)	Fully composted BMW (ex-MBT)	Partially composted BMW (ex-MBT)	AD treated sewage sludge
Kappa values					
DOC	0.4	0.4	0.2	0.3	0.2
NH_4^+	0.5	0.3	0.2	0.4	0.3
Cl^-	0.8	0.7	0.6	0.6	0.4
DOC leached mg C/kg					
One-step L/S10 test	2240	3490	1440	8380	3260
Upflow percolation	2925	3827	1085	8100	2125
NH_4^+ leached mg N/kg					
One-step L/S 10 test	18	693	127	865	8174
Upflow percolation	117	1991	91	168	4533
Cl^- leached mg/kg					
One step L/S 10 test	1885	1619	6595	4053	646
Upflow percolation	1954	2056	2759	3967	606

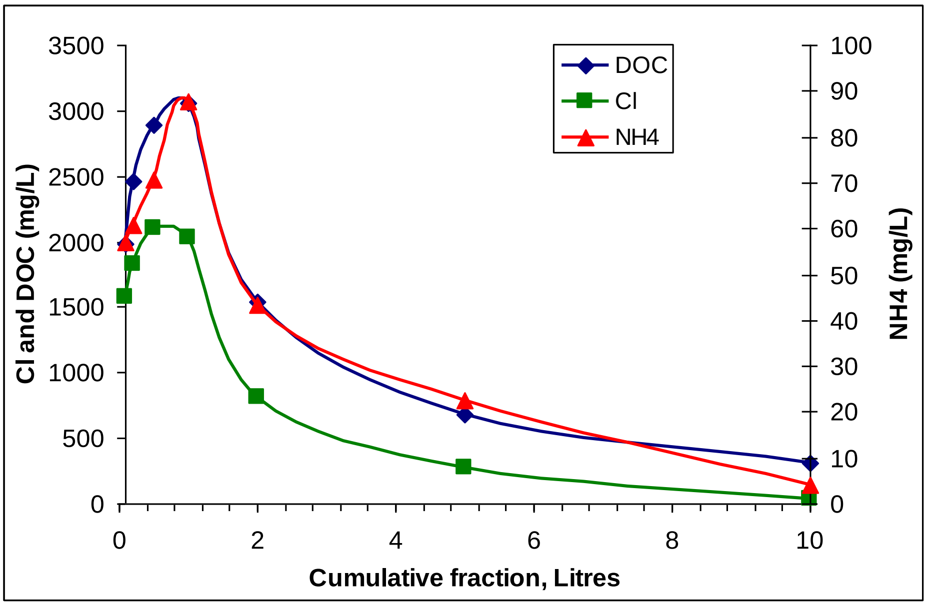

Figure 1. Leaching profiles of DOC, $NH_4^+$and Cl^- from fully composted MSW derived BMW

These studies have shown that leaching tests applied to inorganic wastes may also be applied to organic wastes and that there may be differences between MBT and untreated organic wastes. The full implications of this in terms of landfilling of wastes and the sustainability of landfills require further investigation. It is inconceivable that landfills will not be required in the future as any waste resource management is likely to produce reject materials. These rejects are likely to contain higher levels of pollutants than the untreated waste they were derived from due to cherry-picking from the source waste of materials more amenable to recycling. The behaviour of such materials in landfills should be fully investigated, perhaps moving towards waste acceptance criteria for MBT outputs landfilled.

Kappa values for other determinands, including the priority determinands identified by the project peer reviewers are presented in Annex E3.

3.5 Recycling organic wastes to soil

The recycling of organic wastes to soil may be beneficial for landfill completion, soil restoration, as fertilizers, restoring soil organic matter content, and improving quality of agricultural soils. Many organic wastes such as sewage sludge and greenwaste composts are used in these applications. However soil application needs to be regulated to provide protection from any negative environmental impacts from such actions. Particular environmental concerns relate to increasing the heavy metal content of soils and its impact on soil biology and function, and the leaching of diffuse pollutants such as nitrate to groundwater.

The spreading of organic wastes on land could play a significant role in the diversion of BMW from landfill. The application of treated source segregated BMW components such as PAS100-compliant greenwaste compost to soils including agricultural soils is permitted. However the application of compost like outputs (CLOs) derived from MBT of mixed-source MSW is restricted due to lack of knowledge of the potential contaminants of the CLO such as metals, organic pollutants and contras. CLOs are not currently permitted on agricultural land but may be used in landfill completion and soil restoration activities. Given the uptake of MBT technologies there is a considerable lobby for permitting the application of CLOs to agricultural soils as a long term sustainable outlet.

In this study 18 untreated or partially stabilized BMW samples were tested for metals content, DM, LOI and biodegradability. An evaluation of the data provides some insight into material characteristics that might need to be considered if CLOs were to be recycled to agricultural soils.

a) Metal content of MSW derived BMW samples

Table 3 shows the mean, standard deviation, minimum and maximum metal contents for all the organic wastes characterised in this study. PAS100 limit values are shown for 7 elements of concern (Cd, Cr, Cu, Ni, Pb, Zn and Hg) and whether the waste samples exceed the PAS100 limits. A significant number of the BMW-derived samples failed the PAS 100 limits with 14 of 18 failing for Pb. Most samples derived from MSW exceeded the PAS 100 standard for metals.

Table 3. Heavy metal contents of the organic wastes characterised in this study

Element	Mean mg/kg DM	StDev mg/kg DM	Minimum mg/kg DM	Maximum mg/kg DM	PAS 100 Compost Limit values	Number failing PAS 100		% of BMW derived samples which exceeded PAS limits
						Total	MSW derived	
Al	6963	4343	192	16795	-	-	-	-
Fe	10042	8375	70	40840	-	-	-	-
Mn	229	135	14	537	-	-	-	-
Cd	0.8	0.5	0.1	2.1	1.5	2	2.0	11
Cr	81	82	10	365	100	8	7	39
Cu	132	157	7	660	200	7	6	33
Ni	58	52	3	179	50	16	14	78
Pb	465	931	32	4251	200	14	14	78
Zn	283	214	36	1103	400	10	9	50
Hg	*	*	<0.09	2.5	1.0	3.0	2.0	11
As	6.5	2.9	2.4	12.6	-	-	-	-
Ba	137	96	3	355	-	-	-	-
Mo	6.3	6.3	0.7	24.3	-	-	-	-
Sb	5.2	4.9	0.1	19.3	-	-	-	-
Se	0.8	0.6	0.1	2.8	-	-	-	-
Ag	1.4	1.6	0.3	8.0	-	-	-	-
Co	5.4	3.3	0.3	17.3	-	-	-	-
Sr	-	-	2.0	>360	-	-	-	-
V	-	-	3.0	>40	-	-	-	-

*Concentrations below detectable limits for 10 samples therefore Mean and StDev cannot be calculated

The PAS100 standard is a benchmark for quality composts for all applications including preparation of horticultural growing media. However other wastes permitted to be applied to land, such as sewage sludge, often exceed the PAS100 standard for metals. Table 3 shows the PAS100 metal limits, average metal concentrations for 18 BMW-derived samples, and average metal concentrations for sewage sludge. The regulation of sewage sludge application to agricultural soils is focused on limiting the accumulation of metals in receiving soils rather than metal contents of the sewage sludges (SI 880:1990, Department of the Environment, 1996). The application of MBT-derived CLOs to agriculture might be similarly regulated. Therefore it is recommended that focus on metal contents of MSW-derived BMW intended for recycling to agricultural land should be in line with existing practices for other materials such as sewage sludge, provided it is agreed that the sewage sludge application is acceptable.

Table 4. Comparison of MSW derived BMW samples with sewage sludge metal contents (mg/kg)

Source	Zn	Cu	Ni	Cd	Cr	Pb	Hg
PAS100:2005	400	200	50	1.5	100	200	1
Sewage sludge 1996/7	792	568	57	3.3	157	221	2.4
BMW (18 samples)	412	197	93	1	116	769	nd

Source of sewage sludge data: Gendebien *et al.,* 1999.

Whilst this study adds to the body of knowledge on metal contents of MBT-derived CLOs there is still a lack of data on the content of toxic organic pollutants within different organic wastes. It is recommended that this gap in knowledge is addressed.

b) Nitrogen fertilizer value of organic wastes

Application of organic wastes to agricultural land may be carried out to provide N fertilizer. Anaerobically digested sewage sludge has been applied to agricultural land for many years due to its high N fertilizer value; it is therefore useful to compare the recycling to land of sewage sludge and other treated organic wastes in terms of their relative N fertiliser value. For example consider the recycling of fully composted greenwaste, anaerobically digested BMW, fully composted BMW, partially composted BMW and anaerobically digested sewage sludge to a typical sandy soil of low organic carbon content with the following characteristics: soluble organic carbon 1.2%, N 0.14%, bulk density 1 l/kg, incorporation depth 25 cm, inherent soil respiration rate 23 mg O/kg.day and NVZ zone limit of 170 kg N/ha (based on the Woburn soil used in long term sewage sludge trials (Defra, 2002)).

The total N and free NH_4^+ content of the sewage sludge (Table 5) were much higher and the C/N ratio much lower than the other organic wastes considered. The sewage sludge was also not fully stabilized as indicated by the DR4 and BM100 biodegradability test. This means that the sewage sludge provides an immediate source of N as free NH_4^+ and some slow release N by mineralisation of the decomposable fraction of the organic matter, typically considered to be about 15% of the total N made available in the first year of application (Defra, 2000).

Table 5. Comparison of N-fertilizer value for selected organic waste samples

Parameter	Units	Composted Greenwaste	AD treated BMW	Fully Composted BMW	Partially Composted BMW	AD treated Sewage Sludge
Dry matter content	% wet wt	70.6	33.2	72.7	46.5	18.6
LOI content	%DM	30.2	60.6	25.4	64.9	60.9
Carbon content (LECO)	%DM	17.7	33.9	13.7	38.6	30.5
Total N content (LECO)	%DM	1.2	1.5	0.7	1.4	4.7
NH4+ content (1-step leaching test)	mg N/kg DM	18	693	127	865	8170
C/N ratio		14.8	22.6	19.6	27.6	6.5
Zinc content	mg/kg DM	208	491	511	445	681
DR4 test	g O/kg LOI	18.0	54.4	30.0	171.0	122.0
BM100 test	l/kg LOI	11.7	62.0	105.0	306.0	140.0

Table 5 shows that the N fertilizer value would be much less for the other wastes when compared with sewage sludge. For example the composted greenwaste is fully biostabilized; therefore there would be very little further decomposition and further N mineralisation. The partially composted BMW although not fully stabilized has a high C/N ratio and low N content, therefore there would be little free NH_4^+ released during mineralisation as it would be re-fixed into microbial biomass. To achieve the same N fertilizer value as sewage sludge significantly higher application rates of the other wastes would be needed. This would have implications for the associated application of heavy metals and other pollutants to the soil.

The differential in the loading of other wastes in comparison to sewage sludge to achieve the same N fertilizer value is illustrated in Table 6.

Table 6. Nitrogen fertilizer value and impact of soil zinc and respiration following addition of selected wastes to a sandy soil

	Units	Composted Greenwaste	AD treated BMW	Fully Composted BMW	Partially Composted BMW	AD treated Sewage Sludge
N applied	kg/ha	170	170	170	170	170
DM applied	t/ha	14.2	11.3	12.1	12.1	3.6
Wet weight applied	t/ha	20.1	34.1	17.6	26.1	19.4
N available in first year	%	3.0	7.5	3.0	7.5	15.0
N available in first year	kg/ha	5.1	12.7	5.1	12.7	25.5
C applied	t/ha	2.5	3.8	1.7	4.9	1.1
C applied	mg C/kg	1003	1537	680	1962	441
Soil organic carbon after application	mg C/kg	13003	13537	12680	13962	12441
Soil organic carbon % increase	%	8.4	12.8	5.7	16.4	3.7
Zinc application	kg/ha	2.9	5.5	6.2	5.4	2.4
Additional peak soil respiration rate	mg O/kg.d	7.7	37.4	9.2	150.0	26.9
Base soil respiration rate	mg O/kg.d	23	23	23	23	23

The amounts of waste required to give an N application of 170 kg N/ha have been estimated for the 5 different wastes. It can be seen for example that in the case of the partially composted BMW to achieve the same total N application, the amount of waste would need to be 3.4 times greater in dry matter terms than the sewage sludge. If we assume that the N availability is half that of sewage sludge then this application would provide only a modest N-fertilizer contribution equivalent to about 13 kg/ha. This would double the loading of zinc to the soil compared with sewage sludge. These same application rates would have only a small impact on the soil organic carbon but potentially a large impact on the soil oxygen demand if the wastes were not fully stabilized. The question is therefore whether such increases in oxygen demand is a risk to the soil biology.

c) Recycling organic wastes as soil conditioners

If the same wastes were applied to land as a soil conditioner, e.g. to double the soil organic carbon content in the same sandy soil example then higher tonnages would need to be applied. In this case large amounts of N would also be applied greatly exceeding the NVZ limits. Therefore the question is raised of how available is the N in biologically treated wastes. It might be argued that the fully stabilized composted wastes have very little available N so that even if applied in quantity (Table 7) they pose little threat of enhancing nitrate leaching to groundwater, however, soil respiration would be dramatically increased for the majority of the wastes tested except for the most biologically stabilized wastes. In trials on the long-term effects of sewage sludge applications to soils, negative impacts on Rhizobia have been reported in study plots treated with high applications of sewage sludge of up to 80 tonnes C/ha (Defra, 2002). These responses seem to have been worst in plots also receiving high inputs of zinc or copper and it is possible that the high oxygen demand imparted by the addition of large amounts of organic matter may have enhanced potential toxic effects of the metals. The application rates for soil conditioning would also result in higher metal applications to soil (Table 7), and in the case of zinc, the maximum permissible average annual rate (15 kg/ha) for sewage sludge applications is exceeded over a ten year period (Department of the Environment, 1996). This would restrict further organic amendments to the soil.

Table 7. Potential impact on soils of the application of large amounts of organic matter as soil conditioner

	Units	Composted Greenwaste	AD treated BMW	Fully Composted BMW	Partially Composted BMW	AD treated Sewage Sludge
C applied	t/ha	30	30	30	30	30
C leached	kg/ha	378	327	271	743	221
DM applied	t/ha	169	88	213	74	98
Wet weight applied	t/ha	240	267	310	160	529
Additional peak solid respiration rate	mg O/kg.d	92	292	162	917	731
Base soil respiration rate	mg O/kg.d	23	23	23	23	23
N load	kg/ha	2034	1327	3000	1040	4623
Zinc Load	kg/ha	35.1	43.2	109.0	32.9	66.7

Fully stabilized wastes may contain significant amounts of leachable organic carbon. This is considered to consist mainly of humic material and to be of low biodegradability. This may be degraded in the soil, adsorbed by the soil or leached to contaminate surface and ground water, this may require some consideration, especially as soluble humic acids often chelate and solubilise metals. Fully composted greenwaste applied to land at an application rate of 30 t C/ha (240 t/ha wet weight of compost) would result in 378 kg C/ha leached (1.26% of C is soluble from 1 step leaching test). If it is assumed that this is diluted in water to a concentration of 10 mg C/l (equivalent to 10 g/m^3) this could contaminate 37,800 m^3 of water. If 5000 tonnes compost was applied to land under land restoration, this may lead to the contamination 787,500 m^3 of water to 10 mg C/l. As soil restoration activities may apply organic wastes to several hectares the potential risk from stabilized organic matter may be significant. It is therefore recommended that the potential implications on soil quality and function and the effect on surface and groundwater quality as a result of applying large amounts of stabilized and un-stabilized organic wastes to land are investigated.

For fully stabilized wastes however the leachable organic carbon might be considered as recalcitrant (humic) organic matter and therefore may potentially leach from the soil and contaminate groundwater.

There have been recent developments in the testing of natural organic matter in soil and wastes (van Zomeren and Comans, 2007). Information on speciated organics could be used to assess the significance and potential impact of leachable organic compounds, including those derived from natural degradation and potentially hazardous compounds derived from anthropogenic activities.

3.6 MBT emissions to air

Sampling and analysing wastes from MBT and other waste treatment processes provides useful information on the losses and fate of key elements during processing, especially if samples are taken as a time-course during a biological treatment step. Such analysis may also provide information for predicting the environmental impact of disposal of treated wastes to landfill or if applied to land. The speciation of carbon and nitrogen emissions to air needs also to be considered (CO_2, CH_4, NH_3 and N_2O) in order to assess the impact on greenhouse gas emissions. The relative amounts of these gases emitted from MBT and other bio-treatment processes will depend on the waste characteristics, the prevailing microbiological and process conditions. Also, as many treatment processes are operated in batch and semi-batch modes, the emissions may be transient. Linking gaseous emission monitoring to waste sample analysis and in particular biodegradability, should provide an enhanced approach to predicting the environmental performance of MBT and setting optimum processing conditions to minimise impacts.

Whilst a full study to monitor an MBT facility for both waste characteristics and gaseous emissions was beyond the scope of this project, a scoping study was undertaken at an MBT plant with a tunnel composting facility during its commissioning phase. This pilot study investigated the composting of both source-segregated household waste (SSHW) and residual waste. The aims were to assess the practical feasibility of monitoring emissions, to determine the level of emissions generated at key processing stages and to understand better the relationship between emissions and waste characteristics. At this site it was possible to undertake gas sampling at various key locations including the ambient air, the air within the composting hall, the process air following windrow composting, the compost hall air extraction system (switched on during windrow turning) and the exhaust gas from the gas treatment biofilter.

Measurable concentrations of targeted key gases (CH_4, N_2O, NH_3, CO_2, O_2 and VOCs) were found in most gas samples taken, indicating that monitoring is feasible. The concentration of key gases was similar in the composting hall to the ambient air and only slightly enhanced following windrow turning. The process air (sucked through the windrow) was sampled from three windrows containing source-segregated household waste (2x2 days and 1x2 weeks old) and a fourth windrow containing residual waste (3 weeks old). Elevated levels of CH_4, N_2O, VOCs and NH_3 were found in the 2 day old and 2 week old source-segregated household waste windrows whilst levels were greatly reduced for the 3 week old residual waste windrow. In contrast the CO_2 was higher and the O_2 lower in the three week old windrow containing waste with the lowest oxygen demand, indicating that effective composting was taking place. These snapshot results (Table 8) suggest that the 3 week old windrow was more aerobic compared with the three windrows containing the more biologically active wastes (i.e. higher DR4 values) which could be considered to have a greater potential for emissions of CH_4 and VOCs. Hence, on the basis of CO_2 and O_2 levels, the younger windrows appeared to be insufficiently aerated to match their inherent oxygen demand and may be expected to be more anoxic compared with the 3 week old windrow. In practice this was found to be the case (Table 8). For the two windrows containing 2-day old waste, one windrow produced exceptionally high methane emissions while the other windrow had become so anoxic that the resulting highly acidic conditions actually inhibited high methane generation during the monitoring period (data not included). Elevated levels of methane were detected on the biofilter surface even though the composting facility was working very much under capacity during the monitoring period (data not included).

Table 8. Data from MBT operation

	Process air composition							Waste characteristics			
Windrow age	**CH_4**	**N_2O**	**FID***	**PID***	**NH_4**	**CO_2**	**O_2**	**DM**	**LOI**	**Respiration - DR4**	
	ppm	ppm	ppm	ppm	ppm	%	%	%	%	g O/kg LOI	g O/kg DM
3 weeks	106	0.32	149	8	3	3.4	17.8	59.9	56.4	138	77.8
2 days	426	1.34	1435	115	7	1.61	19.1	42.2	75.4	221	167
2 days	2372	2.16	2900	88	25	2.4	18.1	39.6	76.3	233	178
2 weeks	256	1.49	435	73	12	1.94	18.7	43.0	75.2	192	144

* FID = flame ionisation detector, mostly VOCs including methane

#PID = flame photoionisation detector, VOCs (not methane) and some inorganic compounds

It is clear from the pilot study that it is vitally important to optimise processing conditions during the composting of fresh biodegradable waste, characterised by very high oxygen demand (DR4), since anoxic conditions in windrows have the potential to produce very high levels of methane (organic carbon; TOC), which is not effectively ameliorated through biofiltration. Overall, assuming that dedicated MBT facilities using biofilters in the UK will produce similar findings, the study suggests that such facilities may have the potential to emit much greater loads of TOC to air compared with similar German facilities, which employ Regenerative Thermal Oxidation to treat plant emissions rather than biofilters.

These results suggest that matching the waste characteristics to emissions may indicate potential risks for enhanced greenhouse gas emissions from biological treatments. This approach may also provide the necessary data to model process conditions with the aim of maximising waste biodegradation while minimising environmental impact. It is recommended that further work is carried out to verify these initial findings through a comprehensive study of emissions from MBT plant. This should address the knowledge gap on the performance and efficiency of biofilters for MBT and composting, to inform both the regulation and design of such biofilters.

There is little published information on the performance of biofilters, for example on gas destruction efficiencies at operational sites. There are extensive knowledge gaps on the optimal and most efficient use of biofilters for MBT composting applications in respect of media, particle size, depth, moisture content, air flow, residence time, maintenance and longevity of material used in such filters. Following this initial study it is apparent that there is potential for fugitive emissions from some accelerated composting processes used in MBT and, hence, there is scope for improved regulation such as for the adoption of a suite of analysis for monitoring biofilter emissions from MBT processes.

4. INORGANIC WASTE CHARACTERISATION

4.1 Waste streams

The waste streams selected for inclusion in the programme were output residues from a number of treatment processes:

- filter cakes from a 100,000 tpa continuous batch physico/chemical treatment process handling hazardous and non-hazardous liquid industrial effluents;
- treated municipal solid waste incineration air pollution control (MSWI APC) residues from a 100,000 tpa continuous batch physico/chemical treatment process;
- bottom ash and APC residues from a 35,000 tpa continuous batch full scale European MSW gasification plant to provide data to assess comparability with traditional incineration residues; and
- cores from a European cement stabilization plant for hazardous wastes including MSWI APC residues and metal filter cakes.

4.2 Granular treatment residues

The results are presented in Annex E. Key characteristics, e.g. graphical presentation of total concentrations and landfill WAC performance, are summarised in Annex F. The data management tool leachXS© has enabled a rapid comparison of data to indicate variability of waste streams and to compare new data on the characteristics of treatment residues with traditional wastes. Some examples of the power of leachXS data management tools and the benefits of the comprehensive characterisation toolbox approach are shown in the following plots.

- Figure 2: pH dependent lead leachability of bottom ash from MSW gasification is at similar concentrations to that of MSW IBA (incineration bottom ash) (source of some data is leachXS©). The similar leaching profiles indicate that the mechanism controlling lead leachability is likely to be the same for both generic residues.

- Figure 3. Compliance testing shows Pb leachability is highly variable but compliant at L/S10. Column test data provides context for release at lower liquid to solid ratios.

- Figure 4 presents total concentrations, maximum availability and pH dependent leachability for APC residues from MSW gasification. In the key pH 6-12 range, the Cd, Cu and Zn leachability of untreated gasification APC residues is at least an order of magnitude lower than for untreated APC residues from MSW incineration. Data for treated MSWI APC residues fall between the two.

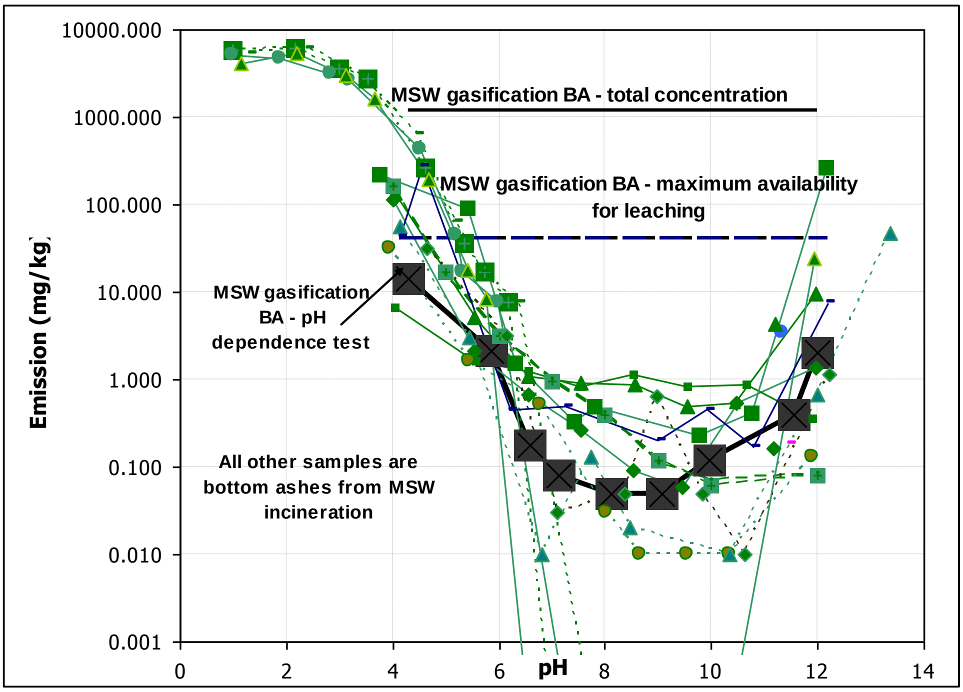

Figure 2. Lead leachability of MSW gasification bottom ash in context of leachXS© data for MSW incineration bottom ash

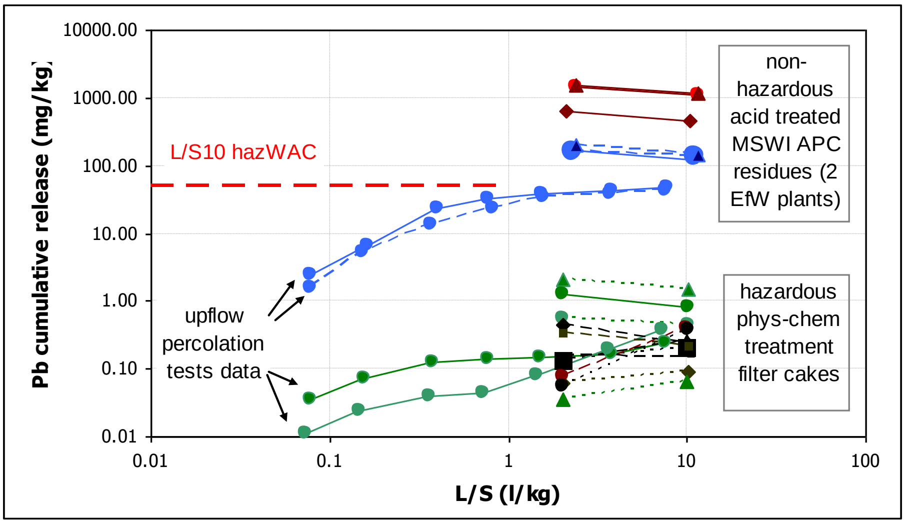

Figure 3. Variability of cumulative lead leaching using batch compliance (L/S2 and 10, BS EN 12457) and upflow percolation test (L/S0.1-10 BS DD CEN/TS 14405, arrowed).

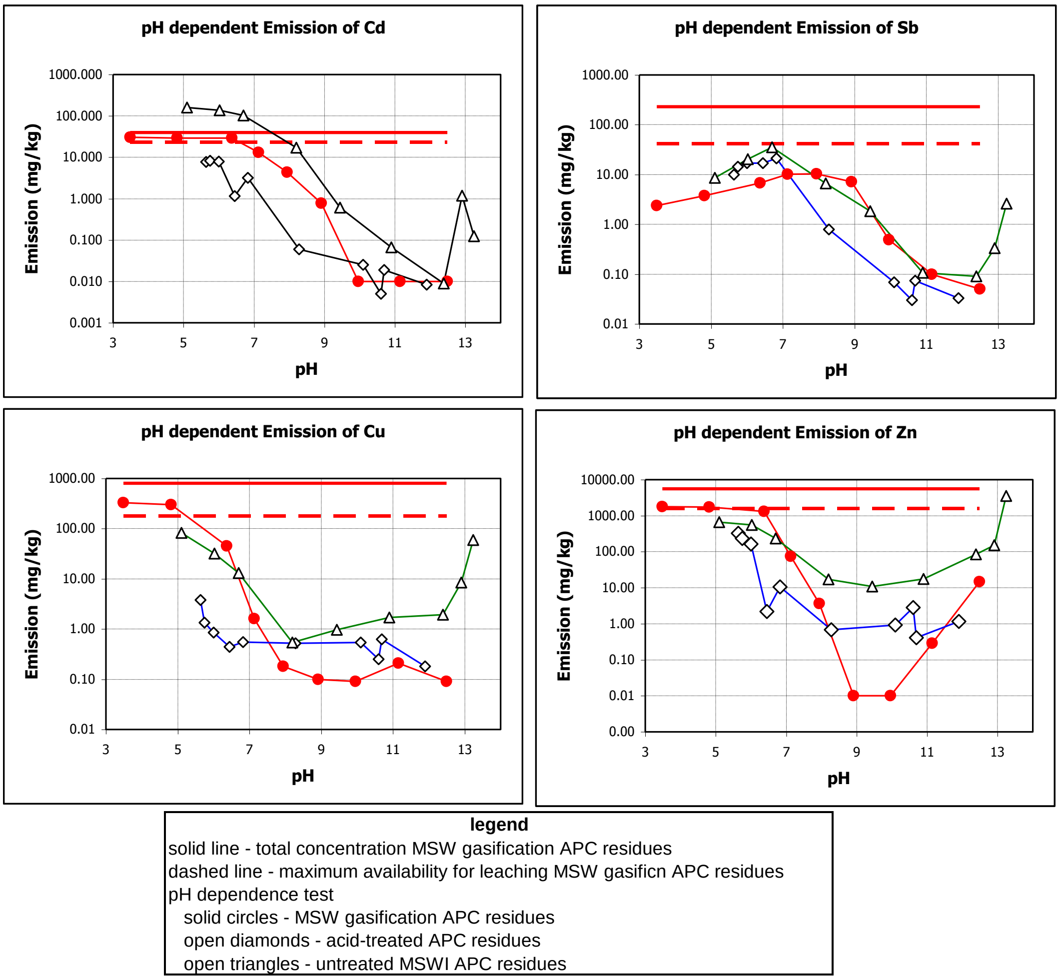

Figure 4. Comparison of pH dependent leachability of APC residues from MSW gasification with untreated and treated APC residues from MSW incineration.

As described in 3.4(b), one of the means of defining a reduction in leachate source term contaminant concentrations with time is the calculation of kappa values using the leaching test concentrations from a column leaching test such as BS DD CEN/TS 14405 upflow percolation test. For those determinands with concentrations above the detection limit in all eluates kappa values have been calculated, and are presented in Annex E3. This includes values for those parameters for which little suitable leaching data exist to date, such as Ba, Mo, F, Ni, Pb and Zn.

The kappa value is the slope of the line when the natural log of the concentration is plotted against liquid to solid ratio. The Environment Agency's LandSim calculation (Environment Agency, 2004) takes the midpoint of the liquid solid ratios for each point (e.g. L/S 5-10 would be plotted as L/S 7.5), whereas the leachXS calculation takes the upper point in each L/S range (i.e. in this example L/S10). There is also the option of additional statistical manipulation. Both calculations are presented in Annex E3. It would appear that the leachXS calculation improves kappa value replication when values of duplicate leaching tests are compared. Further commentary on the kappa values are provided in Annex E3.

4.3 'Monolithic' cement-stabilized wastes

All four samples were stabilized with ordinary Portland cement (OPC) and contained high levels (>69%) of APC residues from MSW energy from waste plant. Two of the samples also contained either metal sludge (P13N) or a substitute binder (P15C). Duplicate testing of crushed cement-stabilized APC residues indicated that granular WAC for Cl and total dissolved solids (TDS) were exceeded by up to a factor of 1.7 (Table 9). The data for the wastes containing APC residues alone (P15N1 and P15N2) indicate that recipe modification to reduce leachability below granular WAC and therefore acceptance to hazardous waste landfill should be achievable. Recipes containing metal filter cake and the substitute binder would present more of a challenge.

With respect to the existing 64 day monWAC for hazardous wastes (Landfill Amendment Regulations, 2005) exceedance of the monolithic waste acceptance criteria was greater both in number of contaminants and degree of non-compliance, than exceedance of granular WAC (Table 9).

Table 9. Cement stabilized waste exceedance of WAC for hazardous landfill

Sample	Granular hazWAC exceedance factor		Existing monolithic hazWAC exceedance factor					
Cement stabilized wastes	**Cl**	**TDS**	**Ba**	**Cu**	**Cl**	**F**	**Pb**	**Sb**
Cement stabilized APC residue (duplicate)	1.0, 1.7	1.4, 1.1	4.6, 6.8	<1, <1	80, 83	1.3, 1.6	1.5,1.5	1.3, 1.6
Cement stabilized APC residue + substitute binder	3.7	2.1	17	<1	140	<1	3.7	<1
Cement stabilized APC residue + metal sludge	2.0	1.0	5.3	4.5	123	1.5	6.6	<1

However, the leaching behaviour of chloride was of the greatest significance. The cement stabilization process was not able to reduce the mobility of the high levels of Cl present in MSWI APC residues, as demonstrated in Figure 5. Both the UK and the (less strict) proposed Dutch limits were exceeded within a few days of the test commencing.

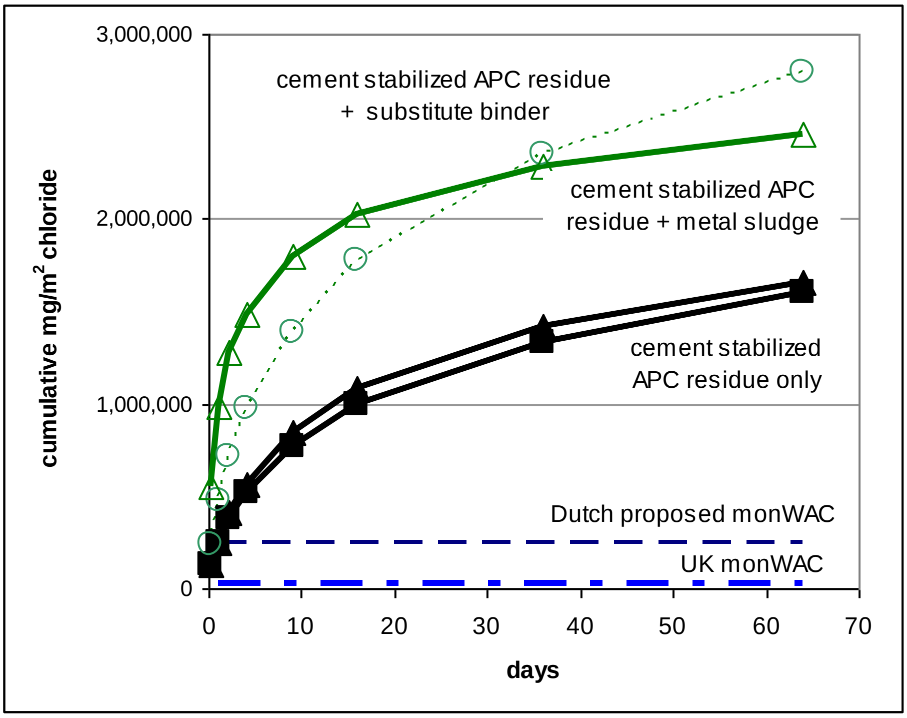

Figure 5. Cumulative chloride release from stabilized APC residues using the Dynamic Monolithic Leaching Test with Periodic Leachant Renewal, (CEN TC292, WI 292055/prEN 15863)

These results are consistent with those emanating from the ProCeSS project led by University College London and funded by DIUS Technology Strategy Board (http://www2.cege.ucl.ac.uk/process/about/index.asp, Lampris *et al.*, 2008).

The chemistry of the stabilization process has been assessed in greater detail by ECN using the geochemical modelling functions of ORCHESTRA within leachXS©. ECN's detailed technical evaluation and demonstration of the power of their modelling tools is provided in Annex D.

4.4 Review of monolithic waste acceptance criteria (monWAC)

The UK waste acceptance criteria (WAC) for monolithic wastes (monWAC) were published in the Landfill (England and Wales) (Amendment) Regulations 2005. The UK monWAC were developed for the Environment Agency (Hall, Drury and Gronow (2005)) by Golder Associates (UK) Ltd based on a leachability dataset for synthetic cement-stabilized MSW incineration (MSWI) air pollution control (APC) residue blocks. The primary mode of contaminant release was assumed to be diffusion. Subsequent reviews of additional datasets and discussions with other European experts indicated that additional modes of contaminant release may also operate. Under this project, testing of cement-stabilized wastes from European production plant provided comprehensive data for reassessing the monolithic WAC.

The monWAC published in the Landfill Amendment Regulations (2005) were derived using synthetic cement-stabilized MSWI APC residues with a very low APC residue content. Golder Associates (UK) Ltd reassessed the original monWAC using the more extensive comparative granular and monolithic leaching test data for the production wastes described in 4.3. These materials contained more realistic levels of APC residue (up to 79%) and more determinands therefore leached consistently above detection limit levels. The reassessment also benefited from the comments of the peer reviewers. In the light of these, in particular, the assumption that the monolithic waste was saturated was revisited. In addition, mercury porosimetry data were used to assess waste porosity and pore throat size distribution. However, it was considered that adoption of some of the comments would have compromised consistency with the development of the WAC for granular wastes, as required by the European Council Decision 2003/33/EC, and were therefore not incorporated into the remodelling.

The reassessment of the modelling is presented in Annex G. A doubling of most of the limits has been proposed for cement-bound wastes. Development of other monWAC would be required on a matrix-specific basis. However, the testing has demonstrated that the dominant leaching mechanisms were dissolution and contaminant depletion rather than diffusion. This suggests that the stabilized waste samples tested were not true monolithic waste samples and that testing as granular materials rather than as monolithic wastes could be more appropriate. This concurs with the recommendation of the Nordic Council of Minsters (Helmar *et al*., 2006) which considers that there should be no differences between the compliance testing of granular and monolithic wastes for landfill acceptance. The current regulatory position in the UK is that monolithic wastes can be crushed and assessed against the granular waste acceptance criteria or assessed against the monolithic waste acceptance criteria using the tank test. This work suggests that there is no need for a change.

The indication that the wastes might not be true monolithic wastes supports research undertaken for Defra by the University of Dundee on Waste Solidification Methods and Stability Assessment (WR0603) (Defra, 2009(b)). The researchers noted that leaching of solidified waste forms is seldom diffusion controlled and recommended higher comprehensive strength levels for monolithic wastes (12 N/mm^2) for landfill acceptance than required by the Landfill Amendment Regulations (2005).

5. KEY FINDINGS

The objectives of this project have been met. The principal findings are summarised below.

- The project has demonstrated the benefits of taking a consistent approach to sampling and testing for main stream industrial residues. The series of sampling plans developed for this project allows replication of the sampling approach to aid interpretation and trend-analysis and can form the basis for a UK–wide generic approach.

- A valuable new public domain dataset on waste treatment residues has been generated to increase the evidence base for policy makers and waste management specialists. The characterisation toolbox recommended in Environment Agency (2005) and ESART (2004) can yield information to answer difficult questions about potential reuse, sustainable landfill, potential environmental impact of residues from new treatment technologies.

- Calculations for landfill diversion of BMW require reliable Dry Matter (DM) and loss on ignition data as well as consistent sample preparation methods for obtaining homogenised BMW sample from untreated material (e.g. MSW or MBT residues). A close correlation between laboratories' DM and LOI data was achieved indicating that the base data were robust. It is recommended that the waste preparation procedures are evaluated and approved in any waste characterisation study, particularly if this involves the preparation of small sub-samples from large mixed MSW type samples.

- A statistically valid correlation between the DR4 and BM100 biodegradability tests was achieved for BMW derived from mixed MSW but the correlation was not the same for non MSW wastes streams (e.g. feathers, food waste). The correlation should therefore only be applied within its original design application for BMW derived from mixed BMW associated with MBT monitoring, as has been applied in the revised MBT monitoring guidance (Environment Agency, 2009).

- BM100 data represent anaerobic biodegradation in the short term (100 days). It may not indicate ultimate biodegradability over an extended time-scale of several decades, but may represent the inherent risk of potential biogas production when landfilled.

- Correlations of the 24 hour non-biological enzyme hydrolysis test (EHT) with the 100 day BM100 test showed the significance of the EHT method as an alternative short-term test method. However, further research is in progress to improve it versatility and validity.

- A comparison of the metal concentrations with PAS100 limits indicated that the majority of the wastes which failed the limits for Cd, Cr, Cu, Ni, Pb and Zn were derived from MSW. Where the material is to be applied to land rather than for use as a quality compost, it may be more appropriate to use limit values for sewage sludge application to land (Department of the Environment, 1996), where sludge application is considered acceptable.

- To achieve the same N-fertiliser value as sewage sludge, a greater quantity of partially stabilized organic waste would need to be applied. This has implications for high BOD loading and adverse anoxic soil conditions, as well as the higher loading of metals that already exceed PAS100 limits. Further research is needed to establish the impact of these anoxic soil conditions on the leachability of contaminants within the treated wastes.

- Fully stabilized composted wastes contain high levels of dissolved organic carbon. Further research is needed to determine the risk to groundwater and surface water from dissolved organic components in the treated wastes, including potentially toxic/ecotoxic compounds derived from anthropogenic activity.

- The upflow percolation leaching test was successfully applied to organic waste streams although the standard method presented technical challenges. Further method development on sample preparation, especially related to moisture content and column packing methods, is recommended.

- Data from the upflow leaching test enabled kappa values to be obtained for the five key organic waste streams (each representing different stages or types of treatment) and for the inorganic treatment residues. In addition to kappa values for major ions, it was possible to generate tentative values for a range of trace determinands for which values are scarce or missing. Further testing is recommended to validate these values and to extend the range of treatment residues for which kappa values can be calculated.

- Pilot study monitoring of an MBT plant showed the importance of optimising processing conditions during the composting of fresh biodegradable waste. The study suggests that such facilities with biofilters may have the potential to emit much greater loads of total organic carbon to air compared with facilities employing Regenerative Thermal Oxidation to treat plant emissions. Matching the waste characteristics to emissions may indicate potential risks for enhanced greenhouse gas emissions from biological treatments. This approach may also provide the necessary data to model process conditions with the aim of maximising waste biodegradation while minimising environmental impact. It is recommended that further work is carried out to verify these initial findings through a full study of emissions and characterisation of waste from MBT to support the design and adoption of a risk-based regulatory approach for monitoring emissions from MBT and composting processes.

- Waste output quality from a single plant can be variable. However, the leaching behaviour of generic wastes between plants can be comparable. Where waste streams can be shown to exhibit a common leaching fingerprint, this means that more extensive EU-wide test data, for example as held in LeachXS©, can be used to put limited site-specific data into context. LeachXS© enables rapid waste characteristic comparisons by plant and waste stream and allows rapid comparison of the characteristics of the old versus the new generation of treatment residues (e.g. gasification vs incineration).

- The stabilized waste dataset was used to reassess the waste acceptance criteria for monolithic wastes. The leaching test data indicate that the cement-stabilized wastes tested did not behave as true monolithic wastes and therefore assessment of these wastes as granular wastes may be more appropriate.

ACKNOWLEDGEMENTS

The authors would like to thank the treatment plant operators for their cooperation in preparing sampling plans and providing samples. We also acknowledge the contribution of: Hans van der Sloot and André van Zomeren of ECN for access to, and training in, leachXS© and for the characterisation of the stabilized wastes; the teams at SINTEF and the Open University for their analytical support, in particular Graham Howell; and Stuart Wagland at Cranfield University. Finally we thank our peer reviewers David Hall of Golder Associates (UK) Ltd and Keith Knox of Knox Associates (UK) Ltd and Defra (Nick Blakey and Jan Gronow) for input at critical decision points in the project.

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

Bardos, P., Chapman, A., Cameron, R., Wheeler, R., Bishop, H., Hadley, P. and Nortcliff, S. (2007) Linking Brownfields Re-Use for Bioenergy Crops with Beneficial Use of Compost-Like Outputs (CLOs) Report for Grantscape, www.grantscape.org.uk. Report of a meeting with CIWM at University of Reading 28 March 2007. Downloadable from www.r3environmental.com.

BS EN 14899:2005 Characterisation of waste – Sampling of waste materials – Framework for the preparation of a Sampling Plan. British Standards Institute, London.

Defra (2000) Fertiliser recommendations for agricultural and horticultural crops (RB209): Seventh edition. http://www.defra.gov.uk/FARM/environment/land-manage/nutrient/fert/rb209/. *Last accessed April 2009.*

Defra (2002). Effects of sewage sludge applications to agricultural soils on soil microbial activity and the implications for agricultural productivity and long term fertility. Report ref: SP0125, CSA4751, 31 July 2002. http://tinyurl.com/d5cdyu *Last accessed March 2009.*

Defra (2007) Waste Strategy for England (2007). http://www.defra.gov.uk/environment/waste/strategy/index.htm *Last accessed March 09*

Defra (2009) Final report of project WR0108. UK support for EU LEACHXS expert database on waste characterisation. (*in prep*).

Defra (2009b) Final report of project WR0603.Non-Radioactive Waste Solidification Methods and Stability Assessment. http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=14748.

Department of the Environment (1996) Code of practice for agricultural use of sewage sludge. http://www.defra.gov.uk/environment/water/quality/sewage/pdf/sludge-cop.pdf. *Last accessed March 2009.*

Environment Agency (2004). LandSim v 2.5: Landfill performance simulation. Available from Golder Associates (UK) Ltd, Nottingham. www.landsim.com/

Environment Agency (2005) Guidance on sampling and testing of wastes to meet waste acceptance procedures, v1, April 2005. Environment Agency, Bristol. http://www.environment-agency.gov.uk/business/sectors/32445.aspx

Environment Agency (2009) Guidance on monitoring of MBT and other treatment processes for landfill allowances (England and Wales) for LATS and LAS. Environment Agency, Bristol. ISBN: 978-1-84911-132-4. http://publications.environment-agency.gov.uk/pdf/SCHO1009BREA-e-e.pdf

ESART (2004) Environmental Services Association Research Trust. A practitioner's guide to testing waste for onward reuse, treatment or disposal acceptance. www.esauk.org/publications/reports/ESART_Practioners_Guide.pdf.
Last accessed March 2009.

European Council (2003) Decision 2003/33/EC of 19th December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 and Appendix II of Directive 1999/31/EEC on the landfill of waste. *Official Journal of the European Communities* L11 16.1.2003.(http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:011:0027:0049:EN:PDF). *Last accessed March 2009*.

Gendebien, A., Carlton-Smith, C., Izzo, M. and Hall, J. (1999) UK Sewage Sludge Survey - National Presentation. Environment Agency R&D Technical Report P165, WRc Swindon.

Godley, A., Frederickson, J., Lewin, K., Smith, R and Blakey, N. (2007). Characterisation of treated and untreated biodegradable wastes. *Proceedings Sardinia 2007: Eleventh International Waste Management and Landfill Symposium,* S Margherita di Pula, CISA Caglari, Italy.

Godley, A.R., Lewin K., Graham, A., Barker, H. and Smith, R. (2004). Biodegradability determination of municipal waste: an evaluation of methods. In proceedings of *Waste 2004: Integrated Waste Management and Pollution Control: Policy, Practice, Research and Solution*. The Waste Conference Ltd., Coventry.

Hall, D.H, Drury, D. and Gronow, J.R. (2005) Monolithic Waste: Modelling of Diffusion Release in Support of Setting the Waste Acceptance Criteria for UK Landfills. *In proceedings of the International Conference Stabilisation/Solidification, Treatment and Remediation – advances in S/S for Waste and Contaminated Land.* Cambridge University, 12-13th April.

Hjelmar, O., Holm, J., and Gudbjerg, J. (2006) Development of criteria for acceptance of monolithic wastes at landfills. *Nordic Council of Ministers*. Copenhagen. ISBN 92-893-1379-X.

Lampris, C., Stegemann J.A., Cheeseman, C.R. (2009) Solidification/stabilisation of air pollution control residues using Portland cement: Physical properties and chloride leaching. Waste Management **29** (3) pp. 1067-1075.

Lewin, K., Turrell, J., Peacock, J., Blakey, N., Gronow, J. and Hall, D. (2008) Application of Waste Characterization Toolbox to Inorganic Treatment Residues. In proceedings of *Waste 2008: Waste and Resource Management - A Shared Responsibility.* Golder Associates (UK) Ltd., Nottingham.

Rodriguez, C., Hiligsmann, S., Ongena, M., Thonart, P. and Charlier, R. (2005). Development of an enzymatic assay for the determination of cellulose bioavailability in municipal solid waste. Biodegradation **16** (5) pp. 415 - 422.

SI 1640:2005 Landfill (England and Wales) (Amendment) Regulations, OPSI, London.

SI 880:1990 Sludge Use in Agriculture (Amendment) Regulations, OPSI, London.

Van der Sloot, H.A., Seignette, P., Comans, R.N.J., van Zomeren, A., Dijkstra, J.J., Meeussen, J.C.L., Kosson, D.S., and Hjelmar, O. (2003). Evaluation of environmental aspects of alternative materials using an integrated approach assisted by a database/expert system. *Advances in Waste Management and Recycling,* Dundee, Scotland, pp. 769-790.

Van Zomeren, A., van der Sloot, H.A., Meeussen, J.C.L., Jacobs, J. and Scharff, H. (2005). Prediction of the long-term leaching behaviour of a sustainable landfill containing predominantly inorganic waste. *Proceedings Sardinia 2005, Tenth Sardinia International Waste Management and Landfill Symposium.* S. Margherita di Pula, CISA, Cagliari.

Van Zomeren, A. and Comans, R.N.J. (2007) Measurement of humic and fulvic acid concentrations and dissolution properties by a rapid batch method, *Environmental Science and Technology*, 2007, **41**, pp. 6755-6761.

Wahlström, M., Laine-Ylijoki, J., Hjelmar, O., Bendz, D. and Rosqvist, H. (2006). Models For Impact Evaluation On Landfill - Aspects for appropriate modelling. Nordic Innovation Centre, Oslo.

Wagland, S.T., Tyrrel, S.F., Godley, A.R. and Smith, R. (2009). Test methods to aid in the evaluation of the diversion of biodegradable municipal waste (BMW) from landfill. *Waste Management*, **29** (3) pp1218-1226.

Wagland, S.T., Godley, A.R., Frederickson, J., Smith, R. and Tyrrel., S.F. (2008). Comparison of a Novel Enzymatic Biodegradability Test Method With Microbial Degradation Methods *Communications in Waste and Resource management,* **9** (3) pp.80-86.